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The role of biogeophysical feedbacks and their impacts in the arctic and boreal climate system

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Abstract

The physical environment in the northern high latitudes including the Arctic cryosphere has undergone dramatic changes due to anthropogenic greenhouse gas warming. Meanwhile, the arctic and subarctic vegetation have been reported to be rather sensitive to such rapid warming. Biogeophysical feedbacks associated with ecosystem responses to climate change are regarded as important contributors to the amplified warming seen over the Arctic. This motivates a study to assess how vegetation dynamics and ecosystem biogeochemistry will evolve under plausible future scenarios, and further how biogeophysical feedbacks associated with vegetation change will influence the climate, carbon cycle and sea ice.

In this thesis, I present findings from studies using an individual-based dynamic vegetation model (LPJ-GUESS) and regional Earth system models (RCA-GUESS, and RCAO-GUESS) to explore the role of biogeophysical feedbacks and their impacts on the Arctic climate system. These models demonstrate good performance in reproducing the present-day dominant vegetation distribution, carbon, water and energy exchange between the land and atmosphere, the mean state of carbon pools and climate, sea ice concentration and areal extent. Under future projections, off-line (non-feedback) simulations using LPJ-GUESS indicate that the pole-ward shift of shrubs and trees and a reduced distribution and abundance of deciduous needle-leaved trees (larch) in favor of evergreen forest is likely to cause positive feedbacks arising from reduced albedo and increased methane emission to outweigh negative feedbacks arising from increased latent heat flux and carbon sequestration. Coupled vegetation-climate simulations using RCA-GUESS project a further carbon sink due to biogeophysical feedbacks, and most of this carbon sink is located in the present-day arctic tundra areas. The net biogeophysical feedback is a result of the balance between the albedo feedback and the evapotranspiration feedback. When evolving under different levels of CO_2-induced warming, biogeophysical feedbacks to near-surface warming differ both in feedback sign and magnitude depending on spatial and temporal scale, varying by season and among sub-regions of the Arctic. When coupling with an ocean sea-ice model, RCAO-GUESS reveals that biogeophysical feedbacks of vegetation change could amplify variations in summer and autumn sea ice areal extent. Increased down-ward long wave radiation aided by a mean sea level pressure anomaly is found to be the main contributing factor to a strengthened sea ice decline. A further investigation is therefore needed to disentangle the complex chain of cause and effect between the Arctic vegetation and sea ice, including the spatial and temporal variability, touched upon in this initial study.

Key words: Arctic and boreal vegetation change, Biogeophysical feedbacks, Albedo, Latent heat, Carbon budget, Representative concentration pathways, Eearth system model, LPJ-GUESS, RCA, Sea ice

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List of Papers

This thesis is based on the following papers, which will be referred to by their Roman numerals. The papers are appended at the end of the thesis. The published papers are reprinted by permission from the copyright holder.

I. Zhang, W., Miller P. A, Smith, B., Wania, R., Koenigk, T. & Döscher, R. 2013. Tundra shrubification and tree-line advance amplify arctic climate warming: results from an individual-based dynamic vegetation model. *Environ. Res. Lett.*, 8, 034023.

II. Zhang, W., Jansson, C., Miller, P. A., Smith, B. & Samuelsson, P. 2014. Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics, *Biogeosciences*, 11, 5503-5519.

III. Zhang, W., Smith, B., Miller, P. A., Jansson, C., & Samuelsson, P. 2014. Evapotranspiration feedback offsets albedo-mediated warming in the boreal zone and Arctic. *Submitted.*

IV. Zhang, W., Döscher, R., Koenigk, T., Miller, P. A., Smith, B., Jansson, C., & Samuelsson, P. 2014. The influence of vegetation feedbacks on recent sea ice dynamics – results from a regional Earth system model. *Manuscript.*

List of Contribution

Paper I	ZW contributed to the study design, performed all simulations and analysis, interpreted the results in discussion with co-authors and led the writing.
Paper II-IV	ZW led the study design, performed all simulations and analysis, interpreted the results in discussion with co-authors and led the writing.

Abstract

The physical environment in the northern high latitudes including the Arctic cryosphere has undergone dramatic changes due to anthropogenic greenhouse gas warming, which since pre-industrial times has been twice or more the rate of global mean warming. Global climate models predict that this accelerated warming will continue for at least the next few decades. Meanwhile, the arctic and subarctic vegetation have been reported to be rather sensitive to such rapid warming. Biogeophysical feedbacks associated with ecosystem responses to climate change are regarded as important contributors to the amplified warming seen over the Arctic. This motivates a study to assess firstly how vegetation dynamics and ecosystem biogeochemistry will evolve under plausible future scenarios, and further how biogeophysical feedbacks associated with vegetation change will influence the climate, carbon cycle and sea ice. In addition, a regional Earth system model (ESM), as a complementary modeling alternative to relatively well-established global ESMs, can describe relevant processes and interactions in more detail and at a finer resolution in time and space. This can lead to better understanding of feedback phenomena characteristic of the Arctic climate system, as well as providing useful information on ecosystem impacts and the associated needs for adaptation they may imply.

In this thesis, I present findings from studies using an individual-based dynamic vegetation model (LPJ-GUESS) and regional Earth system models (RCA-GUESS, and RCAO-GUESS) to explore the role of biogeophysical feedbacks and their impacts on the Arctic climate system. These models demonstrate good performance in reproducing the present-day dominant vegetation distribution, carbon, water and energy exchange between the land and atmosphere, the mean state of carbon pools and climate, sea ice concentration and areal extent. Thereby they provide a robust base-line for understanding and characterizing ecosystem feedbacks to the Arctic climate.

Under future projections, off-line (non-feedback) simulations using LPJ-GUESS indicate that the pole-ward shift of shrubs and trees and a reduced distribution and abundance of deciduous needle-leaved trees (larch) in favor of evergreen forest is likely to cause positive feedbacks arising from reduced albedo and increased methane emission to outweigh negative feedbacks arising from increased latent heat flux and carbon sequestration. Coupled vegetation-climate simulations using RCA-GUESS projects similar changes in vegetation, which results in a further carbon sink due to biogeophysical feedbacks, and most of this carbon sink is located in the present-day arctic tundra areas. The net biogeophysical feedback is a result of the balance between two opposing feedbacks, the albedo feedback and the evapotranspiration feedback. When evolving under different levels of CO_2-induced warming, biogeophysical feedbacks to near-surface warming differ both in feedback sign and magnitude depending on spatial and temporal scale, varying by season and among sub-regions of the Arctic depending on the level of CO_2-induced radiative forcing. Results are discussed in terms of the resilience of ecosystems to climate change. When coupling with an ocean sea-ice model, RCAO-GUESS reveals that biogeophysical feedbacks of vegetation change could amplify variations in summer and autumn sea ice areal extent. Increased down-ward long wave radiation aided by a mean sea level pressure anomaly is found to be the main contributing factor to a strengthened sea ice decline. A further investigation is therefore needed to disentangle the complex chain of cause and effect between the Arctic vegetation and sea ice, including the spatial and temporal variability, touched upon in this initial study.

Sammanfattning

De nordliga höga latitudernas fysiska miljö, inklusive kryosfären i Arktis, har genomgått dramatiska förändringar under de senaste decennierna tack vare uppvärmning och andra klimatförändringar kopplade till antropogena utsläpp av växthusgaser. Uppvärmningen i regionen är ungefär det dubbla jämfört med ökningen i medeltemperaturen globalt. Globala klimatmodeller förutspår att denna förstärkta uppvärmning kommer att fortsätta under kommande decennier. Arktisk och subarktisk vegetation begränsas i sin produktion och utbredning av låga temperaturer och kan därmed förväntas reagera kraftigt och positivt på ökande temperaturer. Effekter såsom ökad tillväxt, densitet och och en högre andel buskar och träd i arktisk vegetation har rapporterats och kopplats till de senaste decenniernas uppvärmning i regionen. Biogeofysiska återkopplingsmekanismer varigenom klimatdrivna förändringar i vegetation inverkar på energibalans i atmosfärens nedre skikt antas spelar en viktig roll i det arktiska klimatsystemet och kan komma att bidra till framtida uppvärmning över Arktis. Mot denna bakgrund undersöker detta arbete dels hur vegetationsdynamik och ekosystemens biogeokemi kan komma att utvecklas under möjlig växthusgasutsläpps- och klimatscenarier för framtiden, dels hur biogeofysiska återkopplingsmekanismer i sin tur kommer att påverka klimatet, kolets kretslopp och havsis. Verktyget för studien har varit en regional jordsystemmodell (eng: Earth System Model) vilken kombinerar en regional modell över fysiska processer i atmosfären och vid jordytan (i en delstudie även i havet) interaktivt kopplad till en dynamisk vegetationsmodell. Genom att simulera det arktiska klimatsystemets viktigaste processer—såväl fysiska som biologiska—på en relativt fin geografisk upplösning kan modellen bidra till en bättre förståelse av återkopplingsprocesser, och samtidigt ge användbar information om klimatförändringarnas ekologiska påverkingar och därtill kopplade anpassningsbehov.

I denna avhandling tillämpar jag den individ-baserade dynamiska vegetationsmodellen LPJ-GUESS och regionala jordsystemmodellerna RCA-GUESS och RCAO-GUESS för att karaktärisera biogeofysiska återkopplingar och deras inverkan på det arktiska klimatsystemet. Modellerna uppvisar goda resultat i jämförelse med oberoende beskrivningar av vegetationsmönster och -utbredning, kol-, vatten- och energiutbyte mellan jordytan och atmosfär, medeltillstånd för kolförråd och klimat, samt havsis koncentration och ytutsträckning. Modellernas prediktioner för dagens

klimat och ekosystem kan därmed anses ge en tillförlitlig utgångspunkt för att beskriva och kvantifiera återkopplingsmekanismer mellan vegetation och klimat.

När det gäller framtida effekter, simuleringar med LPJ-GUESS driven av klimatprojektioner utan återkoppling visar exempelvis på nordliga förskjutningar av utbredningsgränser för buskar och träd och en minskad utbredning av lövfällande barrträd (lärk) i östra Sibirien. Dessa förändringar leder till minskat albedo (reflektans av inkommande solstrålning) och sammanfaller med ökat utsläpp av metan, en kraftig växthusgas, från ekosystemen, samtidigt som avdunstning och därtill kopplade latent värmeflöde ökar och ökad fotosyntes leder till en ökad bindning av koldioxid från atmosfären i vegetationens biomassa. Kopplade simuleringar med RCA-GUESS uppvisar liknande förändringar men tar även hänsyn till återkopplingseffekterna av förändrat albedo och latent värmeflöde på det arktiska klimatet. Resultatet är en förstärkt kolsänka där merparten lokaliseras till dagens arktiska tundraområden. Simuleringar med RCA-GUESS under olika nivåer av CO_2-inducerad uppvärmningen visar att nettoeffekten av de negativa (latent värmeflöde) och positiva (albedo) återkopplingsmekanismerna skiljer sig både i storlek och tecken i tid och rum beroende på CO_2 koncentration och mellan säsonger och sub-regioner av Arktis. Resultat diskuteras i termer av ekosystemens resiliens mot klimatförändringarna. Simuleringar med RCAO-GUESS tar effekter på och av arktisk havsis med i beräkningen. Resultaten visar att biogeofysika återkopplingsmekansimer kan förstärka variationer i isutbredningen på sommaren och hösten, jämfört med simulationer som ej tar hänsyn till effekter av vegetationsförändringar på atmosfären. Ökad långvågig strålning i samband med yttryckanomalier utgör den viktigaste förklarande faktorn för havsisens förstärkta nedgång. Ytterligare undersökningar behövs för att reda ut den komplicerade kedjan av orsak och verkan mellan den arktiska vegetationens och havsisens dynamik, såsom det framkommer i denna förstudie.

中文摘要

由于人为排放温室气体的变暖效应，北极平均变暖速率基于前工业化时代是全球平均变暖速率的两倍或两倍以上。北极对于气候变暖的放大效应使高纬度地区包括北极冰雪圈的物理环境发生了巨大的变化。全球气候模型预测北极的加速变暖将至少持续至未来几十年。同时，报道显示北极和亚北极地区的植被对北极地区的快速升温相当敏感。关于北极地区加速变暖的原因，由生态系统应对气候变化产生的生物地球物理反馈被认为是重要的因素之一。这使得关于评估植被动态和生物地球化学过程如何在未来的气候下演变，及由于植被变化产生的生物地球物理反馈将如何影响气候，碳循环和海冰的研究变得尤为重要。此外，基于区域模式的地球系统模型（ESM），作为全球模式的地球系统模型的一种补充，可以更准确地模拟在时间和空间上具有较高分辨率的相关物理，生物，化学过程及其过程间的相互作用。这为更好地了解北极气候系统的反馈机制，气候变化对生态系统的影响及为如何适应气候变化提供了有用的信息。

本文将介绍如何利用基于个体的动态植被模型（LPJ-GUESS）和区域模式地球系统模型（RCA-GUESS 和 RCAO-GUESS）去探讨生物地球物理反馈在北极气候系统中的作用及其产生的影响。上述模型能够较好的模拟现阶段高纬度地区主要植被的分布，大气和陆地间交换的碳、水、能量通量，土壤碳库，气候，海冰的密度集和面积的平均态。这些过程的模拟对于表征生态系统对未来北极气候的生物地球物理反馈提供了可靠的基础。

在模拟未来植被变化的实验中，LPJ-GUESS 的离线模拟（不考虑反馈作用）表明，灌木林和北方森林显示出向极地迁移的趋势; 西伯利亚的落叶针叶林将被常绿针叶林取代。这些植被的变化将导致由降低的反照率，增加的甲烷排放产生的加剧气候变暖的正反馈超过由增加的潜热通量和碳汇所产生的负反馈。RCA-GUESS 的耦合模拟试验(考虑了反馈作用)也显示了类似的植被迁移。这些植被变化产生的生物地球物理反馈加剧了生态系统的碳汇，并且大多数增加的碳汇来自于目前的北极苔原地区。生物地球物理反馈主要归因于两种对立的反馈(反照率反馈和蒸散量反馈)之间的平衡。在不同浓度 CO_2 产成的辐射强迫下，生物地球物理反馈对于近地表变暖的方向和大小表现出时间和空间上的差异，这些差异主要归因于局部地区的生态系统适应升温和 CO_2 施肥作用的能力。模拟海洋海冰的 RCAO-GUESS 的耦合试验表明植被变化产生的生物地球物理反馈加剧了夏，秋季海冰的变化。在平均海平面气压的辅助下增加的向下长波辐射被认为是造成进一步海冰下降的主要因素之一。因此，对于解释北方植被和海冰的因果关系需要在本文的研究基础上进一步分析它们之间的相关性在空间和时间上表现出的可变性。

“A scientific prediction is not something that is going to happen, but rather something that is happening right now, but no one has ever noticed.”

Contents

Abbreviations

CMIP5: Coupled Model Intercomparison Projects Phase 5
C^4MIP: Coupled Climate Carbon Cycle Model Intercomparison Project
DGVM: dynamic global vegetation model
DLW: downward longwave radiation
ESMs: Earth system models
ET: evapotranspiration
GCMs: general circulation models
GHG: greenhouse gas
IBMs: individual-based models
LAI: leaf area index
LPJ-GUESS: Lund-Potsdam-Jena General Ecosystem Simulator
LSS: land surface scheme
MSLP: mean sea level pressure
NDVI: Normalized Difference Vegetation Index
NEE: net ecosystem exchange
NHLs: the northern high latitudes
NPP: net primary productivity
PHC: Polar Science Center Hydrographic Climatology
PFT: plant functional type
RCA: Rossby Center regional atmospheric model
RCMs: regional climate models
RCO: Rossby Centre regional ocean climate model
RCP: representative concentration pathway
RESMs: regional Earth system models
SIA: sea ice areal extent
SIC: sea ice concentration

1. Introduction

The northern high latitudes (NHLs) including the Arctic cryosphere have undergone startling changes over past three decades and many new records have been set in terms of the changes to its physical environment, for instance, to the concentration, areal extent and thickness of sea ice, surface air temperature, the active layer depth of permafrost, and snow cover extent and duration etc. (ACIA, 2005; AMAP, 2011). Such dramatic changes are attributed to anthropogenic greenhouse gas (GHG) warming, which has been amplified over the Arctic to twice the rate seen in the rest of the world. The Arctic amplification is accelerated by the interactions (i.e. forcings and feedbacks) between components in the Arctic climate system (Serreze and Barry, 2011). The projections of general circulation models (GCMs) or Earth system models (ESMs), such as the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2011) products, clearly indicate that the ongoing accelerated warming will tend to continue till the end of this century (IPCC, 2013).

The rapid warming of the Arctic could have considerable consequences for terrestrial ecosystems in terms of changes in vegetation composition, their structure and functioning, and carbon and water cycling. And indeed much evidence now exits to indicate that the arctic and subarctic vegetation is undergoing rapid change (Epstein et al., 2013). The changes in vegetation will affect climate over wide spatial and temporal scales through both biogeophysical and biogeochemical pathways (Callaghan et al., 2004). As energy and water exchange causes the Arctic system to be sensitive to climate change, the role of biogeophysical feedbacks becomes increasingly important. Positive albedo feedbacks arising from expansion and densification of shrub-lands and forests or from snow-masking by protruding branches and leaves have a large potential to amplify regional climate warming (Chapin et al., 2005; Bonfils et al., 2012). Negative evapotranspiration (ET) feedbacks arising from evaporative cooling or increased reflectance of low clouds tend to dampen the summer warmth (Willeit et al., 2014). Moreover, biogeophysical feedbacks associated with coupled climate–vegetation dynamics will influence biogeochemical feedbacks of terrestrial ecosystems through their influence on the terrestrial carbon and water cycles (Bonan, 2008).

Vegetation-mediated feedbacks are evolving with the GHG-induced warming. The different extents to which species encroachment and displacement occur are expected to trigger biogeophysical feedbacks with large variations across temporal and spatial scales, diverse in their magnitude and feedback sign. The enhanced vegetation activity does not only have effects on local climate conditions, but has also sufficient potential to alter global climate regimes by disturbing energy and moisture transport. The surplus energy over the high latitudes induced by vegetation feedbacks can be transported pole-ward by the atmospheric circulation, causing a warming to the upper-ocean and a melting of sea ice during the warm seasons (Jeong et al., 2014). The feedback chain linking vegetation, atmosphere and sea ice will likely provide an additional positive contribution to the Arctic amplification.

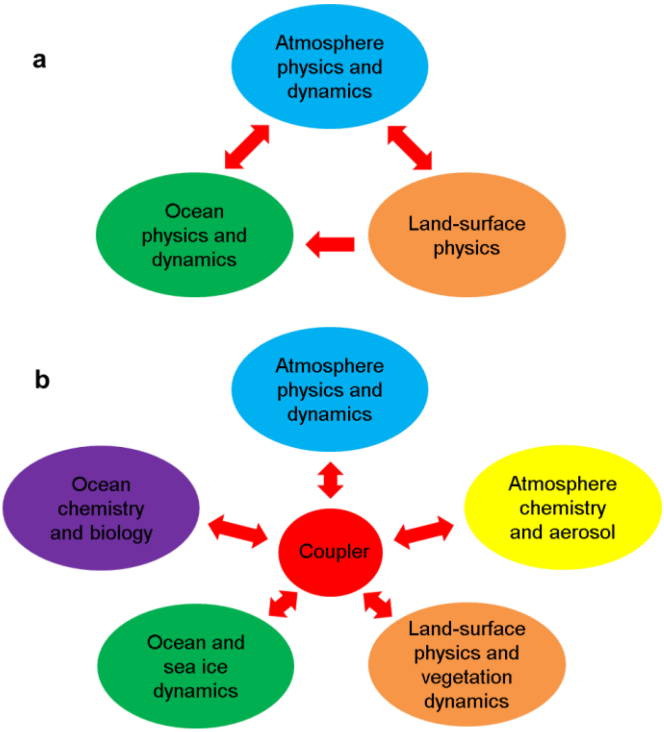

Figure1. The conceptual scheme of a general circulation model (GCM) (a) and an Earth system model (ESM) (b).

ESMs are state-of-the-art climate models providing a sufficiently realistic and spatially explicit representation of physical and biological processes in the Earth system. In common with GCMs, it comprises the core dynamics of physical climate (e.g. transport and exchange of energy like heat and water), but it also incorporates more sophisticated components and processes (e.g. vegetation dynamics, land cover and land use, marine biogeochemistry, clouds and aerosol) to enhance the comprehensiveness in modeling the Earth system (**Figure 1**; Scholze et al., 2012). One advantage of ESMs is their ability to simulate the feedback processes which may amplify or diminish the effects of the initial triggers and then influence climate sensitivity.

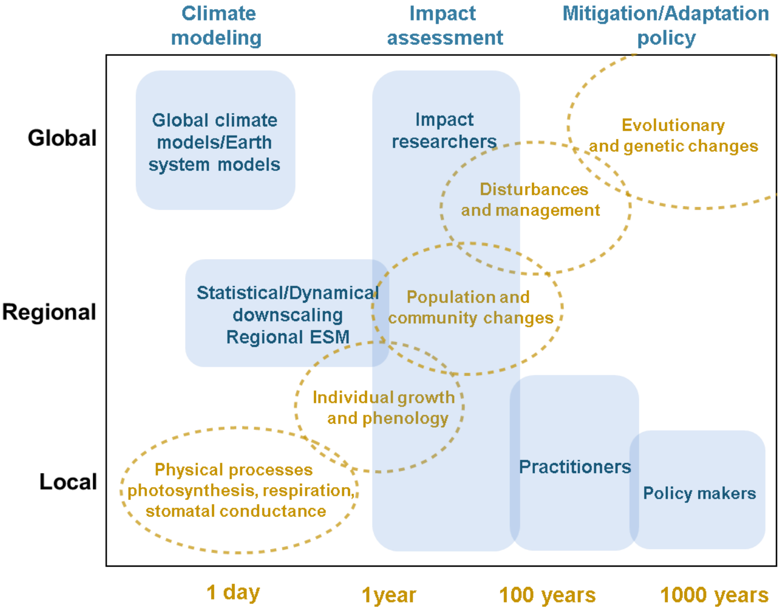

Figure 2. Ecosystem processes (day, year, century and millennium) and Climate services (climate modeling, impact assessment and adaptation policy) from global to local scale.

ESMs have been primarily designed and used for studies at global scale, and therefore they may suffer from having too coarse resolution, without explicitly treating hydrological and ecosystem processes relevant to the landscape scale 10-100 km. To address this issue, regional ESMs (RESMs), developed from regional dynamically-downscaled climate models (RCMs), have become a complementary modeling alternative to elucidate more process details at finer scales, for instance, the biophysically-controlled processes (Giorgi et al., 1995). RESMs bridge the gaps between large-scale and small-scale system changes in time and space. As such, they also bridge the gaps between climate modelers and adaptation-experts and serve as an information-service supplier (**Figure 2**). This PhD thesis comprises a series of modeling studies using an individual-based dynamic vegetation model and fully-coupled RESM to assess the impacts of biogeophysical feedbacks on climate, the carbon cycle and sea ice.

1.1 Arctic and boreal vegetation changes associated with the recent and future warming

1.1.1. The observed changes in arctic and boreal vegetation over the past decades

The distinct geographical patterns of climate (e.g. temperature, sunshine duration, wind and precipitation) and soil properties characterize the distribution of northern terrestrial ecosystems with a transition from closed forests, open forests, shrubs to tundra along the latitudinal zonation in addition to the other transition from forests to treeless areas to barren ground along the altitudinal zonation in some mountainous regions (ACIA, 2005). These zonations are not necessarily consistent across the wide circumpolar Arctic, but they can be easily identified in the Circumpolar Arctic Vegetation Map (Walker et al., 2005) and the Present-day Potential Natural Vegetation Map (Kaplan et al., 2003), both of which are often used to illustrate the present-day distribution of arctic and boreal vegetation. However, increased warming persistent over recent decades with a series of concomitant changes in light and nutrient availability, soil moisture and winter temperature allows woody species to survive, adapt to or relocate to more northerly and harsh environments where they were not fully adapted to, leading to a wide range of changes in ecosystem composition, structure and functioning.

Many lines of evidence ranging from regional to local scales have documented vegetation changes in response to the rapid warming of NHLs. Satellite-derived indices (e.g. NDVI, Normalized Difference Vegetation Index) from most commonly-used satellite data sets in general showed a consistent “greening” pattern and trend in the NHLs, revealing the increased photosynthetic productivity (Goetz et al., 2005; Guay et al., 2014). The most pronounced “greening” was found in the North American tundra (including the North Slope of Alaska) and northeastern Siberia (the northern reach of Siberian needle-leaved deciduous forests). These two regions were coincidently the areas experiencing the largest surface warming in summer over the recent four decades (1961-2004) (Chapin et al., 2005). Repeat photography, field observation records along elevational transects, dendrochronological analysis, and historical documents provided the evidence of tree-line advance in response to local warming, even though the evidence varied depending on the investigation methods and study regions, and driving factors might also be multifaceted (van Bogaert et al., 2011; Mathisen et al., 2014). Plot-scale sampling surveys with a duration up to 20 years discovered that tundra vegetation exhibited strong regional variations in response to warming. The height and abundance of tall shrubs were enhanced, and the change in vascular plant abundance was highly associated with summer warmth (Elmendorf et al., 2012a, b). Manipulation experiments also showed that the experimental warming increased the height and cover of shrubs and graminoids, but vegetation living in the High Arctic might have a lower growth response than those living in the Low Arctic due to limited nutrients and lower diversity (Walker et al., 2006).

The temporary scale for invading species to replace the previous dominant species may range from a few decades to a century, and is influenced by the return time of landscape-scale disturbances, such as forest fires (van der Maarel and Franklin, 2012). But, current observations and studies have already demonstrated arctic and boreal forests have been rather sensitive to recent climate change. This sensitivity highlights the importance of studying how vegetation might evolve with GHG-induced warming scenarios in the future. Nevertheless, there are still few modeling studies with the capability to explicitly reproduce the present-day vegetation distribution, particularly accounting for a sufficient realism to represent transient vegetation dynamics among boreal woody species, wetland grasses and arctic open-ground graminoids, which forms the basis to project future changes in boreal and arctic ecosystems.

1.1.2. Predicted changes in arctic and boreal vegetation in the future

The uncertainties in projections of vegetation changes in the future are determined by both climatic data sets and modeling approaches. The latter is based on either statistical correlations between climate conditions and bioclimatic constraints for biomes or in a coupled process-based manner combining both biogeophysical and biogeochemical mechanisms. Dynamic Global Vegetation Models (DGVMs) describe principal processes and mechanisms concerning plant geography, plant physiology, biogeochemistry, vegetation dynamics and biophysics, which control ecosystems carbon, nutrient, energy and water flux exchanges with the atmosphere. This approach is superior to some statistical models since it captures the transient response of vegetation using process-based knowledge and represents the biotic interactions, such as stomatal control of CO_2 and transpiration (Hickler et al., 2012).

Lucht et al., (2006) used the Lund-Potsdam-Jena DGVM (LPJ-DGVM) to project the change of global ecosystems from the present to the future under the SRES-B1 (2.9 °C of global warming and 550 ppm CO_2 by 2100) and SRES-A2 (5.3 °C of global warming and 856 ppm CO_2 by 2100) scenarios They predicted that boreal evergreen forest will advance its northern edge and see a widespread shift to deciduous species. Its southern boundary in central Asia and Canada will recede, which turns forests into open woodland. These changes are more pronounced in the stronger climate scenario. A state-of-the-art land surface model (CLM4.5) with dynamic vegetation and carbon-nitrogen interaction forced by the outputs of 18 GCMs under the RCP8.5 scenario (an averaged NHL warming of 6-8 °C) also showed a similar pattern of increase and recession of tree covers, particularly from boreal needle-leaved evergreen trees (Yu et al., 2014).

Sensitivity experiments investigating the parameters that control the species distribution in LPJ-DGVM showed that the parameters regulating carbon uptake and light-use efficiency play a predominant role (Jiang et al., 2012).Therefore, temperate broad-leaved species are more sensitive to climate variability, leading to a widespread northward greening in response to anomalous warming However, LPJ-DGVM has parameterized too broad biome types to distinguish deciduous species in needle-leaved from broad-leaved. This issue can be overcome by individual-based models (IBMs). Shuman et al., (2011) used a forest-gap IBM to predict the Siberian Larch distribution after 500 years in response to a warming of 4 °C. They found that a site with a lower diversity of Larch species will be largely replaced by evergreen conifers. Moreover, in the arctic and subarctic tundra, using a machine-learning, multi-class, ecological niche model with relatively fine resolution (4.5 km), Pearson et al., (2013) projected the tree-cover mosaic would shift towards the High Arctic at the North Slope, the Taymyr peninsular and in the North Canadian Archipelago. Nevertheless, there are still many uncertainties regarding the migration rate of forests, since multiple issues intertwined with nutrient cycling, permafrost vulnerability and grazing complicate the prediction of arctic vegetation change (e.g. Zamin and Grogan, 2012; Tchebakova et al., 2009; Yu et al., 2011).

1.2 The impacts of biogeophysical feedbacks to climate, the terrestrial carbon cycle and sea ice dynamics

1.2.1. The impacts of biogeophysical feedbacks on climate

Ecosystem responses to climate change lead to changes in the physical properties of the land surface, for instance, albedo, roughness length, leaf area, rooting depth and the availability of soil moisture, and then trigger biogeophysical feedbacks through the influence on incident solar radiation at the surface, the dissipation of surface energy fluxes, and the partitioning of precipitation into ET and runoff (Foley et al., 2000; Bonan et al., 2008). When increased warming leads to forest advancement into shrub lands and arctic tundra, or when local vegetation becomes more abundant with increased leaf area index (LAI), the land surface is darkened and then absorbs more incoming solar radiation, resulting in a further near-surface warming. This process is defined as a positive albedo feedback to climate change. This effect becomes noticeable in winter and spring, when tree branches or bigger leaves protrude above the snow. On the other hand, tall-stature plants also have a higher roughness length than short plants. The rougher land surface facilitates vertical mixing of water vapor to enhance ET. The surface roughness controlled by the canopy height changes the wind in the planetary boundary layer. The large leaf area increases both the potential for transpiration through leaf stomata and for interception of water on the leaf surface. Changes in ET will affect the surface energy partitioning, convective precipitation and boundary layer structure, leading to changes in near-surface temperature, near-surface humidity and low level cloudiness. In most cases, increased ET will lead to a negative feedback to temperature. The impacts of biogeophysical feedbacks to precipitation are diverse, with indications of positive, negative and neutral effects (Seneviratne et al., 2010; Keuper et al., 2012), and they are likely associated with factors such as wetness of ecosystems, enhanced ET and soil moisture, convective characteristics of climate and land-surface heterogeneities. In the long term, biogeophysical feedbacks can influence climate variability by affecting carbon cycling and thus the atmospheric GHG concentration.

1.2.2 The impacts of biogeophysical feedbacks on the terrestrial carbon cycle

Biogeophysical feedbacks modify the abiotic conditions vegetation growth is reliant upon and interacting with and thus affect the efficiency of the terrestrial biosphere as a sink for CO_2 from the atmosphere (Wramneby et al., 2010). In the shortest time scales associated with terrestrial processes (photosynthesis and ET) (**Figure 2**), changes in the vegetation characteristics (e.g. albedo, roughness length and leaf area) determine how plants are able to use energy and water for carbon assimilation. On seasonal and inter-annual scales, the magnitude and sign of biogeophysical feedbacks may change the timing and variation of the growing season, and soil moisture conditions. These changes will affect seasonal cyclicity of biological events, like budburst, leaf senescence and litter-fall. The overall consequence is to change net primary productivity (NPP), soil organic matter content and soil respiration. On the longest time scales, ecosystem responses to climate are characterized by vegetation succession and migration. They might trigger biogeophysical feedbacks to affect climate at the regional scale, leading to more complex changes in carbon flux compartments, including ecosystem fire disturbance, and in terrestrial carbon pools.

Arctic tundra and boreal forests have sequestered a considerable amount of carbon during historic and recent geological times (Oechel et al., 1993; Ruckstuhl et al., 2008). However, the nature of the current, recent and future C balance of Arctic terrestrial ecosystems is still under debate due to the large uncertainties associated with various methodologies used to estimate regional carbon fluxes or due to the large sensitivities associated with various controlling mechanisms (e.g. gradients of climatic and hydrological variability, disturbances, permafrost vulnerability and nutrient constraints) (Hayes et al., 2011). ESM studies generally agree that biogeophysical feedbacks to climate warming are positive for the NHLs and are likely give rise to an amplified warming in the future (Falloon et al., 2012). However, the amplified warming is also likely to have positive and counteracting effects on both vegetation net primary productivity (NPP) and soil heterotrophic respiration (HR). These responses increase uncertainties in determining whether biogeophysical feedbacks will result in additional carbon sequestration or even in the NHLs acting as a carbon source. Moreover, biogeophysical feedbacks-induced warming have the potential to influence active layer depths in permafrost soils, and allow more carbon release in terms of CO_2 and CH_4 (Field et al., 2007).

1.2.3 The impacts of biogeophysical feedbacks on sea ice dynamics

How biogeophysical feedbacks are linked to sea ice dynamics remains largely unknown since there are very few modelling studies in which the model includes both interactive vegetation dynamics and ocean sea-ice dynamics. Most studies based on observations like satellite-derived NDVI link the sea ice decline with vegetation activities by addressing the association between amplified warming due to sea ice decline and enhanced vegetation productivity due to pronounced warming. Otto et al., (2009) used a coupled atmosphere-ocean GCM ECHAM5-MPIOM including a dynamic vegetation model (JSBACH) to analyze the synergistic effects of different components (atmosphere, ocean, vegetation) to mid-Holocene warming and found that the positive taiga-tundra feedback and the positive sea ice-albedo feedback may strongly reinforce each other in NHLs. Their fully-coupled simulation, including all the feedbacks and synergies, exhibited a larger warming than the other experiments omitting one or two components. The potential for strong vegetation-sea ice interactions is supported by another study (Jeong et al., 2014) using a fully coupled model simulating vegetation feedbacks in doubled CO_2 experiments, finding that vegetation feedbacks can intensify the warming through the enhanced turbulent heat fluxes to the atmosphere. Other studies hypothesize that greater vegetation greenness could intensify the hydrological cycle, and enhance the convective and large scale precipitation (Zhang et al., 2006 and 2007; Swann et al., 2010). However, the above-mentioned coupling studies are based on either vegetation in equilibrium or artificially increased greenness, and are probably not sufficient to capture the transient dynamics associated with vegetation evolving in response to transient, though rapid warming.

1.2.4 Using RESMs for feedback studies

As mentioned before, since most modeling studies analyzing biogeophysical feedbacks focus on the global scale, they are commonly subject to the following limitations. Firstly, models with rather coarse resolution are not able to capture changes occurring at the finer spatial scales of interest for certain feedback processes, for instance, albedo feedback induced from tree-line advance. Tree-line movement seems to be rather insensitive to climate warming on decadal scales (Harsch et al., 2009), and the migration distance is shorter than the rather big grid cells of GCMs/ESMs (more than 100km×100km). Secondly, a global climate model cannot produce climate variations caused by regional scale forcings, for example convective precipitation influenced by topography and coastlines. The circumpolar Arctic has many mountain ranges. The feedback processes concerning these topographical features might be lost in GCMs or ESMs. An RESM, on the other hand, runs at a higher resolution and is developed from the nested or dynamically downscaled climate model, with advantages for capturing regional climatic characteristics. Although it still may be limited by the bias from large scale processes operating outside the model boundary, an RESM indeed improves the local and regional climate information in many cases (Giorgi, 2006). RESMs aim to include the major components of the Earth system, such as atmosphere, land surface with interactive vegetation and ecosystem biogeochemistry, sea ice dynamics and atmospheric chemistry, to understand feedback mechanisms arising from the components' interaction. Smith et al. (2011) and Wramneby et al. (2010) described studies coupling the regional climate model RCA with the individual-based dynamic vegetation model LPJ-GUESS in a European domain. The coupled model showed reasonable agreement with observed ecosystem NPP, vegetation composition, and leaf are index. Wramneby et al., (2010) also applied the model to study a future A1B scenario, and identified three feedback hotspots in Europe, which are dependent on the vegetation response to climate warming and CO_2 fertilization and are diverse among regions. In the Arctic, we are not only concerned with how vegetation change might affect the atmosphere, but also with how it will affect cryosphere and sea ice dynamics. However, there are still large uncertainties as to how the magnitude and sign of biogeophysical feedbacks might vary among regions and across the seasons, depending on the degree of warming and CO_2 fertilization level. This calls for a comprehensive study using an RESM to model the arctic climate system and to improve our understanding of the complex feedback chains linking atmosphere, vegetation and sea ice.

2. Aims and objectives

The main objective of this PhD thesis is to increase our understanding of biogeophysical feedbacks associated with ecosystem responses to climate change and their impacts on climate, carbon cycle and sea ice dynamics, and to improve our abilities to simulate key processes and their interactions within the Arctic Earth system. The future scenarios generated by our regional Earth system model will serve as improved predictions of future climate conditions in the Arctic and provide regional and temporal details to impacts studies, policy makers and adaptation communities with a focus on northern environmental changes. The specific aim of each paper is:

- To simulate the recent and future changes in arctic and boreal upland and wetland ecosystems, and to assess both biogeophysical and biogeochemical feedbacks in the future (using LPJ-GUESS driven by outputs from an A1B GCM scenario downscaled by a regional atmosphere-ocean model RCAO) by accounting for the positive feedback effects of albedo change and CH_4 emission and the negative feedback effects of carbon sequestration and ET change.
- To study how biogeophysical feedbacks might affect the Arctic climate and its terrestrial carbon balance in a warmer, high-CO_2 future climate (i.e. the RCP8.5 scenario) and to identify the aspects of vegetation change that are particularly associated with changes in the terrestrial carbon balance.
- To demonstrate how the trade-off between albedo and ET feedbacks affects inter-annual and seasonal variability of climate, and to highlight the diverse feedback effects to climate associated with ecosystem responses evolving with atmospheric CO_2 concentration pathways.
- To assess the performance of the coupled climate-vegetation-sea ice RESM in simulating climate and sea ice concentration and areal extent, and to analyze how climate-vegetation interactions affect arctic sea ice dynamics.

3. Methods

3.1 LPJ-GUESS, a simulator of vegetation dynamics and ecosystem biogeochemistry

The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) is a process-based model simulating vegetation dynamics, ecosystem biogeochemistry (e.g. the carbon cycle and the nitrogen cycle) and hydrology, customized for landscape, regional and global scales (Smith et al., 2001, 2014). Vegetation dynamics in LPJ-GUESS borrows the "individual-based" concept from forest gap models, which represents the dynamics (demography) of woody vegetation as the emergent outcome of establishment, mortality and competition for light, space and soil resources among individuals from a fixed set of plant functional types (PFTs) and a herbaceous understory. This occurs within replicate patches representing "random samples" of a simulated landscape. PFTs use a set of parameters to represent plant species of similar properties with respect to bioclimatic constraints, phenology, growth form, allometry, tolerance to shading and low light conditions and photosynthetic pathways (Hickler et al., 2004). LPJ-GUESS requires daily climatology (e.g. air temperature, precipitation, incoming shortwave radiation and ambient CO_2 concentration) as forcing to loop the model through ecosystem processes with daily (e.g. photosynthesis, respiration and stomatal regulation) to yearly (e.g. allocation and growth, population dynamics and disturbance) parameterizations. In addition, an improved catchment scale ecosystem hydrology scheme accounting for topography, flow routing and horizontal water movement has recently been developed (Tang, 2014).

In Paper I, the version of LPJ-GUESS (LPJ-GUESS WHyMe) used in the study is customized for both upland and peatland ecosystems in NHLs. In the upland ecosystems, the Arctic-specific PFTs have been adopted to encompass boreal deciduous and evergreen forests, tall and low shrubs and open-ground tundra forbs and graminoids (Wolf et al. 2008). In the peatland ecosystems, the model has incorporated recent developments to LPJ-DGVM by Wania et al. (LPJ WHyMe v1.3.1; Wania et al. 2009a, b, 2010) with regard to soil thawing-freezing processes, peatland hydrology, peatland PFTs, and methane dynamics. The parameter values and bioclimatic limits of all PFTs are given in the supplementary table S1 and S2 in Paper I.

3.2 Regional system models: RCA, RCO and RCAO-GUESS

RCA is the Rossby Centre Atmosphere regional climate model, which was developed based on the numerical weather prediction model HIRLAM (Undén et al., 2002) with a particular focus on maintaining regional energy and water balance to simulate a multi-year climatology with a high degree of realism. The dynamical core of RCA is a two time-level, semi-Lagrangian, and semi-implicit scheme with six-order horizontal diffusion applied to the prognostic variables (Jones et al., 2004a, b; Samuelsson et al., 2011). Kjellström et al. (2005) described further improvements concerning the radiation, turbulence and cloud schemes. A tiling approach to divide each grid cell into forest and open land tiles with or without snow is then employed to address the sub-grid energy balance for the land surface providing the lowest boundary condition to the atmosphere, and gives a better representation of surface processes for the northern regions (Samuelsson et al., 2006). The fourth version of RCA (RCA4) used in Papers II-IV has been recoded and updated mostly to correct known biases in surface processes, for instance, the diurnal cycle of surface temperature and clouds (Samuelsson et al., 2011). Other recent updates involve using new physiography and soil columns based on ECOCLIMAP; using exponential root distributions to remedy the bias due to relatively dry conditions of the soil; using the density and vertical distribution of organic carbon to modify soil properties with respect to heat conduction, heat capacity and water holding capacity; using a prognostic snow albedo that performs better in cold climate conditions; and the introduction of a lake model and lake depth defined from a global lake-depth database.

The ocean component RCO is developed from a widely used Bryan-Cox-Semtner primitive equation ocean model, which represents the 3D ocean structure in geopotential and vertical coordinates with a free surface (Meier, 2002). In addition, RCO incorporates a Hibler-type two-level (open water and ice) dynamic-thermodynamic sea ice model based on an elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997) and Semtner-type thermodynamics (Semtner, 1976). A rotated latitude-longitude grid and a two-equation turbulence closure scheme are used for vertical mixing (Döscher et al., 2010). When RCO is customized for the Arctic domain, 59 unevenly spaced vertical levels are used and the topography is interpolated from the ETOPO5 data set (a digital data base of land and sea-floor elevations on a 5-minute latitude/longitude grid). A closed lateral boundary exists at the Aleutian island chain and an open lateral boundary condition is implemented in the North Atlantic Ocean. The monthly mean data (e.g. temperature and salinity) of the PHC (Polar Science Center Hydrographic Climatology) data set is used to account for the water inflow (Steele et al., 2001). Further forcing is provided by the volume flux of 19 major rivers discharging into the Arctic Ocean (Prange, 2003). To prevent artificial salinity drift due to insufficient description of freshwater runoff and precipitation, sea surface salinity is restored on a timescale of 240 days (Döscher et al., 2010). The ice and snow albedo formulation is based on a modified version of Køltzow (2007) with albedo values depending on the ice surface temperature.

RCAO-GUESS brings together two existing coupled models, namely RCAO and RCA-GUESS. From the technical perspective, RCA is coupled to RCO via the third-party coupling software OASIS4 (Redler et al., 2010), while LPJ-GUESS is invoked by the land surface scheme (LSS) of RCA as a library module (**Figure 3**). RCAO has been described and evaluated for both Baltic Sea and Arctic domains (Döscher et al., 2002 and 2010). In the RCAO model, RCO and RCA run in parallel and exchange information with each other at a frequency of three hours. RCO provides surface state variables such as sea surface temperature, sea ice concentration, ice temperature and snow/ice albedo and RCA returns fluxes of heat (including radiation), freshwater and momentum. In RCA-GUESS, LPJ-GUESS simulates daily LAI and annual vegetative fraction for broadleaved forests, needle-leaved forests and herbaceous vegetation, and passes them to the LSS of RCA to calculate atmospheric resistance, surface resistance and grid-averaged albedo. RCA in turn provides daily air temperature, precipitation, and incoming shortwave radiation to LPJ-GUESS to simulate ecosystem dynamics. More details about the RCA-GUESS coupling can be found in the Paper II. RCA-GUESS has been applied to study coupled climate and vegetation dynamics in many domains, including Europe (Smith et al., 2011; Wramneby et al., 2010), the Arctic (Zhang et al., 2014a, b) and Africa (Wu et al., in prep).

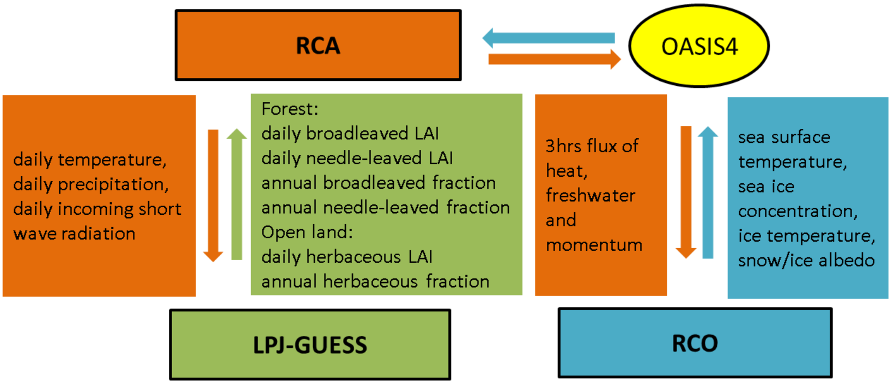

Figure 3. The RCAO-GUESS coupling scheme (Paper IV).

In Paper II, we used the coupled model RCA-GUESS to analyze how biogeophysical feedbacks affect the Arctic terrestrial carbon cycle under a strong future warming representative concentration pathway (RCP) 8.5 scenario. In Paper III; we used the same coupled model to assess how biogeophysical feedback might evolve with the three warming scenarios (RCP2.6, RCP4.5 and RCP8.5) over temporal and spatial scales. In Paper IV, we used the RESM (RCAO-GUESS) to analyze how biogeophysical feedbacks might influence sea ice dynamics.

3.3 Data and experiments

Table 1 summarizes the climatic driving data sets and experiments designed for the studies of this thesis. **Table 2** summarizes the selected variables and the validation data sets employed to evaluate the model's performance. For the model domain, Paper I and Paper IV adopt the RCAO-Arctic domain, which extends from approximately 50°N in the North Atlantic to the Aleutian Islands in the North Pacific (**Figure 4**). The whole domain is integrated at a horizontal resolution of 0.5° for both sub-models RCA and RCO, on a rotated latitude-longitude grid for RCA and a spherical grid for RCO. The simulations in Paper II and III were applied across the Arctic domain of the Coordinated Regional Climate Downscaling Experiment (CORDEX-Arctic). The domain encompasses 150×156 grid points with a uniform resolution of 0.44×0.44° (approximately 50 km) by rotating the pole system over an equatorial domain (**Figure 5**).

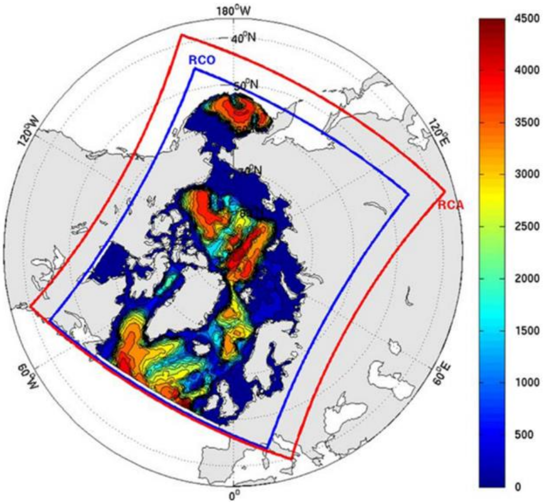

Figure 4. The RCAO arctic domain and bathymetry (m), taken from Döscher et al., 2010.

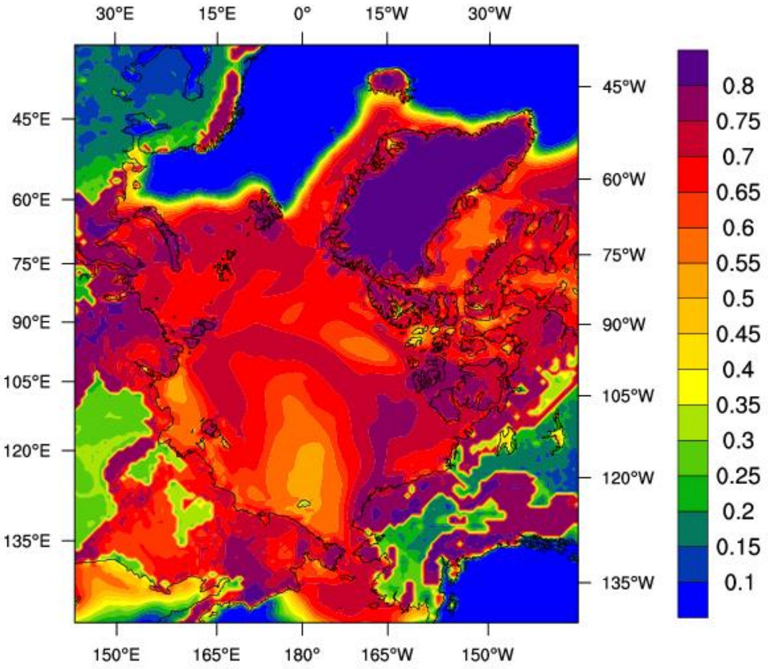

Figure 5. The CORDEX-Arctic domain and spring albedo (0-1).

Table 1 The summary of the climatic driving data sets and experiments designed for the studies of this thesis.

Climate data/lateral force fields (LFF)	**Time period**	**Experiment**	**Paper**
CRU3.0[1]	1901-2006	The off-line simulation of LPJ-GUESS	I
A1B scenario downscaled by RCAO[2] with LFF as GCM ECHAM5/MPI-OM	1961-2080	The off-line simulation of LPJ-GUESS	I
RCP8.5 scenario of EC-Earth[3] CMIP5 outputs as LFF	1961-2100	Two coupled simulations by RCA-GUESS, with and without interactive vegetation dynamics	II
RCP2.6, RCP4.5 and RCP8.5 of EC-Earth CMIP5 outputs as LFF	1961-2100	Six coupled simulations by RCA-GUESS, with and without interactive vegetation dynamics	III
ERA-Interim reanalysis data set[4] as LFF	1989-2012	Two coupled simulations by RCAO-GUESS, with and without interactive vegetation dynamics	IV

[1] Mitchell and Jones 2005; [2] Koenigk et al 2011; [3] Hazelegger et al., 2010; [4] Dee et al., 2011

Table 2. The varaibles and time periods chosen for evaluating models' performance and validation data sets.

Variable	Time period	Validation data sets	Paper
Dominant vegetation distribution (determined by biomass)	1961-1990	A composite vegetation map based on a potential natural vegetation (PNV) map[1], the IGBP land cover dataset 2000-2001[2], and the Circumpolar Arctic Vegetation Map[3] (CAVM)	I
Tree-line determined by biomass	1961-1990	The CAVM tree-line[3]	I
Net ecosystem exchange	1990-1990	Processed-based models and inversion models[4]	I
	2000-2006	Processed-based models and inversion models[4]	
	1901-2080	C^4MIP models[5]	
Net primary productivity	1961-1990	The NPP flux validation data sets: EMDI[6], BAZ[7], GPPDI_1[8], GPPDI_2[9], BOREAL[10]	II
Temperature and precipitation	1961-1990	CRU 3.0 data set	II-IV
		ERA-Interim reanalysis data set	IV
Albedo	1961-1990	the 0.5 degree white-sky albedo from the ISLSCP II MODIS (Collection 4) broadband (300-700 nm) monthly data set for 2002[11]	III
Latent heat flux	1961-1990	the 0.5 degree FLUXNET observation up-scaled dataset constructed using machine learning techniques[12]	III
Sea ice concentration	1992-1996 2007-2012	the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (version 2) data set[13]	IV
Sea ice areal extent	1991-2011	the Sea Ice Trends and Climatologies data set from SMMR and SSM/I-SSMIS2[14]	IV

[1]Kaplan et al 2003; [2] Friedl et al 2010; [3] Walker et al 2005; [4]McGuire et al., 2012; [5]Qian et al., 2010; [6]Olson et al., 2013a; [7]Denissenko et al., 2013; [8]Olson et al., 2013b; [9]Zheng et al., 2013; [10]Gower et al., 2012; [11]Strahler et al., 2009;[12] Jung et al., 2011; [13]Meier et al., 2013; [14]Stroeve, J. et al., 2003

4. Results and discussions

4.1 Tundra shrubification and tree-line advance amplify arctic climate warming (Paper I)

This paper utilizes the offline/uncoupled LPJ-GUESS WHyMe model (i.e. the arctic enabled version) to characterize the arctic and subarctic vegetation and the tree-line boundary across the pan-arctic region for current (1961-1990) and future (2051-2080) time periods. An evaluation of the modeled vegetation was performed using Kappa analysis. Potential land surface feedbacks that were evaluated included net ecosystem exchange of CO_2, net ecosystem atmospheric CH_4 flux, albedo change, and latent heat change.

Results comparing the simulation results driven by the observation data set (CRU TS3.0, 1901–2006) (Mitchell and Jones, 2005) and composite published maps show strong agreement for forests, reasonable agreement for shrubs, and only fair agreement for open-ground vegetation. Future vegetation shows a substantial expansion of forest and a conversion of areas currently dominated by deciduous species to evergreen species in needle-leaved forests, as well as expansion of high shrubs in present-day arctic tundra. The other simulation was driven by the RCAO climate dynamically downscaled from the A1B scenario simulation of the atmosphere–ocean general circulation model ECHAM5/MPI-OM (Koenigk et al., 2011). The results show the pan-Arctic area is largely invaded by tall shrubs and trees because of warm bias in the climate, however, the overall agreement with the CRU-forced run for the total area is substantial. Simulation of the tree-line is reasonable comparing to the CAVM tree-line data set, though with a slight overestimation in northern Canada. A slight carbon sink was simulated with a NEE flux (greater carbon uptake) which increases until 2050, and then declines afterwards. The carbon uptake is strongest in areas where deciduous species in needle-leaved trees converted to evergreen species, and in areas of forest expansion onto shrub-lands or tundra. Methane emissions increase for all months of the year, with hotspots of methane emission in the Hudson Bay lowlands of Canada, and western Siberia. Albedo shifts are larger in the winter with most pronounced shifts occurring in northern Canada and central Siberia in association with increased forest cover and extent leading to a decreasing winter albedo. The largest increase in latent heat flux is found in central Siberia, Alaska, and northern Canada. A reduction of latent heat flux is found in Europe (Finland, France, and Croatia). Our modeling results are largely in agreement with past studies for regions and pan-Arctic simulations of vegetation change. The NEE change implies that a warmer climate may help to maintain the area as a carbon sink at least initially, but shifts in vegetation could weaken this effect or even shift the area to a carbon source.

The results of our study indicate that the variability in biophysical feedbacks both seasonally and regionally will continue in the future warmer climate. The positive feedbacks of decreasing albedo and increasing greenhouse warming may be counterbalanced by negative local feedbacks associated with increased ET. The net effect, however, is likely to be a positive feedback to climate. The study highlights the importance of using dynamic vegetation and biogeochemistry in Earth System Models for assessment of climate impacts on NHLs.

4.2 Biogeophysical feedbacks enhance the future carbon sink (Paper II)

This paper firstly evaluates the ability of the coupled model RCA-GUESS with interactive vegetation dynamics to simulate present-day climate, vegetation distribution, NPP and NEE. The results show that the model output is consistent with the atmosphere-only component model (RCA). Biases in the simulated climate are largely determined by the lateral force fields, which in this case were extracted from the EC-Earth CMIP5 products for the historical period and the RCP8.5 scenario. As for the model's performance in simulating vegetation distribution and carbon fluxes (i.e. NPP, NEE and fire disturbance), the simulations indicate that the arctic and boreal ecosystem types are mostly consistent with a satellite data-based vegetation map; the NPP flux agrees with the observation data sets, particularly in the Arctic tundra area; and the NEE flux extracted from the Arctic tundra area lies within the uncertainty range extracted from the estimations from both offline process-based models (TEM, LPJ GUESS WHyMe and Orchidee, McGuire et al., 2012) and inversion models, indicating that the arctic terrestrial ecosystems are currently acting as a week carbon sink.

Future predictions are based on a comparison of simulations with and without biogeophysical feedbacks. The results of both simulations indicate that the Arctic terrestrial ecosystems will continue to sequester carbon with an increased uptake rate until the 2060–2070s, after which the region will return to being a weaker carbon sink as increased soil respiration and biomass burning outpaces increased net primary productivity. The additional carbon sinks arising from biogeophysical feedbacks are approximately 8.5Gt C, accounting for 22% of the total C sinks, of which 83.5% are located in areas of extant Arctic tundra. Two opposing feedback mechanisms, mediated by albedo and ET changes respectively, contribute to this response. The albedo feedback dominates in the winter and spring seasons, amplifying the near-surface warming by up to 1.35 ℃ in spring, while the ET feedback dominates in the summer months, and leads to a cooling of up to 0.81 ℃. Such feedbacks stimulate vegetation growth due to an earlier onset of the growing season, resulting in compositional changes in woody plants and vegetation redistribution.

4.3 The diversity of biogeophysical feedbacks from low to high RCPs (Paper III)

In this paper, we carried out six experiments with RCA-GUESS forced by three low-to-high RCP scenarios to study how biogeophysical feedbacks might affect temperature and precipitation and then to determine how this is associated with ecosystem changes in response to different levels of CO_2-induced warming.

Our results show that the simulated albedo and latent heat fluxes agree well with observation-based and satellite-based data. The decadal changes in latent heat flux and albedo are also comparable to other off-line simulations. The rescaled sum of the correlations between increased latent heat flux and temperature change and between decreased albedo and temperature change show that the albedo and ET feedbacks become increasingly important in spring and summer respectively from low to high RCP scenario over most land areas. In total, feedback-induced changes in temperature under the RCP2.6 and RCP4.5 scenarios results in additional warming of around 0.3 °C for the period 2070-2099. In contrast, greater biogeophysical feedback results in a decline in the temperature change for the RCP8.5 scenario. The mean change in seasonal precipitation varies little among different RCP scenarios, but the change in the RCP8.5 simulation has larger variations than other two RCP simulations.

The biogeophysical feedbacks lead to contrasting effects on near-surface warming in terms of feedback sign and magnitude, associated with the sub-regional ecosystem responses to climate change. The sub-regions, for example Siberia and North Canada, are expected to experience substantial vegetation change in the future, which in turn leads to larger biogeophysical feedback-mediated changes to ecological climatology, such as a decreasing number of growing degree-days, an earlier spring zero-crossing date, increased annual mean temperature and decreased seasonality. In this paper, we highlight the role of biogeophysical feedbacks to the regional climate are associated with the susceptibility of vegetation to warming and CO_2 fertilization. Accounting for both finer scales of feedbacks and of capturing reasonable vegetation shifts in the susceptible sub-regions in the Earth system model is important to the studies on the impacts of climate change over NHLs.

4.4 Biogeophysical feedbacks enhance sea ice dynamics (Paper IV)

In this paper, we present a RESM study accounting for both interactive vegetation dynamics and sea ice dynamics. The coupled simulations for the periods 1992-1996 and 2007-2011 show that spatiotemporal patterns of sea ice concentrations (SIC) and sea ice areal extent (SIA) are consistent with both previous modelling studies and observations, but vegetation feedbacks cause greater variations in summer and autumn SIA, including in some cases anomalously rapid reductions. The vegetation changes we simulate in the circumpolar Arctic in response to recent climate warming are seen in the slight shifts in the balance between woody and herbaceous species and between evergreen and deciduous species. However, the mean sea level pressure (MSLP) anomaly caused by these vegetation changes can nonetheless alter the transport of energy, leading to increased warming over the land, sea and sea ice surfaces. Consistent with previous modeling studies, we find that increased downward longwave radiation is the dominant factor contributing to the surface warming and further sea ice melt. However, other factors such as sea ice drift due to shifted wind patterns and ocean currents can also play a role in sea ice formation and melting. This highlights the potential importance of including interactive vegetation dynamics in fully-coupled Earth system models, and in particular when simulating and analyzing sea ice dynamics. A further investigation is therefore needed to disentangle the long chain of cause and effect between arctic vegetation and sea ice, including the spatial and temporal variability, touched upon in this initial study.

5. Conclusions and outlook

The objective of this thesis is to use a modeling approach comprising dynamic vegetation to understand the role of biophysical feedbacks in the present and future arctic climate system. The important findings of the thesis can be summarized as below:

- LPJ-GUESS WHyMe is able to reproduce present-day vegetation map reasonably well, and to characterize the potential changes to Arctic vegetation in the plausible warming scenario. A joint consideration of changes to NEE, CH_4, albedo and ET indicate that positive feedbacks induced from declining albedo and carbon sources (fire, soil respiration and CH_4) can compensate the negative feedbacks induced from increased carbon sequestration and ET. This highlights the importance of including dynamic vegetation and biogeochemistry in ESMs to have an overall assessment of the effects of vegetation change on climate over NHLs.

- The simulations using RCA-GUESS based on lateral forcing fields of EC-Earth CMIP5 RCP 8.5 outputs indicate that the mean state of the current Arctic terrestrial carbon balance is neutral or a weak sink, in line with studies using off-line process-based models and inversion models. Biogeophysical feedbacks in the future result in a greater carbon sink through woody species expansion and densification in arctic tundra. Without considering processes involving permafrost carbon, land use and land cover change and nutrient limitation. This feedback estimate is considerable compared to the total carbon sequestration. The impacts of two opposing feedbacks (albedo and ET) on spring and summer temperature are highlighted, and have implications for shifts of seasonality and for timing of the growth season in the future.

- A series of experiments with or without accounting for biogeophysical feedbacks from low to high RCPs scenarios show spatiotemporal changes to near-surface warming due to the trade-off of albedo and ET feedbacks. Higher RCPs tend to trigger strong albedo and ET feedback in spring and summer respectively. The overall effects of biogeophysical feedbacks in the higher RCP scenarios tend to increase growing season length but diminish the seasonality. These effects vary among regions and are determined by ecosystem resilience to climate change. This study improves our understanding on how vegetation-mediated feedbacks interact with different levels of warming and CO_2 fertilization.

- The study using an RESM accounting for both interactive vegetation dynamics and ocean sea-ice dynamics shows that vegetation feedbacks cause greater variations of sea ice extent in summer and autumn, which is more in line with the sea ice observation data. Comparing the spatial patterns of vegetation effects on relevant variables, we conclude that increased DLW is the dominant factor contributing to the surface warming and further sea ice melt. Increased DLW from greater cloudiness and atmospheric humidity caused by increased surface turbulent heat flux and atmospheric circulation caused by MSLP anomalies.

RESMs, as an important modelling tool complementary to ESMs, show the convenience of integrating regional scale models and field information to customize the study to serve regional or local interest. In addition, they provide finer scale of information spatially, and better reveal the feedback chains and relevant processes. The RCAO-GUESS RESM applied in this thesis provide insights in understanding the role of biogeophysical feedbacks and their impacts in arctic and boreal climate systems, However, some simplifying assumptions we have made need to be revised or improved in the future model development.

Firstly, the version of LPJ-GUESS coupled in RCAO-GUESS is not in line with the latest developments to LPJ-GUESS. It still uses the optimal ratio of the carbon to nitrogen (C:N) to determine enzyme activities for photosynthesis. However, slow nitrogen mineralization rates in arctic and boreal ecosystems are a known limitation to vegetation productivity. Secondly, the coupled version still used C3 grass to represent arctic herbaceous vegetation, and this could have underestimated effects and details resulting from shrub species responses to climate warming, as indicated in Paper I. Recent increases in the abundance of shrubs in arctic tundra have been reported in many studies. The latest version of LPJ-GUESS has improved descriptions of processes concerning nitrogen cycle and nitrogen-carbon interaction, Arctic PFTs, wetland hydrology and methane production. Therefore, these two improvements could be readily accomplished as a next step. Thirdly, the snow cover representation in LPJ-GUESS WHyMe is still simplistic at the moment as it assumes a single snow layer and a static snow density. This has probably underestimated the insulation effects of snow cover in the cold regions of NHLs. The insulation effects of snow cover will matter to soil thermal processes and other relevant processes like soil respiration, active layer thawing and the timing of snow duration, inundation and methane emission etc. Last but not least, permafrost vulnerability interacting with soil organic matter content is also an important process that should be included in the model to simulate proper soil thermal conductivities and the biogeochemical carbon cycle. Moreover, RCAO-GUESS needs a further benchmark quantifying how albedo occurs in spring. The positive albedo feedbacks stemming from earlier snow-melt or vegetation masking have not been well distinguished, leading to difficulties in tracing and quantifying the triggers to additional land surface warming resulting from biogeophysical interactions and feedbacks.

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