

**Biogeophysical
feedbacks enhance
Arctic terrestrial
carbon sink**

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Biogeophysical feedbacks enhance Arctic terrestrial carbon sink in regional Earth system dynamics

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Received: 2 April 2014 – Accepted: 12 April 2014 – Published: 12 May 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Continued warming of the Arctic will likely accelerate terrestrial carbon (C) cycling by increasing both uptake and release of C. There are still large uncertainties in modelling Arctic terrestrial ecosystems as a source or sink of C. Most modelling studies assessing or projecting the future fate of C exchange with the atmosphere are based on either stand-alone process-based models or coupled climate–C cycle general circulation models, in either case disregarding biogeophysical feedbacks of land surface changes to the atmosphere. To understand how biogeophysical feedbacks will impact on both climate and C budget over Arctic terrestrial ecosystems, we apply the regional Earth system model RCA-GUESS over the CORDEX-Arctic domain. The model is forced with lateral boundary conditions from an GCMs CMIP5 climate projection under the RCP 8.5 scenario. We perform two simulations with or without interactive vegetation dynamics respectively to assess the impacts of biogeophysical feedbacks. Both simulations indicate that Arctic terrestrial ecosystems will continue to sequester C with an increased uptake rate until 2060s–2070s, after which the C budget will return to a weak C sink as increased soil respiration and biomass burning outpaces increased net primary productivity. The additional C sinks arising from biogeophysical feedbacks are considerable, around 8.5 Gt C, accounting for 22 % of the total C sinks, of which 83.5 % are located in areas of Arctic tundra. Two opposing feedback mechanisms, mediated by albedo and evapotranspiration changes respectively, contribute to this response. Albedo feedback dominates over winter and spring season, amplifying the near-surface warming by up to 1.35 K in spring, while evapotranspiration feedback dominates over summer exerting the evaporative cooling by up to 0.81 K. Such feedbacks stimulate vegetation growth with an earlier onset of growing-season, leading to compositional changes in woody plants and vegetation redistribution.

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1 Introduction

Satellite-derived indices, plot-scale surveys and modelling experiments suggest that Arctic terrestrial ecosystems have undergone structural and compositional changes in response to widespread environmental changes in recent decades (Beck and Goetz, 2011; Elmendorf et al., 2012; Miller and Smith, 2012). Vegetation change in turn feeds back to climate via alterations in biogeochemical forcing (e.g. changes in carbon (C) or nutrient cycling that affects greenhouse house gases (GHG) emissions) or biogeophysical properties of the land surface such as albedo, roughness length, and the partitioning of the return energy fluxes from the surface into latent and sensible heat components (Cox et al., 2000; Brovkin et al., 2006). Biogeophysical feedbacks are particularly important for the northern high latitudes (NHLs). Positive albedo feedbacks arising from expansion and densification of shrublands and forests or snow-masking by protruding branches and leaves dominate over multiple feedback mechanisms leading to a large potential to amplify regional climate warming (Chapin et al., 2005; Bonfils et al., 2012). Moreover, biogeophysical feedback associated with coupled climate–vegetation dynamics will influence biogeochemical feedback to the atmosphere by affecting the terrestrial C and water cycles (Bonan, 2008). Most modelling studies assessing or projecting the state of the C budget for Arctic tundra or the NHLs are based on either stand-alone process-based models or coupled climate–carbon cycle general circulation models (GCMs), also known as Earth system models (ESMs) (Sitch, 2008; Qian et al., 2010; McGuire et al., 2012). In general, these studies disregard biogeophysical feedbacks which likely modify initial climate forcing substantially at the local or regional scale under high GHG emission scenarios and consequently affect biogeochemical cycling. In this regard, it is critical to understand the role of biogeophysical feedback in both Arctic climate change and terrestrial C budget, especially if biogeophysical feedback to near-surface temperature as some estimates indicated might be of the similar order of magnitude as biogeochemical feedback (Betts, 2000; Bathiany et al., 2010).

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1.1 Filling gaps in the biogeophysical feedback loops by employing a regional Earth system model

Traditionally, C stores and fluxes simulated by dynamic vegetation models reflect passive responses of terrestrial ecosystems to spatial and temporal variations in climate, since such climate is generated by climate models which often represent vegetation as either a static or an asynchronous dynamic component in the climate system (Quillet et al., 2010). To fill gaps in the biogeophysical feedback loops relies on climate models being tightly coupled with the DVMs, which likely trigger a cascade of amplifying and dampening effects to affect climate change (Fig. 1). When it comes to Arctic tundra or the NHLs, enhanced absorbed solar radiation and near-surface warming may be expected to directly stimulate photosynthesis of vegetation, resulting in increased growing-season leaf area index (LAI) (Piao et al., 2006) and may also lead to changes in vegetation composition, such as a northward invasion of tall-stature plants (trees and tall shrubs) into extant tundra areas (Tape et al., 2006; Miller and Smith, 2012). Taller statures and bigger leaves lead to enhanced vegetation roughness, which accentuates the vertical mixing of eddy fluxes and causes more efficient transports of momentum, heat and moisture from the canopy to the atmosphere. Accordingly, a negative feedback loop is signified due to increased latent heat, leading to evaporative cooling that counteracts local warming by reducing the portion of sensible heat or reflecting more incoming radiation because of increased cloudiness. On the other hand, invading vegetation or increased LAI may darken the surface, particularly through shading of snow in the late winter and spring, and reduce the surface albedo, leading to a positive feedback to near-surface temperature. Vegetation feedbacks to precipitation have been inconclusive with indications of positive, negative and no feedbacks (Seneviratne et al., 2010; Keuper et al., 2012), but they are likely associated with factors such as wetness of ecosystems, enhanced evapotranspiration and soil moisture, convective characteristics of climate and land surface heterogeneities.

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The ESMs have started to include interactive vegetation dynamics in their land surface components in order to fully address the effects of both biogeochemical and biogeophysical feedbacks arising from land cover change and land management practices (Bathiany et al., 2010; Falloon et al., 2012). However, heterogeneities stemming from local or regional vegetation response to climate change at a variety of time-scales might not be well captured due to their rather coarse resolution or simplified vegetation dynamics. For example, Loranty et al. (2013) pointed out that consistent declines in albedo with increasing tree cover, occurring south of latitudinal tree-line, are poorly represented by ESMs, partly because of their relatively coarse resolution. Rietkerk et al. (2011) also argued that vegetation-environment feedbacks might propagate from local to large scale to trigger critical climate transitions.

Regional climate models (RCMs) are complementary tools to GCMs, providing high-resolution simulations of the climate over a limited domain forced by GCM-derived fields on the lateral domain boundaries. By accounting for physiographic features such as mountain chains, lakes and coastlines in a more detailed way, they tend to provide more reliable local or regional details of climate information to the end-user and policy-making communities (Rummukainen, 2010). Smith et al. (2011) first coupled a dynamic vegetation model (DVM) to an RCM to account for biogeophysical feedbacks of vegetation structural changes on climate. In a case study over Europe, Wramneby et al. (2010) demonstrated both albedo- and evapotranspiration-mediated feedbacks, and found that biogeophysical feedbacks to future warming were relatively modest compared to the radiative forcing of increased global CO₂ concentrations.

1.2 Present studies of terrestrial C balance for Arctic tundra and the NHLs

Arctic tundra and boreal forests have sequestered a considerable amount of C during historic and recent geological times (Oechel et al., 1993; Ruckstuhl et al., 2008). However, the current, recent and future C balance of Arctic terrestrial ecosystems is still under debate due to large uncertainties associated with various methodologies to estimate regional C fluxes or large sensitivities associated with various controlling

active vegetation dynamics, we characterize impacts of biogeophysical feedbacks on both future Arctic climate and terrestrial C budget. Specifically, the aims of this study are to investigate the following questions:

1. How well does RCA-GUESS simulate Arctic climate, vegetation and C fluxes for the recent period?
2. How do biogeophysical feedbacks affect Arctic climate and terrestrial C balance in the future?
3. What types of vegetation change are attributed to the altered terrestrial C budget?

This study excludes the influence of anthropogenic land use change, but is to highlight the importance of including interactive vegetation dynamics as a component in the regional ESM, which can improve predictive understanding for projecting future climate change and provide a unique tool for carbon-related impact research.

2 Methods

2.1 RCA-GUESS, a regional Earth system model

RCA-GUESS (Smith et al., 2011) is a regional ESM, in which the Land Surface Scheme (LSS) of the regional climate model RCA4 is coupled with the dynamic vegetation and ecosystem biogeochemistry simulated by the individual-based vegetation-ecosystem model LPJ-GUESS.

RCA refers to the Rossby Centre Atmosphere regional climate model that has been modified and updated mostly with respect to the parameterization of physical land-surface processes dealing with physiography and cold climate conditions in mid and high latitudes (Samuelsson et al., 2011). The LSS in RCA uses separate tiles for forest and open land. The forest tile is further subdivided into fractions for canopy and forest floor and the proportion of broad-leaved vs. needle-leaved (coniferous) forest.

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The open land tile has separate fractions for vegetation and bare soil. When snow is present, both tiles have a fraction of snow covering the ground. All fractions have their own surface energy balance which are weighted together to provide grid-averaged energy and moisture vapour fluxes as lower boundary conditions for the atmosphere (Samuelsson et al., 2006).

The Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS) is an individual-based vegetation-ecosystem model optimized to resolve heterogeneities of vegetation structures and functions at the regional and continental scale (Smith et al., 2001). It shares mechanistic formulations for canopy biophysics, phenology, plant physiology and ecosystem C cycling with the global model LPJ-DGVM (Sitch et al., 2003) and incorporates improved formulations of ecosystem hydrology (Gerten et al., 2004). However, it differs from the generalized large-area parameterization of vegetation structure and population dynamics used in LPJ-DGVM, adopting instead gap model formalisms based on explicit representations of growth and competition among cohort-averaged woody plant individuals and a herbaceous understory co-occurring within patches differing in age-since-last-disturbance. Woody plants and herbaceous vegetation are parameterized by Plant Functional Types (PFTs), which are parameter sets governing plant traits with regard to morphology, phenology, shade and drought tolerance, fire resistance and bioclimatic limits. LPJ-GUESS has been successfully applied to model dynamic changes of potential natural vegetation (PNV) across biomes of world, including Europe (e.g. Hickler et al., 2012), Arctic and Subarctic regions (e.g. Zhang et al., 2013).

In RCA-GUESS, the vegetation dynamics affects the LSS of RCA by dynamically adjusting the LAI and the relative cover of needle-leaved and broad-leaved forests in the forest tile and herbaceous vegetation in the open-land tile. In this study, the 6 global PFTs used in LPJ-GUESS consist of boreal needle-leaved evergreen trees, boreal intolerant needle-leaved evergreen trees, boreal needle-leaved deciduous trees, temperate broad-leaved deciduous trees, intolerant broad-leaved deciduous trees and C3 grass. The parameter sets for characteristic traits of PFTs are given in Table S1

in the Supplement. The simulated daily LAI and phenology state of the needle-leaved and broad-leaved PFTs in LPJ-GUESS are aggregated to the corresponding forest types in the forest tile of RCA (Eq. 1.1 in Table S2 in the Supplement). The relative cover fractions of forests and herbaceous vegetation within the forest and open land tile are estimated as the foliar projective cover computed from the simulated LAI using Lambert Beer's law (Eqs. 1.2–1.4 in Table S2 in the Supplement). The returned LAI will affect the surface and aerodynamic resistances which are further used by RCA for the calculation of the sensible and latent heat flux (Eqs. 1.5–1.9 in Table S2 in the Supplement). The fractional size of the forest tile is allowed to vary only if the simulated maximum growing-season LAI summed across forest PFTs is lower than 1, signifying marginal or stunted woody plant growth. The relative covers of forests and open-land affect the weighted averaged albedo for each grid cell (Eq. 2.0 in Table S2 in the Supplement). The configuration and behaviour of RCA-GUESS is described in detail by Smith et al. (2011).

2.2 Model domain, driving data and simulation protocols

The simulations 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 $0.44^\circ \times 0.44^\circ$ (approximately 50 km) by rotating the pole system over an equatorial domain. The boundary conditions were taken from the CMIP5 (Coupled Model Intercomparison Project phase 5) simulations of the EC-Earth GCM for the RCP8.5 scenario (Moss et al., 2010).

RCA-GUESS was initialized by a spin-up phase to achieve an equilibrium state for vegetation structure and composition, C pool and climate conditions approximate to the period 1961–1990. Compared to the relatively short spin-up necessary for RCA (only a few months), LPJ-GUESS requires a much longer spinup comprising two stages. In the first stage, LPJ-GUESS is run in an un-coupled mode, forced by climate variables (precipitation, sunshine, temperature) from the CRU TS3.0 (1991–2006) (Climate Research Unit Time Series) observation-based climate dataset (Mitchell and Jones,

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Kaplan PNV dataset supplements the ISLSCP II PNVC dataset with additional details of low- and high-shrub across Arctic tundra. The dominant PNV in the model was derived from the PFT with the largest LAI in each grid cell. The simulated NPP flux was evaluated using data from both Arctic tundra and boreal forests: the Ecosystem Model-Data Intercomparison (EMDI) (Olson et al., 2013a), the Biological Productivity of Ecosystems of Northern Eurasia (BAZ) (Denissenko et al., 2013), the Global Primary Production Data Initiative Product, R2 (GPPDI_1) (Olson et al., 2013b), the Global Primary Production Data Initiative Product, R3 (GPPDI_2) (Zheng et al., 2013) and the NPP Boreal Forest (BOREAL) (Gower et al., 2012). To evaluate net ecosystem exchange (NEE), the residual difference among the fluxes of NPP, HR and fire disturbance, we compared inter-annual variability of NEE anomalies and mean C budget for the Arctic tundra domain (McGuire et al., 2012; Fig. S1 in the Supplement) to the estimates of process-based models (LPJ GUESS WHyMe, Terrestrial Carbon Flux (TCF) model, ORCHIDEE, Terrestrial Ecosystem Model (TEM) 6) and inversions for the period 1990–2006 (for details see McGuire et al., 2012).

2.4 Analysis of impacts of biogeophysical feedbacks to Arctic future climate, terrestrial C budget and vegetation change

The impacts of biogeophysical land–atmosphere feedbacks on the Arctic climate were quantified as mean seasonal and monthly anomalies for variables (2 m temperature, total precipitation) averaged from the period 2071–2100 in the feedback run relative to the non-feedback run. Anomalies of surface albedo and latent heat flux were also calculated to discriminate albedo- from evapotranspiration-mediated feedbacks in their effects on temperature and precipitation.

For the future Arctic terrestrial C budget, we calculated mean C stores and fluxes for Arctic tundra and the CORDEX-Arctic domain respectively, and examined the relative contribution of C sinks from Arctic tundra. We also explored how biogeophysical feedbacks affect C exchange by evaluating the magnitude and occurring year of peak C uptake for both Arctic tundra and boreal forests.

Climate-induced vegetation shifts were characterized as the anomalies of a normalized phenology index and a normalized physiognomy index (Wramneby et al., 2010; Eqs. 2.1–2.2 in table S2 in the Supplement) based on the LAI values of simulated PFTs averaged over the period 2071–2100 relative to 1961–1990. Biogeophysical feedback-induced vegetation shifts were characterized as the anomalies of aforementioned indices for the period 2071–2100 based on the feedback-run relative to the non-feedback run.

3 Results

3.1 The recent Arctic climate, vegetation and C flux

The simulated mean seasonal climate for 1961–1990 shows a cold bias on the order of 2 °C compared to observations over both spring and summer across the entire domain except northern Canada (Fig. 2b, c, f and g). A warm bias on the order of 2 °C occurs over winter of Scandinavia, autumn in eastern Siberia and for all seasons in northern Canada (Fig. 2a, d, e and h). The most pronounced temperature biases are evident in eastern Siberia (except Greenland where both the CRU and WILLMOTT datasets are expected to have significant biases due to poor coverage of measurement sites) which is warmer in winter and colder in summer. The simulated total seasonal precipitation is 5–20 mm higher compared to the validation datasets, with a relatively larger overestimation across the entire domain in spring and autumn (Fig. 3).

The vegetation simulated by RCA-GUESS agrees reasonably well with the validation map in terms of spatial distribution and the percent latitudinal difference of grid cells that each aggregated vegetation class occupies. The belt pattern of herbaceous vegetation across mountain ranges in Scandinavia and eastern Siberia is well displayed in both the model-derived map and the validation map (Fig. 4a and b). The percent latitudinal difference taken by vegetation classes is generally lower than 20 % (Fig. 4c). The overestimation of deciduous or evergreen forests fraction is offset by the underestimation

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of mixed forests fraction. This inconsistency is partly attributed to different definitions of mixed forests in the model and validation map. In the model output, mixed forests are defined as the grid cells with herbaceous fraction < 50 %, and neither evergreen nor deciduous trees fraction is predominant (< 33.3 %). However, the validated mixed forests are classed as lands dominated by trees with a percent canopy cover > 60 % and height exceeding 2 m, consisting of tree communities with interspersed mixtures or mosaics of deciduous and evergreen types, but none of which exceed 60 % of landscape (Love-land et al., 2000). Deciduous forests are overestimated for the herbaceous lands at the latitudes 69–73° N, locating the tree-line further north in the northern Canada and eastern Siberia.

The simulated mean annual NPP for 1961–1990 across Arctic tundra area (Far East Siberia, Alaska, northern Canada, eastern Siberia) is comparable to the validation datasets, seldom exceeding $200 \text{ gC m}^{-2} \text{ yr}^{-1}$ (Fig. 5a). Averaged over the Arctic tundra, the simulated NPP for 1990–2006 is $266\text{--}268 \text{ gC m}^{-2} \text{ yr}^{-1}$ (Table 1), which is broadly in line with previous estimates ($243\text{--}252 \text{ gC m}^{-2} \text{ yr}^{-1}$ for 1960s) by the LPJ-DGVM model reported by Sitch et al. (2007). For European forest, simulated NPP exceeds observations by some $200\text{--}300 \text{ gC m}^{-2} \text{ yr}^{-1}$ (Fig. S2). This deviation may indicate that nitrogen as limitation and land use change as a driver are important for predicting European forest NPP, as we have not account for both in this study. Likewise, without considering these two factors, RCA-GUESS with lateral forcing fields as the reanalysis dataset ERA-40 (Smith et al., 2011), and LPJ-GUESS stand-alone simulations driven with the CRU climate (Wolf et al., 2008) also simulated NPP on the order of $500\text{--}600 \text{ gC m}^{-2} \text{ yr}^{-1}$.

The simulated inter-annual variation of NEE anomalies for 1990–2006 from both RCA-GUESS runs fall within uncertainty ranges of both process-based models and inversion models (Fig. 5b). The RCA-GUESS feedback run shows a downward trend similar to the estimates of process-based models (LPJ-GUESS WHyMe, ORCHIDEE, TCF), indicating a slight trend towards increased carbon uptake (Table 1; Fig. S3). In the non-feedback run, the trend is positive, similar to results from TEM and the

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ensemble mean of inversions estimates. Overall, mean annual NPP flux is simulated to exceed the sum of respiration and wildfire C emissions, resulting in a net sink of C (negative NEE) into the biosphere. Biogeophysical feedbacks have a marginal impact on this net sink, reducing it by some 5%.

3.2 Impacts of biogeophysical feedbacks on future Arctic climate

The influence of biogeophysical feedbacks on the simulated mean climate for 2071–2100 varies seasonally (Fig. 6a–d). Albedo feedback dominates and causes an enhanced warming in winter and spring, with the greatest additional warming of 1.35 K in spring (Fig. 7a). Evapotranspiration feedback starts to offset albedo feedback from spring, and reduces the warming by 0.81 K in summer over the Arctic as a whole, but with only a moderate influence in autumn (Figs. 6a–d and 7a). The most pronounced amplification of warming ($\sim 3^\circ\text{C}$) occurs in spring across tundra areas of Siberia and northern Canada. In Fennoscandia, only the Scandes mountain range is influenced, with some additional warming in winter and cooling in summer, which is in accordance with results reported by Wramneby et al. (2010). The impacts of biogeophysical feedbacks on precipitation are not as noticeable as for temperature. The greatest change in precipitation occurs in summer with an increase of 3.57 mm over land areas (Figs. 6e–h and 7b). In contrast to the slight albedo decline around 0.05 in summer, albedo in autumn, winter and spring is reduced significantly across the whole tundra area with the greatest reduction around 0.2 in spring (Fig. 6i–l). Sporadic increases of albedo are found in the larch forest belt of central Siberia from autumn to spring. The increase of latent heat flux is manifest in spring and summer for most land areas except for northern Canada and eastern Siberia where there is a reduction in magnitude (Fig. 6m–p).

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3.3 Impacts of biogeophysical feedbacks on future Arctic vegetation patterns and C budget

The phenological response to the simulated climate change effects on vegetation composition is not consistent across the entire CORDEX-Arctic domain, in which Scandes mountain range, north-western Siberia, eastern Siberia coast and northern Canada show a substantial increase in the relative abundance of evergreen PFTs, but north-eastern Europe, Taymyr Peninsula, Far East Siberia and high Canada Arctic show an increased abundance of deciduous PFTs (Fig. 8a). Biogeophysical feedbacks tend to alleviate the tendency of the above shifting in Far East Siberia, but reinforce it in Taymyr Peninsula (Fig. 8b). The poleward transitions from grassy PFTs to woody PFTs indicate that the tree-line boundary moves further north as a result of future climate favourable to the growth of trees (Fig. 8c). The biogeophysical feedbacks further enhance the advance of woody plants into Arctic tundra in Far East Siberia and Western Siberia (Fig. 8d). Compared to climate-induced shifts in vegetation abundance, effects of biogeophysical feedbacks to vegetation distribution is relatively smaller, less than 30 % in terms of changes in the normalized phenology and physiognomy indices.

The inter-annual variation of NEE anomaly for 1991–2100 in the RCA-GUESS non-feedback run indicates that the total C uptake rate starts to increase rapidly since 2020s, reaching the largest value in 2060s, being dampened thereafter till 2090s (Fig. 9a). However, the RCA-GUESS feedback run reveals that biogeophysical feedbacks are able to further enhance C uptake since 2020s, and postpone the arrival of the largest rate of C uptake for 15 years. We sort the grid cells with the largest NEE flux increased and delayed over 1991–2100. Most grid cells with the enhanced C uptake are found in Arctic tundra, while boreal forests show more grid cells with the largest NEE flux decreased (Fig. 9b and c). In total, by the end of 2100, the CORDEX-Arctic domain will gain 38.7 GtC (Table 2), of which 35.6 GtC is sequestered by Arctic tundra. This estimation is comparable to the estimates of C4MIP simulations around 38 ± 20 GtC for the NHLs (Qian et al., 2012). Most of the C gains are allocated to vegetation biomass.

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Litter and soil C stores are increased by 0.5 and 1.2 GtC respectively for Arctic tundra, but they are reduced by 1.8 and 6.4 GtC for the CORDEX-Arctic domain. The biogeophysical feedbacks bring about 22 % of the total C sinks, around 8.5 GtC, of which 83.5 % are gained from Arctic tundra.

4 Discussion

4.1 The regional climate simulations

The bias of the down-scaled climate could be inherited from biases in the lateral boundary conditions provided by EC-Earth or be attributed to shortcomings of models structures, formulations and parameterizations. Our simulated warm bias retained all over the year in northern Canada for 1961–1990 coincides with the bias existing in the lateral boundary conditions provided by global simulations of EC-Earth. The latter shows a warm bias of 1–4 K for 1980–1999 compared to the reanalysis data (Koenigk et al., 2013). However, in general, the twentieth century Arctic climate in EC-Earth is relatively cold because of the overestimated sea ice thickness and extent. This might result in the cold bias in spring and summer seen in our simulations across almost the entire domain. Berg et al. (2013) compared the ERA-Interim climate to the RCA4 down-scaled climate using spectral nudging techniques with the lateral force fields as the ERA-Interim climate, identifying winter-time warm bias in eastern Siberia and summer-time cold bias across the entire domain. Our simulations show similar patterns. Samuelsen et al. (2011) pointed out that some studies showed RCA underestimates snow albedo in cold climate regions. The snow-albedo feedback mechanisms could lead to higher air temperature and less snow accumulation. This probably explains few instances of the most pronounced warm bias found in the mountain range of Eastern Siberia. Comparing to the consistency of simulated temperature bias between RCA-GUESS and EC-Earth, precipitation bias indicates more inconsistency, for instance, RCA simulates more precipitation in the basins of Barents Sea and Bering Strait than

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EC-Earth. Overall, in contrast with the EC-Earth global simulations, the down-scaled results demonstrate improved climate predictions by damping the biases and resolving explicit spatial details in surface climate characteristics forced by orography, lake, coastlines and vegetation distribution.

RCMs are able to capture the finer scale of physical process and feedback impacts than GCMs, however, differences in GCMs as boundary conditions seem to be more important than the differences in RCMs in predicting climate. For that matter, comparing to the results for the latitudes above 60° N from standalone simulations of LPJ-GUESS forced with the CMIP5 products (Alström et al., 2012), the inter-annual variation of the cumulative NEE simulated by both the RCA-GUESS runs agrees well the ensemble mean from 1990 to 2020, and started to increase C uptake more rapidly afterwards (Fig. S4). This means that EC-Earth provides much reliable climate forcing as the lateral boundary condition of RCMs.

4.2 Regional climate change impacts on vegetation dynamics and ecosystem biogeochemistry

Distinct geographical patterns of vegetation distribution in the Arctic and NHLs are largely shaped by regional climate patterns in temperature and precipitation, while other factors like soil properties, topographical barriers, land use change, permafrost vulnerability are additional determinants (Morales et al., 2005; Koca et al., 2006; Jiang et al., 2012). Zhang et al. (2013) demonstrated that LPJ-GUESS shows a generally good performance in replicating vegetation patterns across the Arctic, in particular capturing forest–shrub–tundra transitions observed in the Canadian Arctic, northern Alaska, Taymyr Peninsula, and Scandes Mountains under the present-day climate. RCA-GUESS simulates vegetation shifts comparable with previous studies: effects of climatic warming and elevated CO₂ allow the bioclimatic niche for boreal or temperate forests to move towards higher latitudes and elevations (Fig. 8c; Morales et al., 2007; Wolf et al., 2008; Zhang et al., 2013); the longer length and higher temperature in the growing-season allows faster establishments of broad-leaved summergreen (e.g. birch)

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forests, competing against evergreen forests dominated by species of spruce and pine, typical for the boreal zone (Fig. 8a and c; Hickler et al., 2012; Miller and Smith, 2012; Jiang et al., 2012); the warmer winter and changing precipitation patterns allows boreal summergreen (larch) trees in Siberia to give way to boreal evergreen and temperate summergreen trees (Fig. 8a; Kaplan et al., 2003; Shuman et al., 2011; Zhang et al., 2013).

Numerous modelling studies have explored how climate-, CO₂- and land use-driven variations in NPP, HR and disturbances fluxes may influence the future fate of the present-day sink of atmospheric CO₂ within the terrestrial biosphere (Ahlström et al., 2012; Brovkin et al., 2006; Poulter et al., 2011). Our simulated mean NEE flux averaged by 1991–2006 for the Arctic tundra have a common response to the recent climate as other process-based models, implying that both coupled and uncoupled process-based models agree that recent rising NPP in response to the near-surface warming is faster than increased soil respiration. The inter-annual variation of NEE anomalies among all the models do not deviate too much from the ensemble mean of inversion models top-down estimates, because they are well constrained by relative strength of compartment fluxes. For instance, ORCHIDEE determines the high end of uncertainty range of estimated NPP and RH, while RCA-GUESS simulates more fire disturbances resulting in a larger inter-annual variation (Table 1). RCA-GUESS and LPJ-GUESS WHyMe share the same fire process, in which fires are determined by the amount of above-ground litter and soil moisture threshold. However, LPJ-GUESS WHyMe is forced by the observation-based climate and adopting Arctic-prescribed PFTs, which depicts the simulated tree-line boundary with more accuracy (Zhang et al., 2013). The rapid increase of C uptake emerges since 2020s in both RCA-GUESS runs are attributed to substantial climate-induced vegetation shifts and a prolonged growing-season length. However, C gains eventually decline as the increased HR flux in response to the continuous warming of climate outpaces the increased NPP flux. Previous studies based on the stand-alone simulations with dynamic vegetation models demonstrate the simi-

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lar effect (Cao and Woodard, 1998; Cramer et al., 2001; Wolfgang et al., 2006; Zhang et al., 2013).

4.3 Implications of biogeophysical feedbacks to future Arctic climate and C balance

5 The net impacts of biogeophysical feedbacks of future climate largely result from the opposing effects of two feedback mechanisms. The amplified warming occurring in winter and spring is associated with positive feedbacks arising from substantial reductions of albedo. Winter- and spring-time albedo reductions indicate that the underlying snow is masked and shaded by stems and leaves of woody vegetation, which increases
10 both in extent and local density, exhibiting an earlier onset of growing-season in the warmer future climate. The attenuated warming in summer is associated with negative feedbacks arising from increased evapotranspiration that overtakes positive feedbacks arising from albedo. The enhanced evapotranspiration is linked to a higher overall LAI (leaf surface for evaporation) as well as denser forest cover, which increases surface
15 roughness, promoting a more dynamic exchange of water vapour and energy with the atmosphere.

On an annual basis, the net effect of these feedbacks on temperature averages a modest 0.0069 Kyr^{-1} over the period 1991–2100. In terms of their effects on the seasonal cycle of Arctic vegetation, however, the feedbacks result in an earlier, longer and
20 more uniform vegetation period, in terms of growing-season temperatures (Fig. 7a), promoting a substantial increase in vegetation productivity. Studies with other (global) ESMs have reported comparable vegetation-mediated feedbacks on near-surface temperature around 0.0028 Kyr^{-1} from the 1870s to the 2080s for the NHLs as a whole (Falloon et al., 2012).

25 Using an iterative coupling approach, Matthes et al. (2011) explored the effects of vegetation changes simulated by LPJ-GUESS on the climate simulated by the HIRLAM regional climate model across the Arctic. They found that woody vegetation spread under a SRES A1B emission scenario led to a temperature adjustment of between

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–1.5 K and 3 K. This temperature adjustment was larger than that given rise by effects of freezing/thawing of soil moisture and top organic soil horizons. As in our study the largest warming was simulated in winter on areas with a vegetation shift from non-wood tundra to forest tundra or from forest tundra to forest, but the thermal sensitivity is expected to become larger if we accept for interactive vegetation responses.

The sensitivity of vegetation distribution to biogeophysical feedback effects seems relatively modest (Fig. 8b and d), however, the additional C sinks arising from biogeophysical feedbacks are considerable (Table 2). A longer growing-season, denser forest covers and invasion of trees to tundra result in a further enhanced vegetation productivity, which postpones the arrival of the peak C uptake rate for Arctic terrestrial ecosystems. Vegetation succession may play more important role than the effect of a prolonged growing-season in gaining these additional C sinks, as most of which are gained from Arctic Tundra (Table 2).

4.4 Perspectives to improve regional Earth system model

Our study highlights the significance of accounting for local biogeophysical interactions between vegetation and the atmosphere in regional Earth system dynamics. Accounting for feedbacks not only resulted in more rapid warming on an annual average basis, but caused adjustments in the timing and character of the growing-season that affected vegetation productivity and net carbon balance, with further implications for the climate evolution.

Swann et al. (2010) advanced a hypothesis that positive albedo feedback would stimulate the growth of vegetation, leading to an increased flux of water vapour to the atmosphere, strengthening radiative forcing. Due to mixing in the atmosphere, such a feedback mechanism would be expected to affect climate not only over land but might trigger greater sea surface warming and subsequent positive sea ice feedbacks, in turn warming the land surface. They found radiative forcing from water vapour to be of a similar magnitude to the direct short-wave forcing from albedo. Therefore, adding

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on ocean component to our regional ESM will allow us to fully address the interaction between ocean, climate and land surface.

Discrepancies between the simulated and actual vegetation distributions could propagate the bias of climate forcing. One cause of such discrepancies is the presence of land use in some parts of the Arctic. Incorporating observed land use as a model driver could reduce discrepancies and model bias. Moreover, it is important to evaluate the algorithm for deriving albedo change from simulated changes in vegetation relative cover fraction and LAI. Brovkin et al. (2013) presents an approach which may be applied to evaluate vegetation cover and land surface albedo for the regional ESM. Furthermore, transient simulations of vegetation distribution should be tailored to better capture a variety of Arctic and subarctic landscapes, such as tall and low shrubs, graminoid and forbs. Finally, ecosystem nitrogen (N) cycling and N-limitations on plant production, now included in LPJ-GUESS (Smith et al., 2014), are important to account for in the NHLs climate, in which soil mineralisation processes may significantly limit the available of N for plant uptake and growth (Zaehle et al., 2014).

5 Conclusion

Our simulations with a regional ESM suggest that in the present climate, Arctic ecosystems are acting as a weak C sink, consistent with findings from some other process-based models and inversion studies. Under an RCP 8.5 future climate scenario, an increased C uptake rate is projected until 2060s–2070s, after which C uptake declines as increased soil respiration and biomass burning outpaces further increases in vegetation net primary productivity. Biogeophysical feedbacks of vegetation change, leading to an earlier, longer growing-season and milder peak temperatures in summer, enhance the initial increase in carbon sink by accentuating NPP and postpone the peak C uptake rate by some 15 years. Integrated over the 21st century, the additional C sinks arising from biogeophysical feedbacks is some 8.5 Gt C, or 22 % of the total C sinks, of which 83.5 % are located in areas currently classified as Arctic tundra. The net effect

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of biogeophysical feedbacks to the regional climate result from two opposing feedback mechanisms, namely albedo feedbacks and evapotranspiration feedbacks. The former dominates over winter and spring season, amplifying the near-surface warming by up to 1.35 K in spring while the latter dominates over summer exerting the evaporative cooling by up to 0.81 K.

Supplementary material related to this article is available online at <http://www.biogeosciences-discuss.net/11/6715/2014/bgd-11-6715-2014-supplement.pdf>.

Acknowledgements. The model simulations were made on the computing resource National Supercomputer Centre (NSC) Krypton in Linköping of Sweden. The study is funded by Swedish Research Council FORMAS for the project Advanced Simulation of Arctic Climate and Impact on Northern Regions (ADSIMNOR). The authors thank Rossby Centre of Swedish Meteorological and Hydrological Institute (SMHI) for coordinating this project, and thank David McGuire and Anders Ahlström for providing additional data to evaluate our results. The study is a contribution to the strategic research areas Modelling the Regional and Global Earth System (MERGE) and Biodiversity and Ecosystem Services in a Changing Climate (BECC), the Lund University Centre for the study of Climate and Carbon Cycle (LUCCI) and the Nordic Centre of Excellence DEFROST.

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Table 1. Mean carbon budget of Arctic tundra simulated by process-based models, inversion models (McGuire et al., 2012) and RCA-GUESS for the period 1990–2006.

Model ($\text{gCm}^{-2}\text{yr}^{-1}$)	NPP	RH	NEP	FIRE	NEE	The slope of the linear trend
LPJ-GUESS WHyMe	−130	106	−24	1	−23	−0.53
ORCHIDEE	−361	330	−31	−	−31	−0.63
TEM6	−107	97	−10	8	−2	0.25
TCF	−181	183	−2	−	−2	−0.62
The ensemble mean of inversion models	−	−	−	−	−13	0.2
RCA-GUESS	−266	233	−33	15	−18	−0.35
RCA-GUESS nf. ¹	−268	234	−34	15	−19	0.24

¹nf.: the non-feedback run.

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Table 2. Carbon budget for the Arctic tundra and Cordex-Arctic domains simulated by RCA-GUESS for the period 1991–2100.

Domains	C flux (Gt C)					C stores (Gt C)		
	NPP	RH	NEP	FIRE	NEE	VegC	LittC	SoilC
Arctic tundra fb. ¹	−302.1	257.7	−44.4	8.8	−35.6	33.7	0.5	1.2
Arctic tundra nf. ²	−288.9	251.8	−37.1	8.6	−28.5	29.6	−1.3	0.2
Arctic tundra diff. ³	−13.2	5.9	−7.3	0.2	−7.1	4.1	1.8	1
CORDEX-Arctic fb.	−541.2	474.5	−67.2	28	−38.7	46.9	−1.8	−6.4
CORDEX-Arctic nf.	−525.3	467.1	−58.2	28	−30.2	42.1	−4	−7.7
CORDEX-Arctic diff.	−15.9	7.4	−9	0	−8.5	4.8	2.2	1.3

¹fb.: the feedback run,

²nf.: the non-feedback run,

³diff.: the feedback run – the non-feedback run. Note: the negative values in C flux mean C uptake, but in C stocks mean absolute changes of C stores.

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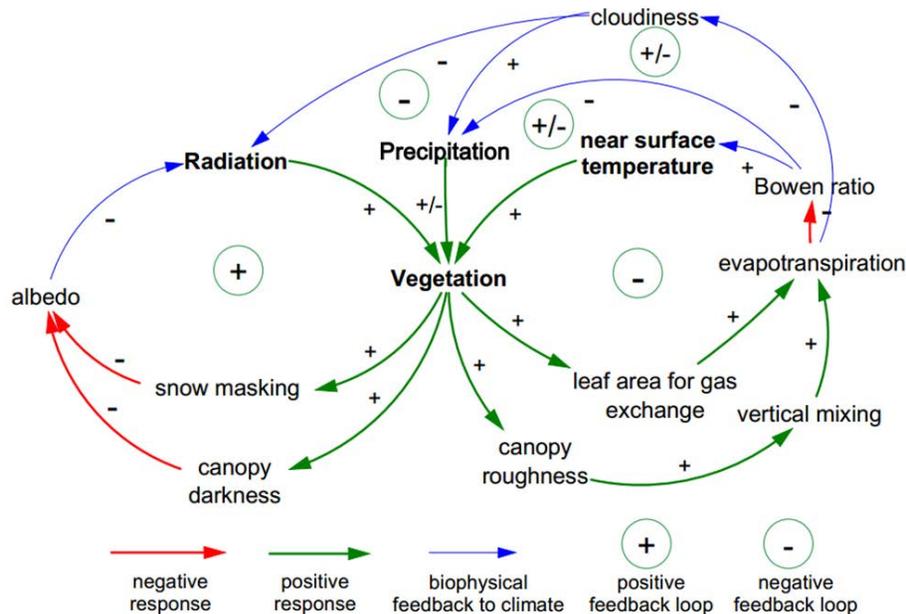


Fig. 1. Diagram of climate-vegetation interaction feedback loops that comprise positive responses (green), negative responses (red) arising from vegetation change and consequent biogeophysical feedbacks to climate (blue).

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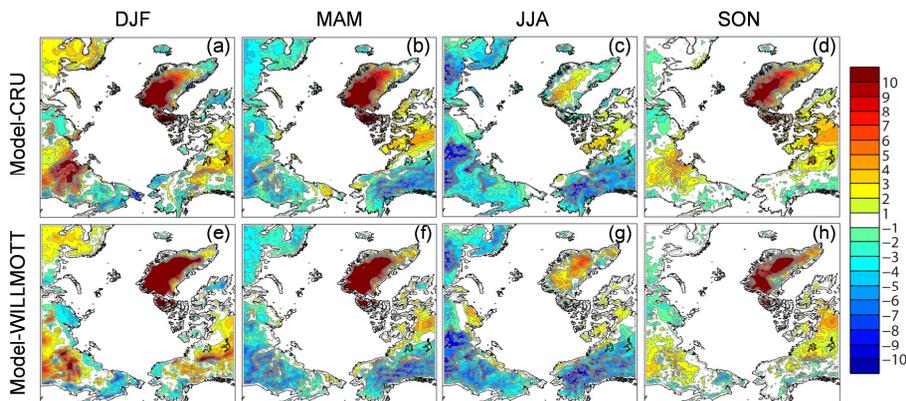


Fig. 2. The mean seasonal 2 m temperature anomalies ($^{\circ}\text{C}$) relative to the CRU and WILLMOT datasets for the period 1961–1990. **(a, e)** Winter, December to February (DJF). **(b, f)** Spring, March to May (MAM). **(c, g)** Summer, June to August (JJA). **(d, h)** Autumn, September to November (SON).

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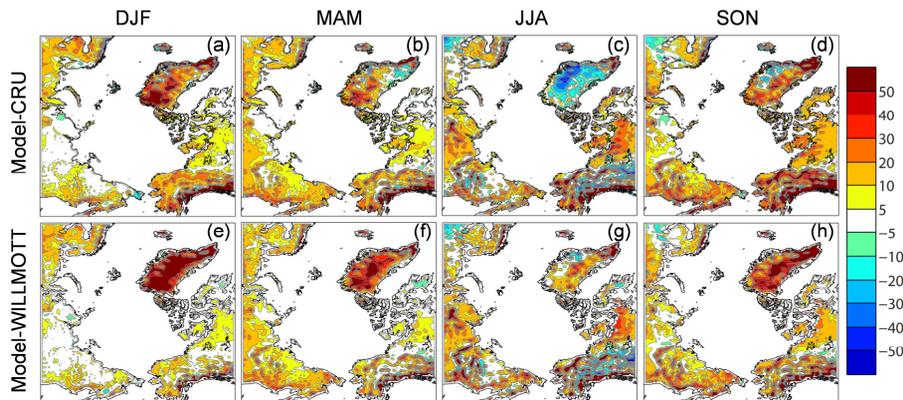


Fig. 3. The total seasonal precipitation anomalies (mm) relative to the CRU and WILLMOT datasets for the period 1961–1990. **(a, e)** Winter, December to February (DJF). **(b, f)** Spring, March to May (MAM). **(c, g)** Summer, June to August (JJA). **(d, h)** Autumn, September to November (SON).

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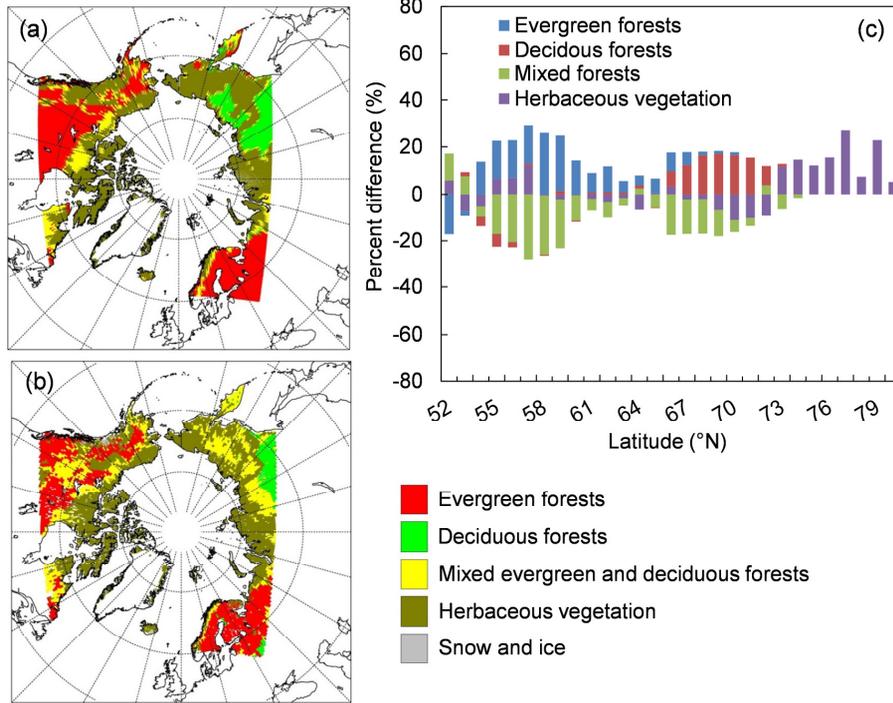


Fig. 4. The dominant potential natural vegetation (PNV) distribution comparison for the recent period. **(a)** The tile-weighted PNV simulated by RCA-GUESS for the period 1961–1990. **(b)** The validation map derived from the ISLSCP II Potential Natural Vegetation Cover dataset (Ramanakutty and Foley, 2010) and Kaplan PNV map (Kaplan et al., 2003). **(c)** Percent difference for the number of grid cells each aggregated vegetation class occupies between the simulation and validation at the latitudes 52–80° N.

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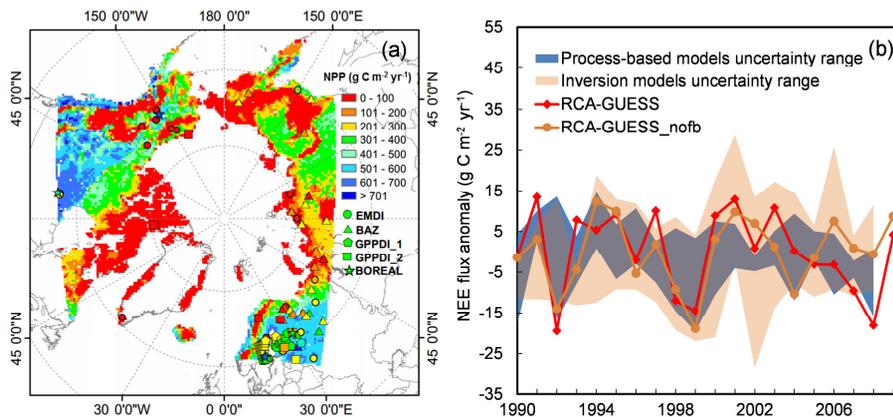


Fig. 5. (a) The spatial distribution of the simulated mean NPP flux for the period 1961–1990 and the NPP flux validation datasets (EMDI (Olson et al., 2013a), BAZ (Denissenko et al., 2013), GPPDI_1 (Olson et al., 2013b), GPPDI_2 (Zheng et al., 2013), BOREAL (Gower et al., 2012)). (b) The inter-annual variation of NEE anomalies of the RCA-GUESS feedback and non-feedback runs, the uncertainty ranges of process-based models (LPJ-GUESS WHyMe, TEM6, TCF, Orchidee) and inversion models for the period 1990–2009.

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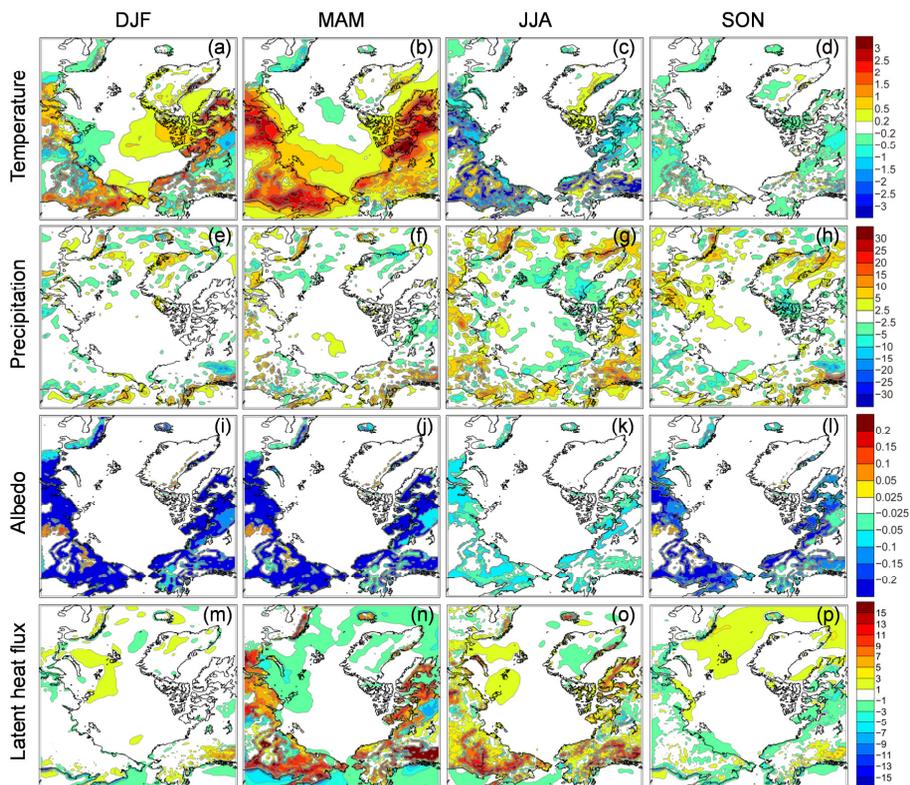


Fig. 6. The effects of biophysical feedbacks to 2 m temperature ($^{\circ}C$) and total precipitation (mm), albedo (–) and latent heat flux (Wm^{-2}) on a seasonal basis. **(a, e, i, m)** Winter, December to February (DJF). **(b, f, j, n)** Spring, Mar to May (MAM). **(c, g, k, o)** Summer, June to August (JJA). **(d, h, l, p)** Autumn, September to November (SON).

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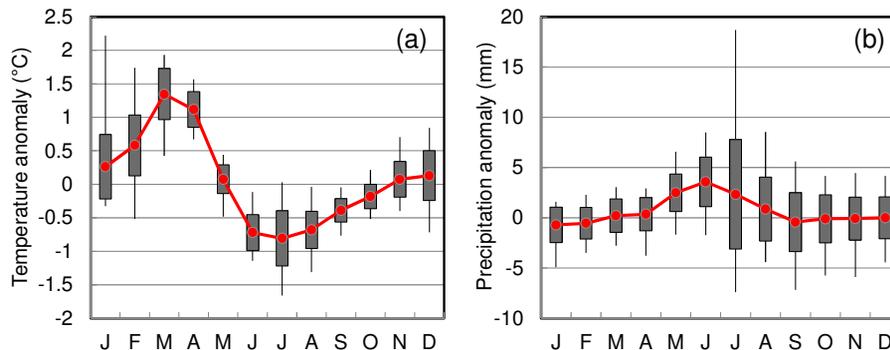


Fig. 7. The seasonal cycle of **(a)** temperature anomaly ($^{\circ}\text{C}$) and **(b)** precipitation anomaly (mm) arising from biogeophysical feedbacks for the period 2071–2100. Each boxplot shows mean (red line), one SD range (black shading) and maximum and minimum values (whiskers) for monthly climate variables.

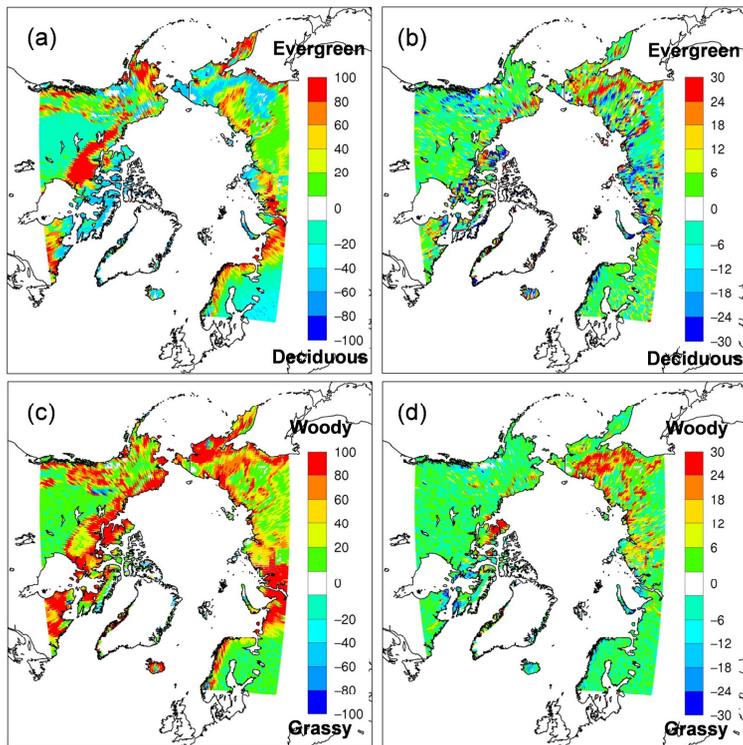


Fig. 8. Normalized phenology index anomalies (%) (Wramneby et al., 2010) quantified by the shift in the relative abundance between evergreen and deciduous PFTs due to (a) climate change from the period 1961–1990 to the period 2071–2100; (b) the effects of biogeophysical feedbacks for the period 2071–2100. Normalized physiognomy index anomalies (%) quantified by the shift in the relative abundance between woody and herbaceous PFTs due to (c) climate change from the period 1961–1990 to the period 2071–2100; (d) the effects of biophysical feedbacks for the period 2071–2100.

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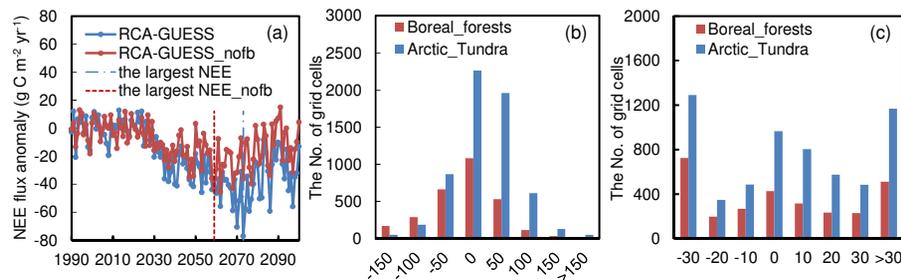


Fig. 9. (a) The inter-annual variation of NEE anomalies of both RCA-GUESS feedback and non-feedback runs from 1991 to 2100 for Arctic tundra. (nofb: the non-feedback run; negative value: carbon sink; the vertical dash and dash-dot lines denote the year with the largest NEE over the whole period in each run). (b) The inter-annual variation of NEE anomalies for both the peak C uptake rate (gCm⁻²yr⁻¹) in both boreal forests and Arctic tundra. (c) The number of grid cells for the shift of the year (yr) with the peak C uptake rate in both boreal forests and Arctic tundra.

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