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2014 Environ. Res. Lett. 9 094007

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Intensified Arctic warming under greenhouse warming by vegetation–atmosphere–sea ice interaction

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Received 8 May 2014, revised 20 August 2014

Accepted for publication 20 August 2014

Published 23 September 2014

Abstract

Observations and modeling studies indicate that enhanced vegetation activities over high latitudes under an elevated CO₂ concentration accelerate surface warming by reducing the surface albedo. In this study, we suggest that vegetation-atmosphere-sea ice interactions over high latitudes can induce an additional amplification of Arctic warming. Our hypothesis is tested by a series of coupled vegetation-climate model simulations under 2xCO₂ environments. The increased vegetation activities over high latitudes under a 2xCO₂ condition induce additional surface warming and turbulent heat fluxes to the atmosphere, which are transported to the Arctic through the atmosphere. This causes additional sea-ice melting and upper-ocean warming during the warm season. As a consequence, the Arctic and high-latitude warming is greatly amplified in the following winter and spring, which further promotes vegetation activities the following year. We conclude that the vegetation-atmosphere-sea ice interaction gives rise to additional positive feedback of the Arctic amplification.

Keywords: vegetation feedback, Arctic warming, global climate model, sea ice, climate feedback

1. Introduction

The high latitudes and Arctic have experienced substantial climate warming in recent decades, during which the degree and rate have been much higher and faster than global averages due to various climate feedback effects associated with the rapid melting of sea ice and snow (ACIA 2005, Chapin *et al* 2005, Kug *et al* 2010, Rothrock *et al* 1999, Screen and Simmonds 2010, Serreze *et al* 2000). The

accompanying effects are conspicuous changes in vegetation across the pan-Arctic landmasses. Contrary to our apprehension, human-induced increase in greenhouse gases and associated changes in climate conditions have been favorable for some plant species that live under harsh climate conditions in high latitudes and in sub-Arctic regions. The warming and lengthening of the growing season have led to increased vegetation greenness in the Arctic tundra and in grassland areas and have stimulated the expansion of shrub plants in Pan-Arctic regions for the last several decades (Bunn *et al* 2007, Jeong *et al* 2011, Tape *et al* 2006, Tucker *et al* 2001, Xu *et al* 2013, Zhou *et al* 2001b).

However, these changes are not only responses to a changing climate but also have sufficient potential to alter the entire climate system by disturbing surface energy fluxes and

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the hydrological cycle (Bhatt *et al* 2010, Bonan *et al* 1992, Bunn *et al* 2007, Foley 2005, Tape *et al* 2006, Tucker *et al* 2001, Zhou *et al* 2001a). It is widely recognized that enhanced vegetation activities over high latitudes have a net positive feedback effect on climate warming, primarily by reducing surface albedo as vegetation colonizes previously snow-covered or barren surfaces of relatively high albedo (Levis *et al* 1999, Notaro and Liu 2008, Notaro *et al* 2007, O'ishi and Abe-Ouchi 2009, Swann *et al* 2010, Zhang and Walsh 2007). In addition to the local feedback effect, we suggest here that the vegetation feedback effect under global warming may further exacerbate the high-latitude and pan-Arctic warming through a strong physical coupling with the Arctic sea ice change. By taking advantage of a vegetation-climate coupled model, we investigate possible vegetation changes under a $2\times\text{CO}_2$ climate and its feedback effects on surface climate and associated energy budgets in the high-latitude/Arctic climate system. In particular, the remote influence of vegetation change on Arctic warming in the presence of coupling with Arctic sea ice is a primary focus of our present study.

2. Vegetation-climate coupled model simulations

We utilized a vegetation-climate coupled model: the Community Climate System Model version 3 (CCSM3) (Collins *et al* 2006), developed by the National Center for Atmospheric Research. To save much of the computing time involved with fully dynamical ocean circulation as it reaches an equilibrium state, the present study employed an interactive mixed-layer slab ocean model (SOM) coupled with a thermodynamic sea ice model instead of full-depth ocean dynamics. The ocean-heat transport for the SOM, the Q -flux, is estimated from a 50-year control simulation of the CCSM3 forced with the observed climatological mean sea surface temperature and sea ice concentration from the Met Office Hadley Centre in the UK (Rayner 2003). The equilibrium climate sensitivity of the CCSM3 with the SOM to anthropogenic forcing is known to be almost similar to that of the fully-coupled version of CCSM3 (Kiehl *et al* 2006). In the present study, we updated the cloud scheme in the original CCSM3 with the freeze-dry modification (Vavrus and Waliser 2008) to reduce an excessive cloud bias in the Arctic. We used a version with a horizontal resolution of T42 (approximately $2.8^\circ \times 2.8^\circ$) and 26 hybrid-sigma vertical levels.

This model incorporates a dynamic global vegetation model (DGVM) (Levis *et al* 2004), which simulates the evolution of vegetation cover and structure under given climate conditions. Therefore, synchronous vegetation-climate coupling enables the model to include biogeophysical interactions. The biogeochemical interaction is not fully considered in this study, but the perturbed atmospheric CO_2 concentration affects vegetation activities through the CO_2 fertilization effect. By using the CCSM3 with the fully interactive DGVM, two equilibrium simulations that represent the present (P) and future (F) climate were performed under present (355 ppmv) and doubled (710 ppmv) levels of

CO_2 concentration, respectively. These simulations represent equilibrium climate-vegetation conditions under the given CO_2 concentrations. An additional future climate simulation (FV) was performed by turning the interactive DGVM off and prescribing global vegetation distribution and phenology with the present condition taken from the present (P) simulation instead. The difference between the two future simulations, F minus FV , is regarded to represent the vegetation feedback effect in response to greenhouse warming. All three simulations were run for 200 years, and the average for the last 50 years of data was utilized in the analysis. The configuration of the modeling simulations performed in the present study is similar to that of Levis *et al* (1999). The present study uses a newer and more comprehensive model with interactive sea ice and an ocean to examine a vegetation-atmosphere-sea ice interaction. More recent studies by Zhang and Walsh (2006, 2007) and Swann *et al* (2010) also investigated the impacts of enhanced vegetation, but their experiments assumed idealized changes in vegetation (e.g. adding more deciduous trees or doubling the leaf area index over the high latitudes). Our present study more explicitly estimates possible changes in vegetation for all of the major plant species under a $2\times\text{CO}_2$ environment based on the DGVM. More importantly, these previous studies focused mainly on the warm season; however, our present study pays attention to the vegetation feedback effects in the following autumn and winter as well.

3. Results

When comparing the P and F simulations, salient vegetation changes in response to the elevated CO_2 concentration are captured (figure 1). Over the high-latitude continents, where low temperature and low solar radiation are primary limiting factors for the survival and growth of vegetation (Chapin 1983, 1987), all of the simulated plant species (six plant functional types) over the focused region show an increase in their areal distribution and leaf growth (i.e. leaf area index) under a doubled- CO_2 climate (figure 1(c)). The permafrost region, which is almost barren in the present climate, becomes more vegetated, and the enhanced tree growth and northward expansion of the boreal forest are prominent in the high-latitude continental areas (figures 1(a), (b)). In addition to the temperature warming, enhanced moisture availability over the northern high latitudes under a warmer climate (Min *et al* 2008) and an increased CO_2 fertilization effect (Hemming *et al* 2013) may have contributed to these changes.

This enhancement of vegetation activity greatly affects the simulated temperature warming. Figures 2(a)–(d) compare changes in the near-surface air temperature in response to doubled CO_2 : one figure includes the interactive vegetation feedback effect ($F-P$), and the other one excludes the vegetation feedback effect ($FV-P$). In both of the future simulations, notable warming is found over the mid- to high latitudes, but the signal changes considerably with the inclusion of vegetation feedback. Without the interactive vegetation feedback, there is quite a uniform warming of

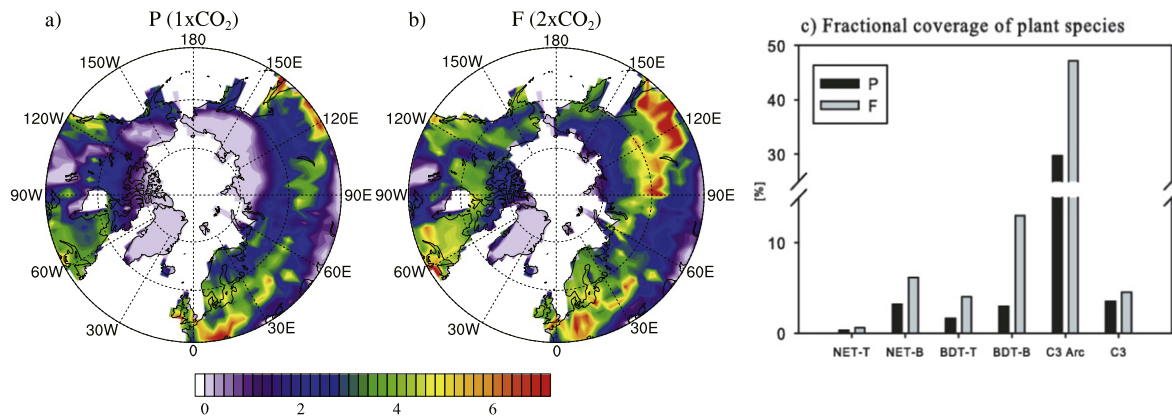


Figure 1. Mean leaf area index (LAI) in the growing season (May to September) for (a) the present (*P*) and (b) future (*F*) simulation and (c) the fractional coverage of the plant species (NET: needleleaf evergreen tree, BDT: broadleaf deciduous tree, C3: grasses with a C3 pathway. T, B, and C in the suffix indicates temperate, boreal and the Arctic, respectively) over a high latitude north of 60°N. The LAI represents the leaf abundance, which is the fractional area of the plant’s leaf surface relative to the surface area.

2–3 K over most of the northern high-latitude land and ocean during the warm season (May to September) (figure 2(a)). However, the inclusion of vegetation feedback enhances the warming to 3–5 K over the circumpolar high-latitude land area where most of the vegetation change occurs, as shown in figures 1(a), (b).

During the following cold season (October to February), the amplification of surface warming by vegetation feedback is still prominent, with the amplitude comparable to that of the warm season. The elevated CO₂ greatly warms the Arctic (6–8 K) and high-latitude land (4–6 K) even without the vegetation feedback effect (figure 2(b)). However, when the vegetation feedback is included, the warming becomes much stronger over the high-latitude land and over the Arctic Ocean (figure 2(d)). This is unexpected because the direct feedback effect of the vegetation change becomes minimal as incident sunlight becomes nearly zero during this period of the year; therefore, the direct albedo feedback associated with the surface vegetation change is expected to be weak.

In order to examine the effect of vegetation feedback quantitatively, the difference of the surface air temperature between the two future simulations (*F-FV*) and the vegetation feedback effect is calculated in figures 2(e), (f). During the warm season, the vegetation feedback effect amplifies warming by about 1–3 K over the circumpolar high-latitude land, but relatively modest changes are found over the Arctic Ocean. In the following cold season, about 1 K of the warming effect is found over a large area of the Arctic Ocean and at high latitudes. A striking feature is found in the zonal mean of the surface air temperature change associated with the vegetation feedback (figure 2(g)). In the boreal summer (June to August) the enhanced surface warming is mainly confined within 65–75°N, where the vegetation changes are largest. This high-latitude warming signal appears to propagate poleward with time, and the strongest warming effect of more than 2 K emerges in the Arctic (north of 80°N) during September to November. Apparently, there are no terrestrial vegetation activities in the Arctic Ocean in the simulations or in reality; so, the amplified warming over this region is

considered a remote response—delayed by a season—to the vegetation feedback over the high latitudes. The most important question is what causes this delayed and remote impact on the Arctic Ocean. A possible explanation is that it is caused by subsequent feedbacks associated with sea ice and oceanic processes in the Arctic. The enhanced vegetation initially induces warming over the circumpolar region in the growing season (figure 2(e)), which leads to more melting of Arctic sea ice and warming of the upper ocean. Then, following autumn and winter, an enhanced heat release from the less ice-covered and warmer ocean surface leads to the delayed warming in the Arctic. Figure 3, which indicates that Arctic sea ice reduces more in the *F* than in the *FV* simulation, supports this possibility. The physical processes associated with the high-latitude warming by vegetation feedback and atmospheric processes that link the vegetation and sea ice are discussed in detail below.

First, changes in surface variables, including radiation, heat fluxes and clouds, caused by the vegetation feedback effect are analyzed (summarized in table 1). The intensified surface warming over high-latitude land during the warm season is mostly contributed by a boosted absorption of solar radiation at the surface (+5.49 W m⁻² in MAM and +13.19 W m⁻² in JJA) associated with reduced surface albedo due to enhanced greenness. The albedo effect on absorbed solar radiation is greatest in spring (–2.12% in MAM) when vegetated surfaces with lower albedo contrasts with a highly reflective snow-covered surface, but this effect becomes less effective in summer (–0.29% in JJA) as snow melts away in the high latitudes. Moreover, as the snow-cover fraction decreases to 3.84% in spring and to 1.79% in summer, enhanced snow-albedo feedback is also involved in this process, as indicated by Zhang and Walsh (2006). However, a strong amplification effect on warming by the vegetation feedback is found in summer (+1.95 K in JJA), not in spring. This is attributed to a large increase in the absorption of solar radiation at the surface (+13.19 W m⁻² in JJA), while an enhanced release of surface longwave radiation from warmer surface temperatures (–5.04 W m⁻² in JJA) is less than the

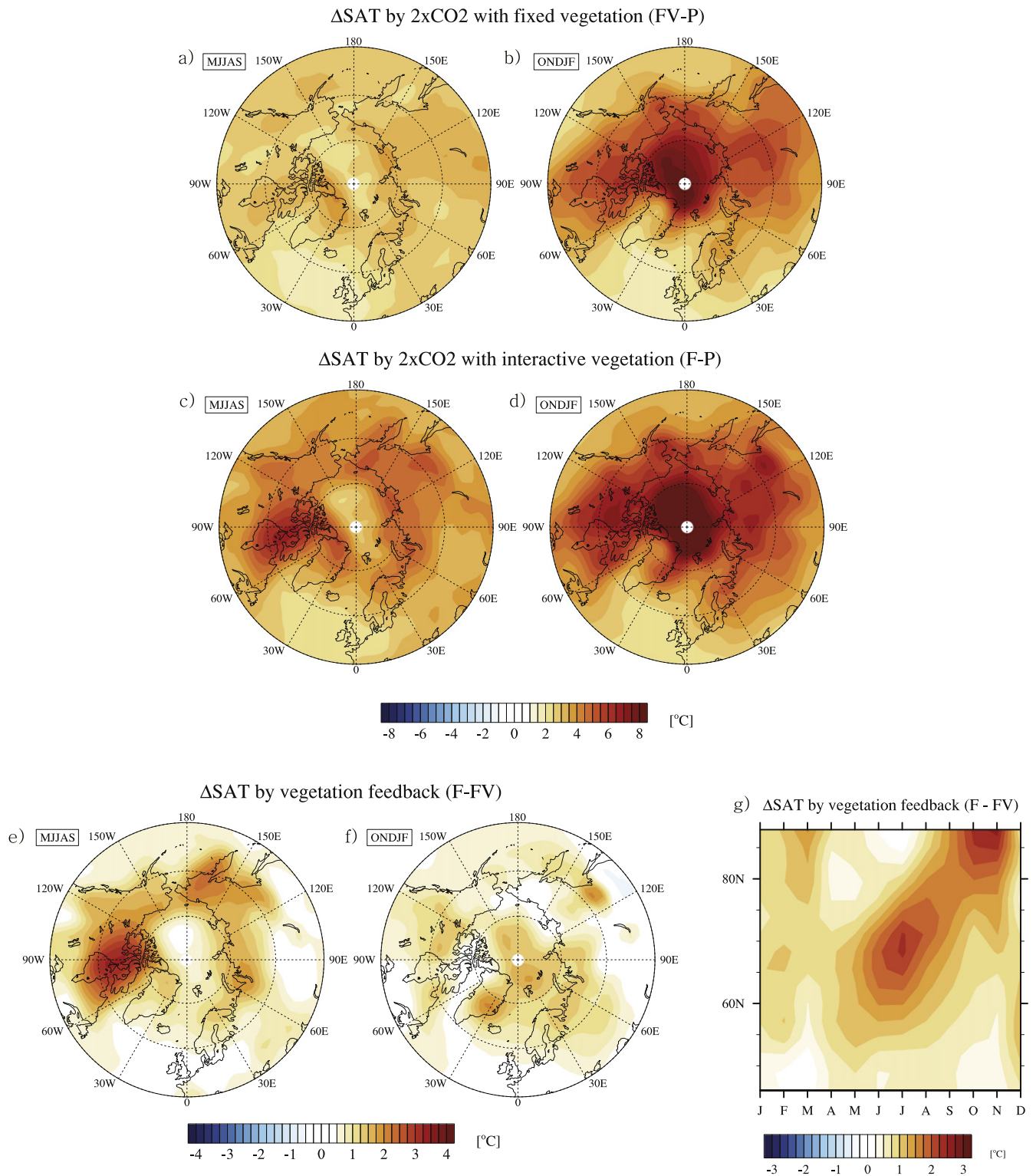


Figure 2. Surface air temperature difference between the *FV* and *P* simulation (a), (b), the *F* and *P* simulation (c), (d) and the *F* and *FV* simulation (e), (f). The zonal mean of the surface air temperature difference between the *F* and *FV* simulation (g).

increased absorption of the solar radiation. A minor part of this increase in solar radiation is due to a weak decrease in surface albedo (−0.29% in JJA), but the large decrease in low clouds (−6.98% in JJA) that are highly reflective to solar radiation in the Arctic is more important. As a consequence, in summer, net radiation at the surface increases greatly

(+8.15 W m^{−2}) over the circumpolar high latitudes. The net radiation increase is balanced mostly by increases in the sensible (+4.12 W m^{−2}) and latent heat flux (+4.35 W m^{−2}). In figures 4(a), (b), large increases in the sensible and latent heat flux (evaporation) are found over the circumpolar high-latitude land, indicating that these changes are directly associated

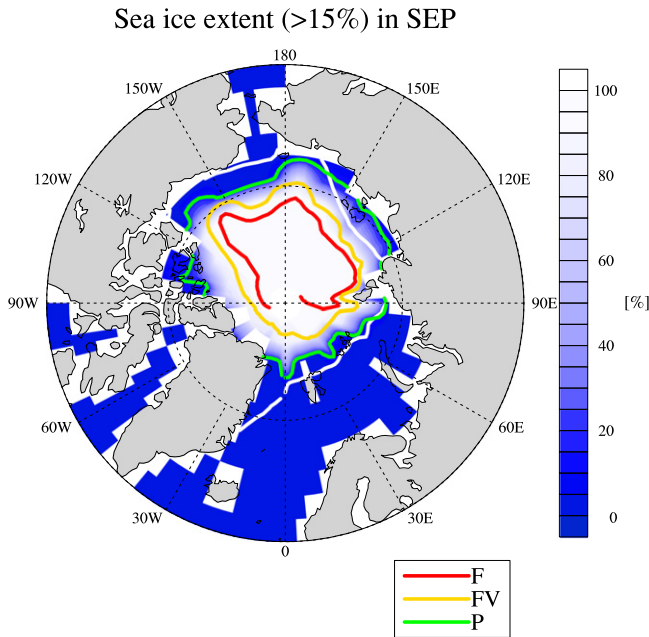


Figure 3. Lines indicate sea ice extents where the ocean is covered with more than 15% sea ice (the red, yellow and green line indicates the sea ice extent in the *F*, *FV* and *P* simulations, respectively). The white line is an average sea ice extent for the period of 1981–2000, as estimated from HadISST data. The shading indicates the simulated average sea ice concentration for September in the *P* simulation.

with the vegetation feedback. The sensible heat flux increase directly warms the lower atmosphere, and the latent heat flux increase can warm the lower atmosphere when it leads to condensation. The enhanced transpiration from vegetation ($+4.74 \text{ W m}^{-2}$) contributes mostly to the increase in latent heat flux. Schweiger *et al* (2008) suggested that near-surface warming caused by enhanced heat release from the ocean’s surface associated with sea ice loss propagates to the lower troposphere by turbulent mixing where the associated decrease in relative humidity and heightened atmospheric boundary layer can lead to a decrease in low clouds. In our results, even though it is a case over land surface, similar changes are found. In the present study, Surface evaporation increases by the vegetation feedback effect (figure 4(a)), but relative humidity at the near surface decreases instead (figure 4(d)). This is thought to be due to the relatively large increase in temperature ($+1.95 \text{ K}$), leading to an increase in saturation vapor pressure. This is somewhat different from previous studies by Zhang and Walsh (2006, 2007) that indicated increases in convective clouds and precipitation in a model simulation with enhanced vegetation. They examined the impacts of enhanced vegetation in a present climate condition, but the vegetation feedback effect is estimated under a future climate condition ($2\times\text{CO}_2$) in our study. The difference in mean state could be associated with such a difference.

Large-scale atmospheric circulation change associated with the vegetation feedback effect also contributes to the amplification of surface warming by inducing high-pressure anomalies over the Arctic. In summer, circumpolar warming

associated with the vegetation feedback reduces the meridional temperature gradient over high latitudes (40–80 N), causing tropospheric westerly winds to weaken over 40–70 N (figures 5(a), (b)). The spatial pattern of the sea level pressure change by the vegetation feedback effect (figure 5(c)) shows high-pressure anomalies over the Arctic and low-pressure anomalies over the extratropics. Although it’s a case in the summer, the pattern looks quite similar to the negative phase of the Arctic Oscillation pattern. The high-pressure anomalies can suppress atmospheric upward motion and cloud formation, which can also contribute to an increase in solar radiation input at the surface.

In the following autumn (September to November), over the high-latitude land, the intensified near-surface warming by the vegetation feedback is still found over land (0.98 K north of 60 N), but the enhanced absorption of solar radiation is minimal (0.07 W m^{-2}). Over the Arctic Ocean, a stronger warming effect is found instead ($+1.55 \text{ K}$), which is mainly attributed to latent ($+1.60 \text{ W m}^{-2}$) and longwave radiation ($+0.89 \text{ W m}^{-2}$ upward) and partly attributed to sensible heat ($+0.39 \text{ W m}^{-2}$), increases from the warmer ($+0.17 \text{ K}$) and less sea-ice-covered (-24.32%) ocean’s surface, as shown in figure 3.

We have found that the energy transport through the atmosphere can account for the remote and delayed influence that originated from the high-latitude greening. Figure 6 shows a change in the northward atmospheric energy transport (NET) by the vegetation feedback effect. Here, the energy represents the moist static energy (MSE) in the troposphere. The MSE is defined by the sum of internal ($c_p T$), potential (gz) and latent (Lq) energy in which c_p is the specific heat of air at constant pressure, T is the temperature, g is the gravitational acceleration, z is the geopotential, L is the latent heat of vaporization at 0°C and q is the specific humidity. The NET is defined as the meridional MSE flux ($\text{MSE} \times v$) vertically integrated from 1000 to 200 hPa, from which the daily mean MSE and meridional wind (v) were utilized.

It is argued that the poleward energy transport from high latitudes (north of 60 N) to the Arctic is greatly enhanced during the warm season (June to September); this energy is mostly contributed by sensible heat and moisture transport. The additional heat and moisture provided by enhanced vegetation activities through enhanced evapotranspiration and SW absorption are transported northward by the ubiquitous atmospheric circulation and eddy activities.

The NET increase is found throughout the growing season, which peaks in summer before gradually decreasing in autumn. The warming over the Arctic induced by the vegetation feedback is, however, minimal in summer but highest in autumn, as seen in figure 2(g). This delay is caused by the large heat capacity of the ocean and the latent heat of sea ice. The excessive heat transported through the atmosphere to the Arctic is primarily used to promote the melting of the Arctic sea ice (-20.98% in sea ice extent and -11.02 cm in ice thickness in JJA) and to warm the upper ocean ($+0.79 \text{ K}$ in JJA) until mid-September when Arctic sea ice is at its minimum extent (figure 3 and table 1). Consequently, more SW radiation can penetrate into the less ice-

Table 1. Changes in the model simulated variables by the vegetation feedback effect (F-FV).

| Variables | Units | High-latitude land (north of 60 °N) | | | The Arctic Ocean (north of 70 °N) | |
|----------------------|------------------|-------------------------------------|--------------|--------------|-----------------------------------|---------------|
| | | MAM | JJA | SON | JJA | SON |
| Sfc. air temperature | K | 0.90 | 1.95 | 0.98 | 1.23 | 1.55 |
| Net SW down | Wm ⁻² | 5.49 | 13.19 | 0.07 | 0.37 | 0.00 |
| Net LW down | Wm ⁻² | -1.21 | -5.04 | -0.34 | -0.89 | -0.70 |
| Latent heat | Wm ⁻² | 1.76 | 4.35 | 1.38 | 1.60 | 1.00 |
| Sensible heat | Wm ⁻² | 1.89 | 4.12 | -0.60 | -0.01 | 0.39 |
| Surface albedo | % | -2.12 | -0.29 | -3.39 | -1.27 | -3.00 |
| Low cloud | % | -1.05 | -6.98 | 0.39 | -1.11 | 0.15 |
| High cloud | % | 1.41 | 0.83 | 1.65 | 1.29 | 0.40 |
| Sea ice extent | % ^a | — | — | — | -20.98 | -24.32 |
| Sea ice thickness | cm | — | — | — | -11.02 | -6.78 |
| Mixed layer temp. | K | — | — | — | 0.79 | 0.17 |
| Snowcover fraction | % | -3.84 | -1.79 | -3.12 | — | — |

^a Fractional to value in the present simulation (*P*).

Values represent mean differences between the *F* and *FV* simulation. Energy fluxes indicate surface values (positive downward). Bold indicates that the difference is statistically significant at a 99% confidence level (*t*-test)

covered ocean, and excessive energy transported from the lower latitudes is kept in the upper ocean. As the Arctic climate system enters the sea ice freezing phase, the Arctic Ocean starts to release large amounts of energy as a latent (+1.00 Wm⁻² in SON) and sensible (+0.39 Wm⁻² in SON) heat flux to the relatively colder atmosphere through the less ice-covered part of the ocean (-24.32% in sea ice extent in SON). Thus, it is concluded that the vegetation feedback in the high latitudes and the energy transport during the warm season induces a remote changes in the Arctic Ocean and the sea ice, and subsequent ice-albedo feedback greatly intensifies the surface warming over the Arctic Ocean (+1.55 K in SON).

The intensified Arctic warming in autumn and winter along with the sea ice coupling may have further promoted vegetation growth in the high latitudes in the following spring and summer. To examine this, surface air temperature change linked to Arctic sea ice change by the vegetation feedback effect is estimated in figure 6. The statistical coherence between the Arctic sea ice extent and the surface air temperature is estimated by regressions of monthly surface air temperature anomalies onto the Arctic sea ice extent, simulated in the *P* experiment: $\text{Reg}(\text{SIE}_P, \text{SAT}_P)$. Then, the change in the Arctic sea ice extent by the vegetation feedback effect (*F-FV*) is multiplied to the regression coefficients: $\text{Reg}(\text{SIE}_P, \text{SAT}_P) \times (\text{SIE}_F - \text{SIE}_{FV})$. Figure 7 indicates that the surface air temperature change associated with the SIE change by the vegetation-feedback, which accounts for a considerable amount of the Arctic and the circumpolar high-latitude warming throughout the year. In the winter and the following spring, a large increase in surface air temperature is especially found over the North Atlantic sector of the Arctic Ocean and the northernmost part of the continents. This can lead to a lengthening of the growing season and to enhanced vegetation activities in the next growing season, continuing the positive feedback chain.

4. Summary and discussion

In the present study, an intensified warming over the Arctic and high latitudes by vegetation-atmosphere-sea ice coupling in response to enhanced greenhouse gas forcings is investigated. This hypothesis is tested by a series of vegetation-climate coupled model simulations under 2xCO₂ environments with and without the vegetation feedback effect. The remote interaction with the Arctic sea ice and ocean is considered through the use of an interactive sea ice and ocean model. Results suggest that enhanced vegetation activities under a 2xCO₂ condition initially amplify surface warming in the high-latitude continental regions during the growing season, which enhances turbulent heat fluxes to the atmosphere. This invokes an enhanced remote and delayed warming over the Arctic. The surplus energy over the high latitudes induced by the vegetation feedback is transported poleward by the atmosphere, which causes more melting of sea ice and warming of the upper-ocean during the warm season. Consequently, in the following winter and spring, an enhanced heat release from the less ice-covered and warmer ocean amplifies warming over the Arctic. This feedback chain connected by vegetation, atmosphere and sea ice processes provides additional positive feedback of the Arctic amplification.

However, these results cannot be considered quantitatively realistic, particularly because of the equilibrium experimental design and several important limitations in the used modeling system. First of all, this study considered the biogeophysical feedback effect only, which is primarily associated with terrestrial albedo change; however, the biogeochemical feedback effect (i.e. carbon cycle feedback) was not included. For instance, the thawing of the permafrost has a tremendous potential to alter the global climate by releasing previously inaccessible soil carbon, but this effect is not explicitly considered in the current modeling system. Secondly, a limitation comes from the vegetation-sea-ice feedback that was examined though the use of a thermodynamic

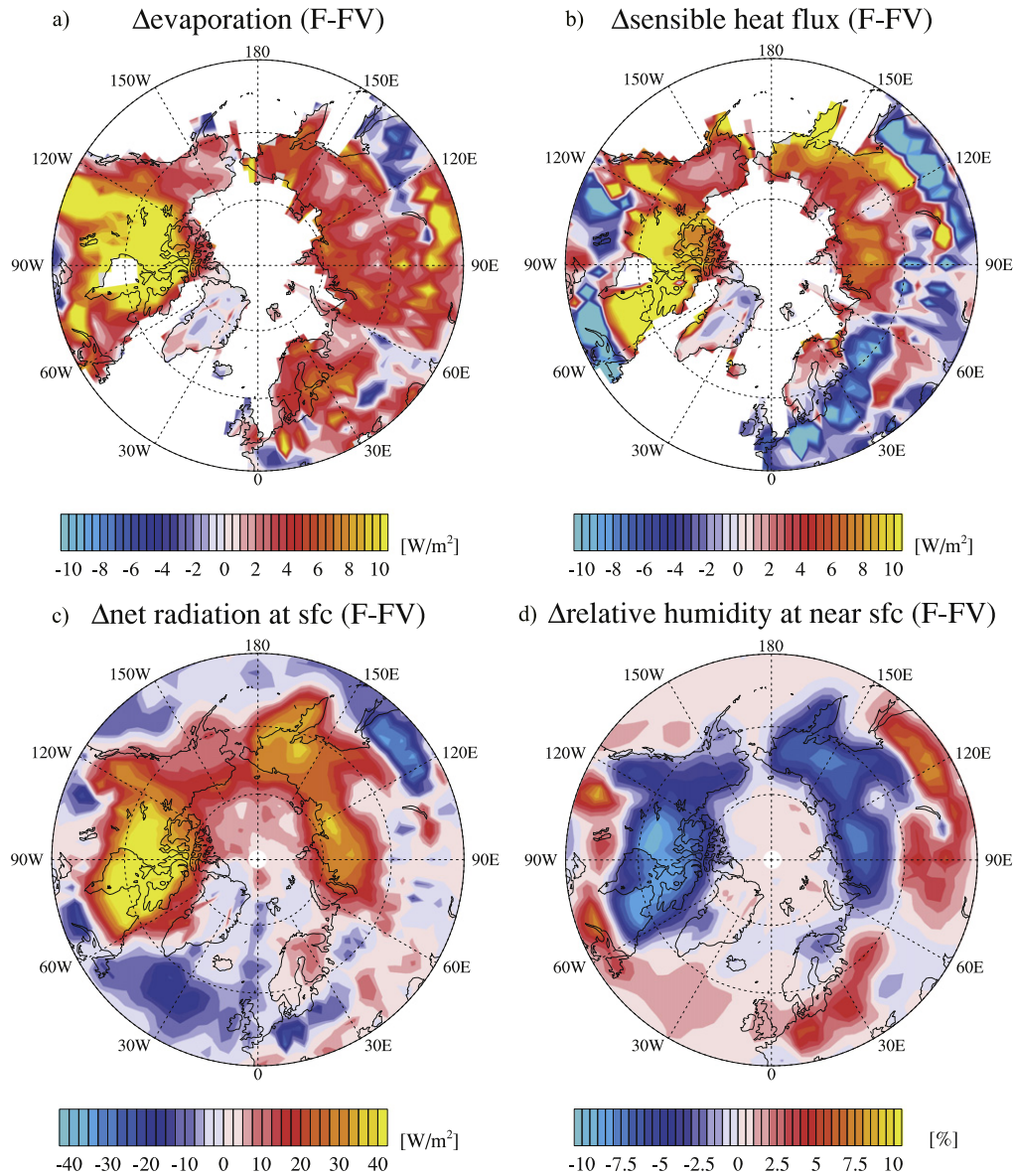


Figure 4. Changes in (a) evaporation, (b) sensible heat flux, (c) net radiation (shortwave and longwave) at the surface and (d) relative humidity at the near surface by the vegetation feedback effect (*F-FV*). The evaporation and sensible heat flux is positive upward, but the net radiation is positive downward.

sea ice model coupled to a slab ocean model. This modeling system largely simulated an additional warming of the upper ocean and more melting of sea ice from the vegetation feedback, but it is not capable of simulating further interactions with the deeper ocean and with dynamic sea ice. For instance, the atmospheric response to the vegetation feedback indicates weakened zonal wind at high latitudes (40–70 N) and high-pressure anomalies over the Arctic (figures 5(b), (c)). Ogi and Wallace (2007) and Overland and Wang (2010) suggested that atmospheric winds associated with this high-pressure pattern can further reduce sea ice, but this effect is missing in the present study. In addition, the upper-ocean warming may affect the stratification as well as the meridional overturning circulation at longer time scales; these are effects that were not considered in the present modeling system. There is a relatively modest and uniform increase in the

surface temperature over the ocean in figure 2, which could be partly due to the missing ocean circulation in this study. Another important limitation is the discrepancy of simulated vegetation. Despite great advances in modeling of dynamic vegetation, most vegetation models still have a large bias in simulating the present state of vegetation activities compared to observations. The used model tends to underestimate tree cover but overestimate grass species over the northern high latitudes (Bonan and Levis 2006). Because relatively tall trees and shrub species have stronger feedback effects than grasses due to their stronger interaction with snow (Sturm *et al* 2001), the present results may also be affected by this discrepancy. Furthermore, the snow-albedo feedback due to the snow-masking effect of vegetation is poorly represented by most climate models (Loranty *et al* 2014).

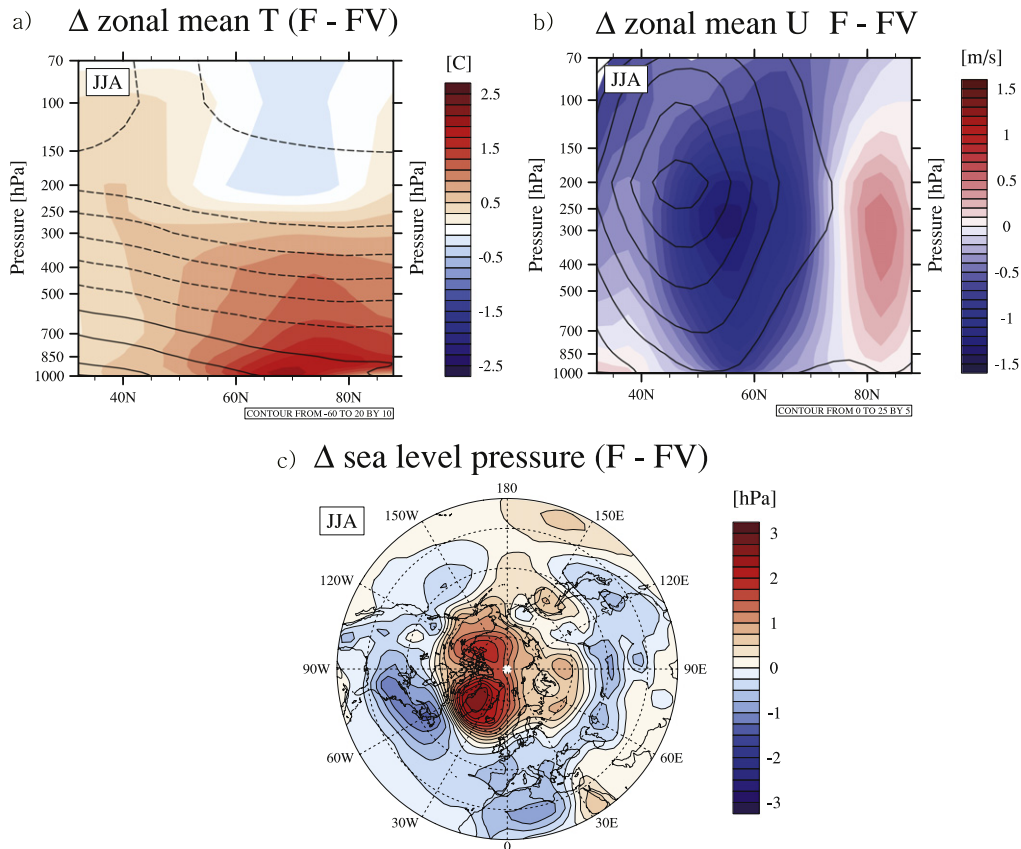


Figure 5. (a) Zonal mean of air temperature, zonal wind and (c) sea-level pressure changes by the vegetation feedback effect (*F-FV*) in JJA. For the air temperature and zonal wind, the shading indicates the difference between the *F* and *FV* simulation, and the contour lines indicate the climatological mean value in a *P* simulation (the dashed and solid line indicates a negative and positive value, respectively).

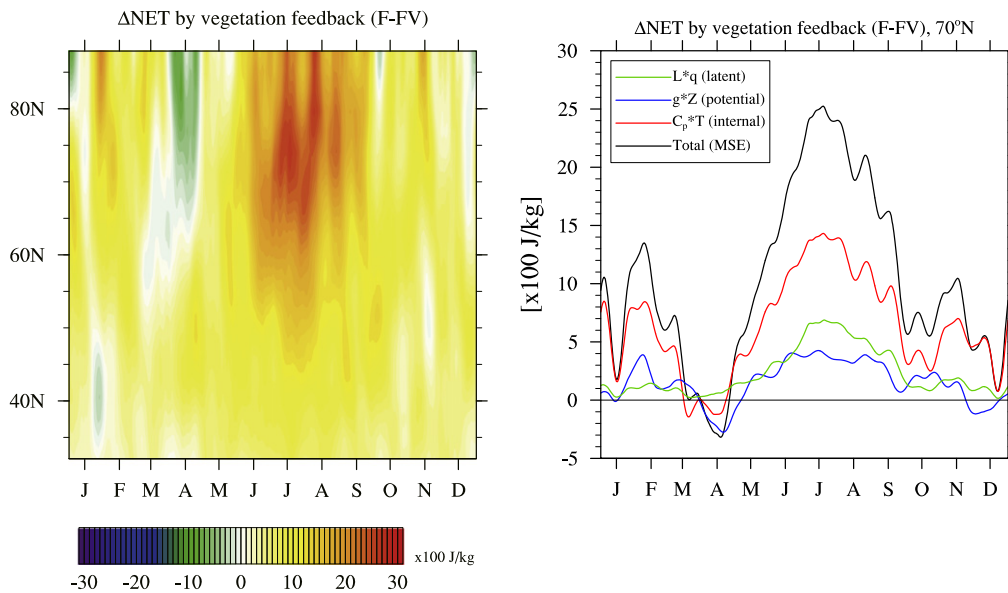


Figure 6. Left: tropospheric (1000–200 hPa) *NET* change by the vegetation feedback effect (*F-FV*). Right: changes in the components of *NET* at 70°N. A ten-day running average is applied for the time dimension. Here, the atmospheric energy is estimated by the moist static energy-summation of the atmospheric latent, potential and internal energy.

Most of the climate models that participate in CMIP3 and CMIP5 efforts underestimated the rapid surface warming and Arctic sea ice loss in recent decades after the late 1990s (Stroeve *et al* 2007, Stroeve *et al* 2012). The underestimated

Arctic warming is possibly associated with natural variabilities not fully resolved by those simulations. For instance, a recent study by Ding *et al* (2014) suggests that the negative trend in the North Atlantic Oscillation induced by tropical

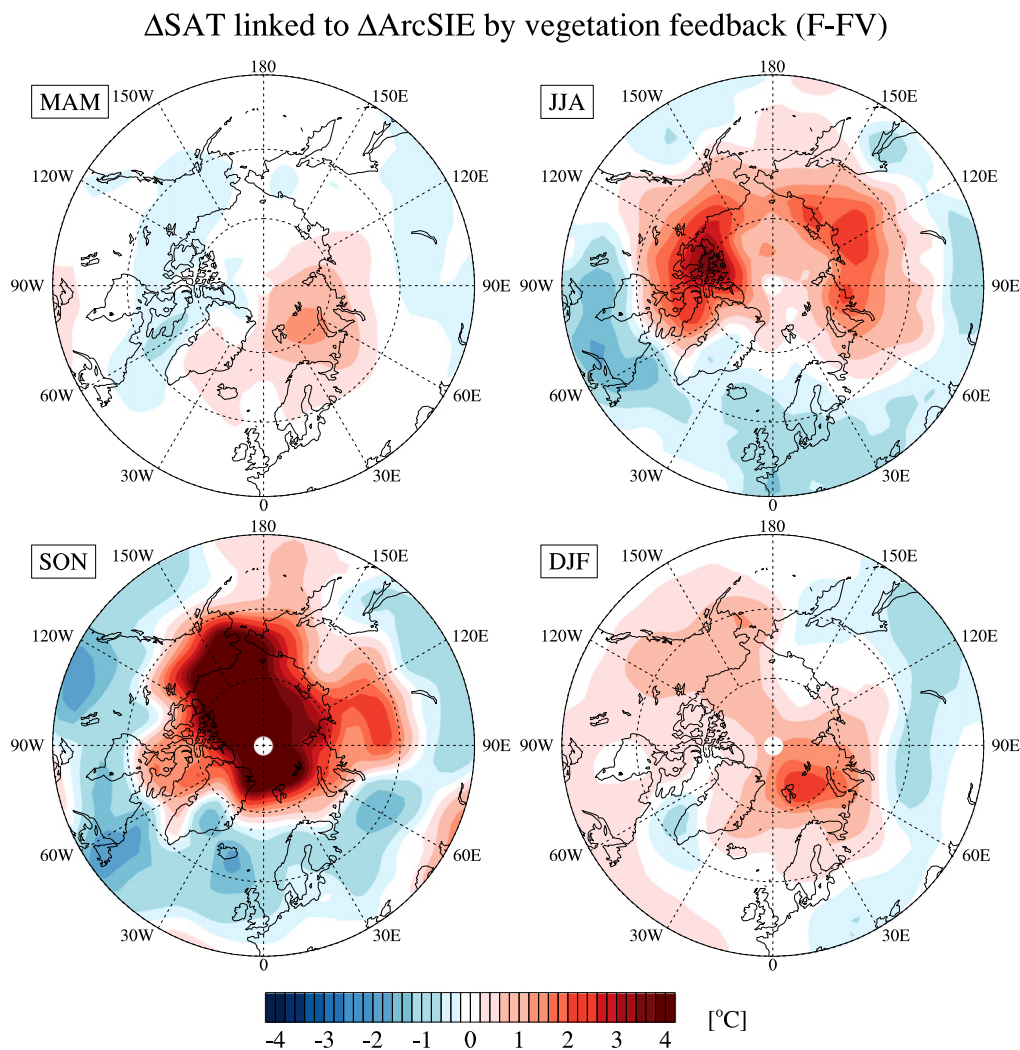


Figure 7. Statistically projected surface air temperature change associated with the Arctic sea ice extent (SIE) change by the vegetation feedback effect based on a regression analysis. The SIE is the summation of the areal extent where the sea ice concentration is greater than 15% over the Arctic sea (north of 70 N), and the SAT is the surface air temperature. Details of the calculation are in the text.

forcings is strongly associated with the recent warming in the Arctic, but these effects were poorly simulated by the CMIP5 model. The climate models' deficiencies in simulating complicated feedback processes involved in the Arctic climate system are also responsible for the discrepancy. Among many climate feedback processes involved in the Arctic climate change, Boe *et al* (2009) suggested that weaker warming in the Arctic is mostly due to excessive longwave radiation feedback and cloud bias of climate models. Our finding suggests that the exclusion of the vegetation feedback in climate models (e.g. CMIP3 models) may have also contributed to the underestimated Arctic warming, as most models have not fully considered vegetation changes in their scenario simulations. Currently, most CMIP5 simulations include the vegetation feedback effect, as the Earth system model (ESM) that incorporates the dynamic vegetation model is widely utilized for the scenario simulations. However, the overall performances of vegetation models and vegetation feedback effects have not been systematically assessed yet. We plan to further investigate the vegetation-atmosphere-sea

ice coupling using an ESM with a fully coupled dynamic ocean model and with terrestrial biogeochemistry.

Acknowledgements

JHJ was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education, Science and Technology (2012M1A2A2671852). This work was partly supported by the National Research Foundation of Korea Grant funded by the Korean Government (MEST) (NRF-2011-0021069, PN13063). HL was supported by the Swedish Research Council (VR). This research contributes to the Swedish strategic research areas Modelling the Regional and Global Earth system (MERGE), and Biodiversity and Ecosystem services in a Changing Climate (BECC). The datasets used in this study were produced by the CCSM3. The source code and all of the required input datasets were provided by NCAR, Boulder, Colorado, USA (downloaded at <http://www>).

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