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Key Points:

- Sea ice concentration and extent are simulated by a fully coupled regional Earth system model, including interactive vegetation dynamics
- Interactive vegetation dynamics increase the interannual variations of seasonal sea ice cover
- Increased downwelling longwave radiation induced by vegetation feedbacks enhances sea ice melting

Supporting Information:

- Supporting Information S1

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The Interplay of Recent Vegetation and Sea Ice Dynamics—Results From a Regional Earth System Model Over the Arctic

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Abstract Recent accelerated warming over the Arctic coincides with sea ice reduction and shifting patterns of land cover. We use a state-of-the-art regional Earth system model, RCAO-GUESS, which comprises a dynamic vegetation model (LPJ-GUESS), a regional atmosphere model (RCA), and an ocean sea ice model (RCO), to explore the dynamic coupling between vegetation and sea ice during 1989–2011. Our results show that RCAO-GUESS captures recent trends in observed sea ice concentration and extent, with the inclusion of vegetation dynamics resulting in larger, more realistic variations in summer and autumn than the model that does not account for vegetation dynamics. Vegetation feedbacks induce concomitant changes in downwelling longwave radiation, near-surface temperature, mean sea level pressure, and sea ice reductions, suggesting a feedback chain linking vegetation change to sea ice dynamics. This study highlights the importance of including interactive vegetation dynamics in modeling the Arctic climate system, particularly when predicting sea ice dynamics.

Plain Language Summary Recent accelerated warming over the Arctic is associated with dramatic changes in the physical environment, among which unprecedented sea ice decline has received particular attention. In this study, we use a regional Earth system model accounting for interactive coupling between the atmosphere, land vegetation, and sea ice dynamics to explore their potential links. Our model simulates observed spatiotemporal patterns of sea ice thickness and extent reasonably well. Furthermore, the results show that feedbacks of warming-driven vegetation changes on the near-surface radiation balance can cause greater variations in sea ice between seasons, which can contribute to an accelerated trend of sea ice reduction. The changes in mean sea level pressure caused by vegetation changes can alter the transport of energy and warm the land, sea, and sea ice surfaces. Downwelling longwave radiation is the dominant factor contributing to the near-surface warming and increased sea ice melting. Our study highlights the importance of adopting fully coupled Earth system models that account for interactive effects of vegetation dynamics on the physical climate system, in particular when analyzing the reduction of sea ice in the Arctic.

1. Introduction

Observed rates of warming in the northern high latitudes (NHL) and the Arctic continue to be more than twice the global average and drive dramatic changes in the physical environment, including reductions in the areal pattern, concentration and thickness of sea ice, the extent and duration of snow cover, and the active layer depth and temperature of permafrost (AMAP, 2019; Overland et al., 2019). Among these changes, the rapid loss of Arctic sea ice has received particular attention, because it plays a significant role in accelerating anthropogenic warming through reduced ice albedo and other feedbacks (Koenigk et al., 2011; Richter-Menge & Jeffries, 2011). Such reductions in summer sea ice are expected to affect energy exchange between the ocean and atmosphere and thereafter atmospheric circulation patterns, causing tangible effects on the weather and climate of the Arctic as well as globally (Bhatt et al., 2014; Vihma, 2014).

Owing to complex interactions between Earth system components (i.e., land, ocean, and atmosphere) and a large year-to-year variability superimposed on the declining trend of sea ice area and extent, the causes and feedbacks associated with observed, rapid changes in Arctic sea ice are still under debate (Kapsch et al., 2013;

Lee et al., 2017; Screen & Simmonds, 2010; Zhang et al., 2012). The reduction in surface albedo associated with the loss of bright sea ice in favor of a dark ocean surface is often regarded as the most significant feedback mechanism, amplifying near-surface warming and reinforcing sea ice melting. However, enhanced evaporation as a result of a larger open water coverage may give rise to more atmospheric water vapor and cloud cover during the following winter and spring, potentially offsetting the albedo effect in terms of surface radiation balance. Resulting cloud-radiation feedbacks can be an important contributor to sea ice reduction, because clouds may amplify warming through greenhouse gas (GHG) effects of water vapor and compensate for the reduction of incoming shortwave radiation due to reflection (Screen & Simmonds, 2010). Meier et al. (2014) suggest that longwave radiation may be a dominant driver of initial sea ice reduction in spring. Moreover, there is uncertainty as to the extent to which observed increases in atmospheric moisture in the Arctic arise from lateral atmospheric transport from midlatitudes (Zhang et al., 2012), versus intensified local evaporation (Bintanja & Selten, 2014).

Vegetation cover and density, particularly of trees and tall shrubs, are a pivotal player in linking components of the Arctic and boreal climate system, regulating the land surface energy balance, affecting the hydrological cycle, and altering the atmospheric GHG concentration by controlling ecosystem uptake or release of carbon in the form of CO₂ and methane (Zhang et al., 2014, 2018). Field-based mapping, ecosystem flux tower measurements, and modeling experiments all consistently suggest that the composition, structure, distribution, and productivity of vegetation in the NHL are highly sensitive to recent or potential future climatic warming (Elmendorf et al., 2012; IPCC, 2013; AMAP, 2019; Zhang et al., 2018).

Observations have revealed both a negative correlation between summer sea ice extent and air temperature and a positive correlation between summer warmth and vegetation productivity (Bhatt et al., 2010; Dutrieux et al., 2012). Other studies show that sea ice decline has impacts on Arctic GHG exchange (e.g., CO₂ uptake, respiration, and methane release) and ecological interactions (e.g., mixing population, restricting gene flow, and changing habitats) (Parmentier et al., 2013; Post et al., 2013), but no significant trends in Alaskan fire occurrence have been detected in recent decades (Earl & Simmonds, 2018). However, a mechanistic link between ecosystem responses to climate warming, on the one hand, and sea ice dynamics, on the other, has to date not been clearly demonstrated. This is because it is extremely challenging to separate vegetation feedback signals based only on observations, in particular when compounded with the large-scale patterns of the atmospheric circulation and remote atmospheric teleconnections. Elucidating causal mechanisms linking vegetation dynamics to sea ice dynamics is important to inform and establish confidence in models of the coupled Arctic climate system, necessary to preempt future changes and guide environmental and conservation policy.

Earth system models (ESM) simulate interactive coupling between the atmosphere, ocean, biosphere, and sea ice and allow us to investigate the causes and consequences of regional and global climate shifts under forcing such as emissions-driven increase in atmospheric GHG. Compared to global ESM, regional ESM are capable of representing more realistic physical land-to-ocean processes since coastlines and topographic and orographic features can be represented at higher resolution for lower computational cost (Giorgi, 2019). These high-resolution details are essential to identify and quantify local and regional feedbacks. Most regional ESM studies to date address either interaction between the atmosphere and ocean-sea ice or interaction between the atmosphere and land. This study is among the first to explore feedbacks linking vegetation dynamics to sea ice dynamics via the physical state of the atmosphere and surface. To this end, we employed a regional ESM, RCAO-GUESS, which integrates the component models: the 3-D dynamic ocean-sea ice model RCO, the regional atmosphere model RCA, and the dynamic vegetation model LPJ-GUESS (Smith et al., 2001). The specific aims of our study are to address the following questions: (1) How well does the fully coupled regional ESM simulate sea ice dynamics? (2) What are the impacts of interactive vegetation on sea ice dynamics? (3) What feedback mechanisms may exist to explain the links between Arctic vegetation dynamics and sea ice dynamics?

2. Materials and Methods

2.1. RCA—The Atmospheric Component of RCAO-GUESS

The atmospheric component, RCA (Rossby Centre Atmosphere regional climate model), is originally based on the numerical weather prediction model HIRLAM (High Resolution Limited Area Model) (Undén et al.,

2002). The model has a particular focus on maintaining regional energy and water balance to simulate a multiyear climatology with a high degree of realism. Earlier versions of RCA are described by Jones, Willén, et al. (2004), Jones, Wyser, et al. (2004), Kjellström et al. (2005), and Samuelsson et al. (2011). Since RCA3, a tiled surface scheme was introduced to RCA to address subgrid scale energy balances and fluxes for forest, open land, and snow (Samuelsson et al., 2006). This study uses the version RCA4, the details of which are described by Samuelsson et al. (2015).

2.2. RCO—The Ocean Component of RCAO-GUESS

The ocean component, RCO, is developed from a widely used Bryan-Cox-Semtner primitive equation ocean model, which represents the 3-D ocean structure in geopotential and vertical coordinates with a free surface (Meier, 2002). RCO incorporates a Hibler-type two-level (open water and ice) dynamic-thermodynamic sea ice model based on an elastic-viscous-plastic (EVP) rheology (Hunke & Dukowicz, 1997) and Semtner-type thermodynamics (Semtner, 1976). A rotated latitude-longitude grid and a two-equation turbulence closure scheme are used to simulate vertical mixing of water (Döscher et al., 2010). RCO has 59 unevenly distributed vertical levels with the bottom topography interpolated from the ETOPO5 data set (Data Announcement 88-MGG-02, 1988). Vertical resolution is 3 m at the surface, gradually decreasing to 200 m at 5,000 m.

2.3. LPJ-GUESS—The Vegetation Dynamics Component of RCAO-GUESS

LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) is a process-based model simulating vegetation dynamics, ecosystem biogeochemistry, and hydrology, customized for landscape and regional and global scales (Smith et al., 2001). Vegetation dynamics are simulated following the “individual-based” concept of forest gap models, which represent the dynamics and demography of woody vegetation as the emergent outcome of establishment, mortality, and competition for light, space, and soil resources among co-occurring individuals from a fixed set of plant functional types (PFTs) and a herbaceous understory within replicate patches representing “random samples” of a simulated landscape (Smith et al., 2001). PFTs use a set of parameters to represent plant species of similar properties regarding bioclimatic constraints, phenology, growth form, allometry, tolerance to light conditions, and photosynthetic pathway (Hickler et al., 2004). Parameters of six PFTs to represent Arctic and boreal trees and herbaceous vegetation are given in Table S1 in the supporting information.

2.4. The Coupled Regional Earth System Model RCAO-GUESS

RCAO-GUESS merges the architecture of two existing coupled models, RCAO and RCA-GUESS (Figure S1). 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. RCAO has previously been described and evaluated for both the Baltic Sea and Arctic domains (Döscher et al., 2002, 2010). In RCAO, RCO and RCA run in parallel and exchange data with each other every 3 hr. RCO provides ocean surface state variables such as sea surface temperature, SIC, ice temperature, and snow/ice albedo to RCA. RCA provides RCO with fluxes of heat, freshwater (i.e., precipitation minus evaporation), and momentum. In addition, river runoff is applied from climatological data. This is necessary because the complete hydrological runoff area over the land is not covered by the model domain. In RCA-GUESS, RCA provides daily air temperature, precipitation, and incoming shortwave radiation to LPJ-GUESS. In response, LPJ-GUESS updates daily LAI and annual vegetative fraction for broad-leaved forests, needle-leaved forests, and grass in the LSS of RCA for calculating surface energy fluxes (Smith et al., 2011).

2.5. Experiments and Data

The domain of this study extends from approximately 50°N in the North Atlantic to the Aleutian Islands in the North Pacific (Figure S2). Both RCA and RCO were integrated at a horizontal resolution of 0.5°, on rotated latitude-longitude grids for RCA and spherical grids for RCO. The lateral boundaries of RCAO-GUESS were forced with the ERA-Interim reanalysis data (Dee et al., 2011) for 1989–2011. The lateral driving fields consist of temperature, zonal, and meridional winds and specific humidity at 24 vertical model levels up to approximately 15 hPa at the top level. All three component models were initialized to a realistic state for the start of the target analysis period, as a preliminary first step. In LPJ-GUESS, we used the detrended climate data (1960–1989) from the CRU 3.1 data set (Harris et al., 2014) and a fixed atmospheric CO₂ concentration of 317 ppm to spin up the model for 300 years and to generate the vegetation and carbon pool states appropriate to 1990.

To disentangle the impacts of interactive vegetation dynamics on sea ice dynamics from other influences, we carried out two experiments: the AOV run, the fully coupled simulation accounting for the atmosphere, ocean, and vegetation dynamics, and the AO run, an identical run except that we fixed the vegetation state as in 1990 for the full length of the simulation. A spectral nudging was implemented for the interior domain during the experimental setup to remedy the bias in the mean sea level pressure and surface winds induced from large circulation components of the driving files without significantly affecting radiative fluxes, temperature, and precipitation (for details of the spectral nudging characteristics, see Berg et al., 2013). To evaluate SIC and SIE, we used the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (Version 2) data set (Meier et al., 2013) and the Sea Ice Trends and Climatologies data set from SMMR and SSM/I-SSMIS (Stroeve, 2003), respectively. To quantify impacts of interactive vegetation dynamics on Arctic sea ice dynamics, we averaged and compared the relevant variables from two 5-year periods (i.e., 1992–1996 and 2007–2011), which represent endpoints of an episode of pronounced sea ice decline in the observational records.

3. Results

Various regions and seas in the Arctic Ocean mentioned in this section are depicted in Figure S3. Their geographical boundaries are defined by Serreze and Barry (2014).

3.1. Changes in the Species Abundance Among Vegetation Dynamics

Changes in the relative abundance of evergreen and deciduous trees, and between woody and herbaceous species, of the Arctic and boreal vegetation, were characterized by the Normalized Phenology Index (NPI) (%) and the Normalized Physiognomy Index (NPMI) (%) (for equations, see Figure 1 caption), respectively, for 2007–2011 relative to 1992–1996. These two indices were calculated based on the leaf area index (LAI) of the PFTs as simulated by our model. An increase in NPI, indicating some replacement of deciduous needle-leaved trees by evergreen needle-leaved trees, was seen at the southern edge of central Siberia but coincided with a reduction of total tree cover (Figure 1). In contrast, coverage of deciduous species increased in Beringia, Taymyr Peninsula, and West Hudson Bay (Figure 1a). In central and eastern Siberia, Northern Canada, and Alaska, there was a noticeable increase in the percentage of woody species, indicating establishment and a northward shift of trees in the Arctic tundra (Figure 1b).

3.2. Interannual Variations of the Total Sea Ice Areal Extent

As the lowest SIE was most often observed in September (Simmonds, 2015), we compared the temporal variations (1991–2011) of the SIE in September simulated by the AOV run and the AO run with the observations. Both runs captured the negative SIE trend seen in the observations, but the AOV run showed a larger negative trend (slope: $-0.08 \times 10^6 \text{ km}^2 \text{ year}^{-1}$, and R^2 : 0.4), which is closer to the observations (slope: $-0.13 \times 10^6 \text{ km}^2 \text{ year}^{-1}$, and R^2 : 0.67) than the AO run (slope: $-0.06 \times 10^6 \text{ km}^2 \text{ year}^{-1}$, and R^2 : 0.5) (Figure 2a). In addition, the AOV run captured the large yearly declines seen in the observed September SIE for the years 2005 and 2011. This was not reproduced by the AO run. Differences in the total SIE between two runs increased during the later years of the study period, especially in summer (i.e., June–August) and autumn (i.e., September–November) seasons (Figure 2b), reflecting a greater reduction of sea ice (Figure 2b) in the AOV run. Relative to the AO run, the AOV run simulated a higher SIE in winter and spring during 1991–2003 and a lower SIE for most seasons during 2004–2011. The seasonality of modeled SIE for the period 1992–1996 agreed more closely with observations during spring and summer than during autumn and winter (Figure 2c). For the period 2007–2011, the model captured summer SIE better than the period 1992–1996, especially in the AOV run, but in winter and spring, both runs underestimated SIE.

3.3. Impacts of Vegetation Feedbacks on Sea Ice Concentration

The AOV run reproduced reasonable spatial distribution of SIC for different seasons, compared to the observed data sets (Figures S4 and S5). Here we focus on vegetation feedback-induced differences in SIC. For 1992–1996 (Figures 3a–3d) impacts of vegetation change on sea ice were minor compared to the later period 2007–2011 (Figures 3e–3h). For 1992–1996, there was a reduction of SIC that started in winter and spring in the Kara Sea and spread along the Beringia coast to the Beaufort Sea in summer and autumn (Figures 3a–3d). The most substantial reduction of SIC occurred in autumn in the Laptev Sea. In contrast, increases of SIC were found in Chukchi Sea and Barents Sea (winter), Baffin Bay and Russian Arctic

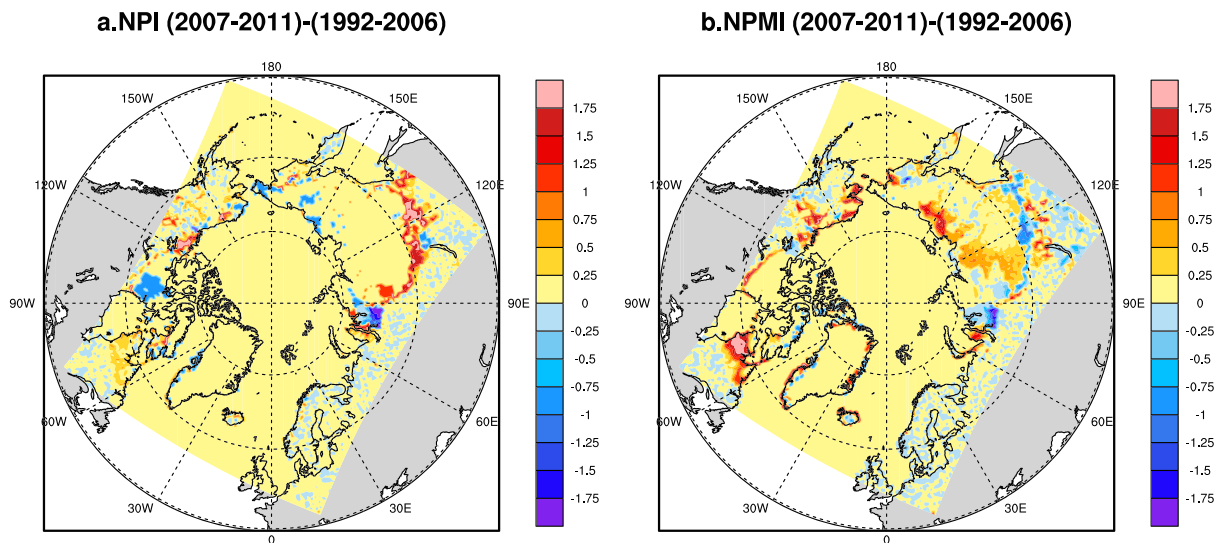


Figure 1. The change in the relative abundance between evergreen (eg) and deciduous (dec) trees and between woody (w) and herbaceous (h) species from 1992–1996 to 2007–2011. (a) The percentage of change in the normalized phenology index (%) $NPI = (LAI_{eg} - LAI_{dec}) / (LAI_{eg} + LAI_{dec})$ (positive: more evergreen; negative: more deciduous). (b) The percentage of change in the normalized physiognomy index (%) $NPMI = (LAI_w - LAI_h) / (LAI_w + LAI_h)$ (positive: more woody; negative: more herbaceous).

Basin (all seasons), and Greenland Sea (spring to autumn). Vegetation-induced changes in SIC are more pronounced in 2007–2011 than in 1992–1996, in particular for summer and autumn (Figures 3e–3h). Baffin Bay and Hudson Bay experienced a reduction in winter and spring. A substantial reduction (10–25%) of SIC in summer and autumn occurred in the North America Arctic Basin and Russian Arctic Basin. However, there was also an increase of SIC in the Laptev Sea and the East Siberian Sea in summer, which was in contrast to the reductions seen there in 1992–1996.

3.4. Links Between Vegetation Dynamics and Sea Ice Dynamics

To understand feedback mechanisms linking vegetation change to sea ice dynamics, we presented spatial patterns of seasonal anomalies (i.e., the AOV run minus the AO run) for relevant variables (e.g., mean sea level pressure, 2 m air temperature, downwelling longwave radiation, and precipitable water) between 2007–2011 and 1992–1996. Albedo changes induced by shifting vegetation patterns (Figure 1) caused surface heating imbalances, leading to sea level pressure anomalies in different seasons (Figures 4a–4d). This is associated with a reduction in surface albedo, notably during the period of snow lying in winter and spring: Increased heating of the land surface (due to a lower albedo) could lift up more cold surface air to the

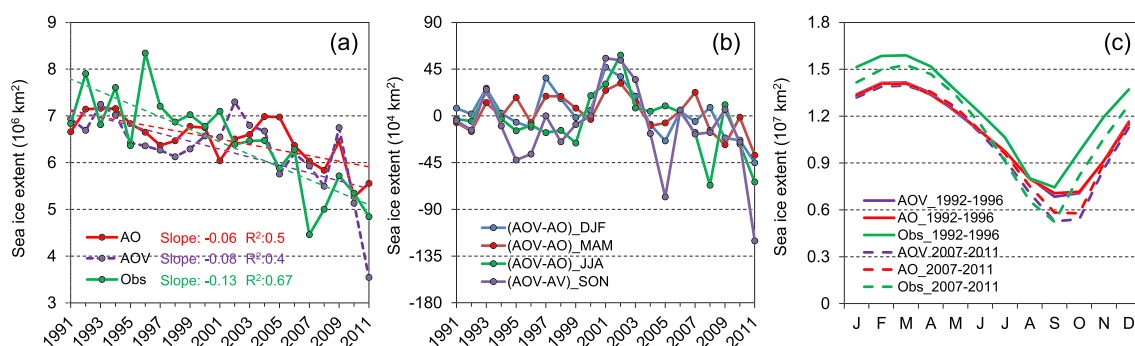


Figure 2. The interannual and seasonal variations of sea ice extent (km^2) in the AOV run, the AO run, and the observation data sets (Stroeve, 2003). (a) The interannual variations of September sea ice extent. The dash lines indicate linear regression lines for interannual variations. (b) The interannual variations of sea ice extent for four seasons: winter (DJF), spring (MAM), summer (JJA), and winter (SON). (c) Seasonal variations of sea ice extent for the periods 1992–1996 and 2007–2011.

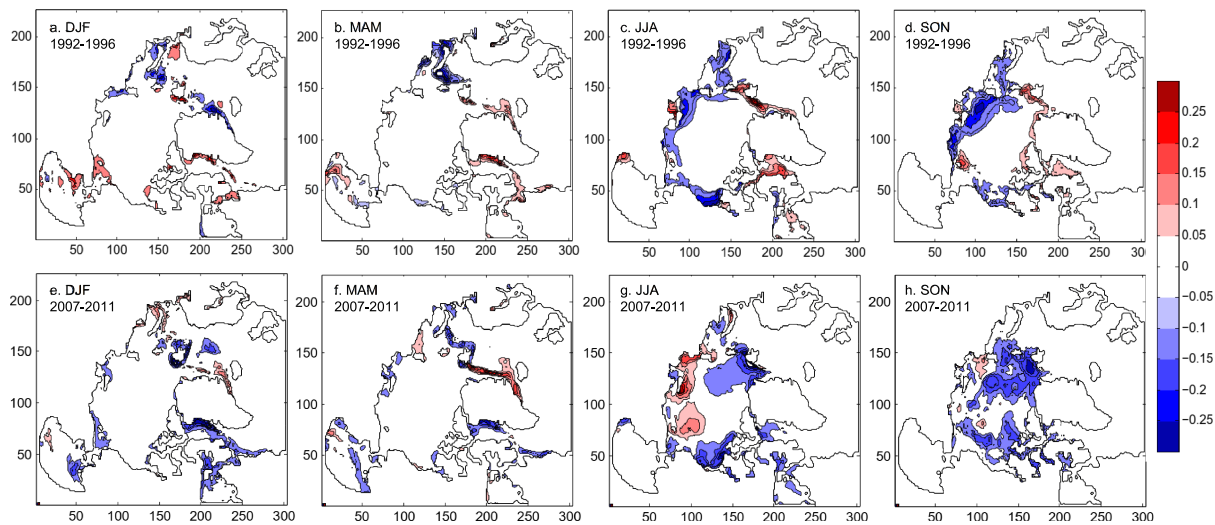


Figure 3. Changes in seasonal sea ice concentration (0–1) change due to interactive vegetation in the period 1992–1996 (a–d) and changes in seasonal sea ice concentration (0–1) change due to interactive vegetation in the period 2007–2011 (e–h).

atmosphere, leading to anomalous low pressure (e.g., over West Siberia and North Canada in spring and over Far East and East Siberia in summer) (Figures 4a, 4b, 4m, and 4n). In summer, the East Siberian Sea and Greenland showed anomalously high pressure. The resulting change to the pattern of mean sea level pressure altered atmospheric and oceanic circulation, which in turn altered the spatial distribution of the cloud cover anomaly. We used the precipitable water to indicate cloud cover with relatively condensed water vapor. In autumn, positive sea level pressure anomalies were corresponded negatively to precipitable water anomalies (Figures 4d and 4h), indicating that higher sea level pressure suppressed the upward atmospheric motion of air masses and cloud formation. The precipitable water anomaly pattern also corresponded well to the downwelling longwave radiation anomaly pattern, indicating that increased downward longwave radiation resulted from increased water vapor in the atmosphere (Figures 4i–4l). The downwelling longwave radiation anomalies had a similar spatial pattern as the air temperature anomalies, indicating that the downwelling longwave radiation might dominate the contribution to the increased warming over land and the sea surface. Luo et al. (2017) have also demonstrated the key role played by the precipitable water and the consequential increases in downwelling longwave radiation and warming, which may promote sea ice decline.

The seasonal and spatial patterns of seasonal sea ice anomalies were closely related to the spatial patterns of 2 m air temperature anomalies (Figures 3e–4h and 4m–4p). For instance, in autumn, the European Arctic basin, the Laptev Sea, Kara Sea, and Beaufort Sea experienced a substantial sea ice decline (Figure 4d), coincident with additional warming in those seas (Figure 4p). In contrast, summer SIC increased in the East Siberian Sea and Laptev Sea (Figure 4c), regions that experienced additional cooling (Figure 4o).

4. Discussion

The shifting patterns of vegetation during the two decades simulated by our study are similar to Zhang et al. (2013), in which LPJ-GUESS was driven by observed climate fields. These also agree well with vegetation greening and browning trends inferred from satellite observations (1981–2016) for NHL (60–90°N) by Winkler et al. (2019). This provides confidence that LPJ-GUESS can capture the expansion of woody species seen in observations over the Arctic and boreal study area in response to recent warming. The simulation with interactive vegetation dynamics produced a more rapid sea ice loss in summer and autumn than the simulation without accounting for interactive vegetation (Figure 2b), suggesting that the fully coupled model may have increased the internal variability of the simulated climate system. Consistent with this finding, Zhang et al. (2018) showed that vegetation feedbacks in the regional atmosphere model with interactive vegetation dynamics (RCA-GUESS) produced additional seasonal variability of precipitation in stronger anthropogenic warming scenarios.

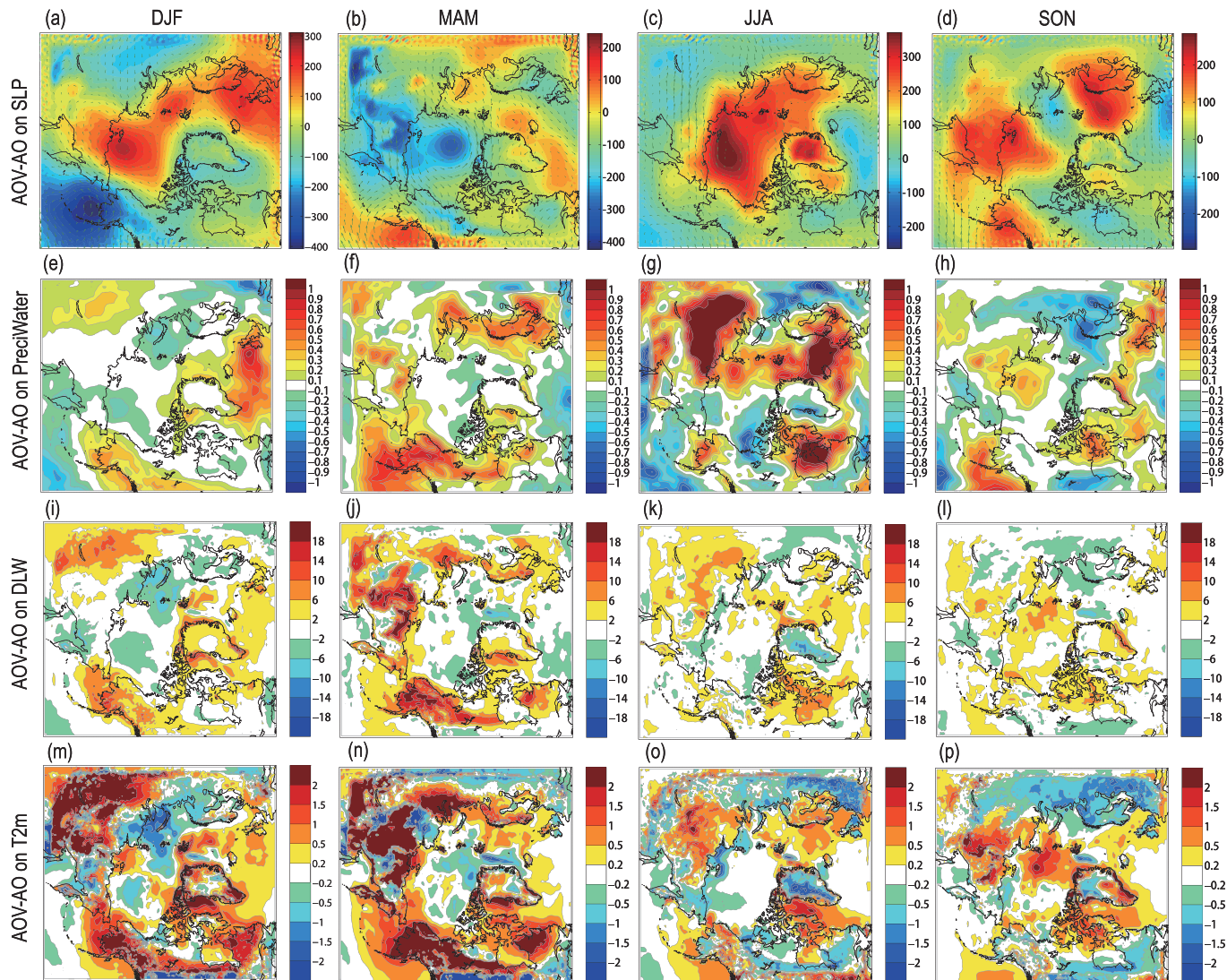


Figure 4. Mean seasonal changes in (a–d) sea level pressure (SLP) (Pa), (e–h) precipitable water (PreciWater) (mm), (i–l) downwelling longwave radiation (DLW) (W m^{-2}), and (m–p) 2 m air temperature (T2m) ($^{\circ}\text{C}$) due to interactive vegetation in the period 2007–2011.

Increased occurrence of woody species in the circumpolar Arctic tundra, especially deciduous trees or tall shrubs, has lower albedo values and higher evapotranspiration rates in the growing season than tundra vegetation (Kasurinen et al., 2014; Sturm et al., 2005). These changes could lead to two positive feedbacks, namely, albedo feedback and GHG feedback, each contributing to near-surface warming but with one effect dominating in different seasons. Effects of albedo change on energy fluxes are more noticeable in the spring and summer over land (Figures S7 and S8) and characterized by the surface darkened by the stems and leaves of expanded vegetation protruding above the snowpack. This leads to more incoming shortwave radiation absorbed by the land surface, triggering earlier snowmelt (Belke-Brea et al., 2020). Meanwhile, the atmospheric water vapor is expected to increase due to earlier snowmelt, increased evapotranspiration of species with deeper roots, and greater leaf area in summer and enhanced sea ice melting. Therefore, near-surface heating was regulated by the confounding effects of shortwave and longwave radiation. Our results further show that the decreased downwelling shortwave radiation due to the increased clouds was outweighed by the increased downwelling longwave radiation due to the increased atmospheric water vapor (Figure S6). For seasonal and spatial patterns, the changes in downwelling longwave radiation coincide with the changes in near-surface 2 m air temperature and SIC (Figure 4). These results suggest that the albedo

effect on the net surface shortwave radiation may be secondary to the effects of GHG and atmospheric circulation to cause additional near-surface warming. The increased downwelling longwave radiation could be the dominant factor contributing to the modeled, local, and seasonal SIC, even though other factors such as changes to sea ice drift due to altered winds and ocean currents may play a role in causing sea ice formation, circulation, and melting (Döscher et al., 2010).

Based on prescribed increases in LAI and vegetation cover—not a dynamic coupling between the atmosphere and biosphere—in a general circulation model (GCM), Zhang and Walsh (2006, 2007) and Swann et al. (2010) all found that the greener Arctic could intensify vegetation transpiration and subsequently enhance convective and large-scale activities of precipitation or increase atmospheric water vapor. Moreover, Jeong et al. (2014) used a fully coupled vegetation-atmosphere-sea ice GCM to study the impacts of vegetation dynamics on near-surface warming and sea ice melting in a doubled CO₂ (2 × CO₂) experiment. While the fully coupled GCM employed in their study used a much lower grid resolution compared with the present study, they likewise found that interactive vegetation dynamics could decrease sea ice cover and warm the upper-ocean during the warm seasons, leading to amplified warming in the following winter and spring months and a positive feedback to vegetation growth. Jeong et al. (2014) inferred that growing season vegetation feedbacks could induce anomalously high sea level pressure in the Arctic Ocean and over Greenland, a finding also apparent in our results (Figure 4c). While these earlier studies are based on either a sudden, artificial prescription of an altered vegetation distribution or the equilibrium state of vegetation after a period of abrupt climate change following a sudden CO₂ increase, they consistently highlight the fact that vegetation dynamics could intensify the hydrological cycle and induce additional surface warming through the GHG effects of water vapor. Our study confirms the qualitative conclusions of these earlier studies, under the more realistic conditions of transient change in external forcing and in responding state of the vegetation, ocean, and sea ice, with higher spatial resolution, capturing coastal and orographic effects.

5. Summary

We present a regional ESM study accounting for both interactive vegetation dynamics and sea ice dynamics. Our results show that RCAO-GUESS captures recent trends in observed sea ice concentration and extent, with the inclusion of vegetation dynamics resulting in larger, more realistic variations in summer and autumn than the model that does not account for vegetation dynamics. Even though this inferred long feedback chain is only based on the endpoint episodes of the study period, it shows consistent patterns of changes in near-surface warming, precipitation, and sea ice reduction for the entire period but with higher magnitudes (Figures S9 and S10). This highlights the potential importance of including interactive vegetation dynamics in fully coupled global and regional Earth system models, and in particular when seeking to predict or understand sea ice dynamics in response to climate change. The mean sea level pressure anomaly caused by the vegetation changes we simulate can alter the transport of energy and warm the land, sea, and sea ice surfaces. Consistent with previous modeling studies, we find that downwelling longwave radiation is the dominant contributing factor to local surface warming and sea ice melting. Disentangling the drivers of particular annual or multiannual events in a complex system using a complex model with three interacting, dynamic components, each with its own limitations (as with all models), is a challenging task. We believe that one way forward might be to first confront and evaluate individually all model components with a range of multiyear observations and metrics, after which the coupled systems could be evaluated in a factorial manner. We have begun such a process by comparing AO and AOV runs in this work, but one could get further insights from additional ocean-only and vegetation-only experiments forced with reanalysis data and/or RCA output from the AO and AOV runs.

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