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Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming

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Abstract
Deciduous shrub abundance is increasing across the Arctic in response to climatic warming. In a recent field manipulation experiment in which shrubs were removed from a plot and compared to a control plot with shrubs, Blok *et al* (2010 *Glob. Change Biol.* **16** 1296–305) found that shrubs protect the ground through shading, resulting in a ∼9% shallower active layer thickness (ALT) under shrubs compared to grassy-tundra, which led them to argue that continued Arctic shrub expansion could mitigate future permafrost thaw. We utilize the Community Land Model (CLM4) coupled to the Community Atmosphere Model (CAM4) to evaluate this hypothesis. CLM4 simulates shallower ALT (~ -11 cm) under shrubs, consistent with the field manipulation study. However, in an idealized pan-Arctic +20% shrub area experiment, atmospheric heating, driven mainly by surface albedo changes related to protrusion of shrub stems above the spring snowpack, leads to soil warming and deeper ALT ($\sim +10$ cm). Therefore, if climate feedbacks are considered, shrub expansion may actually increase rather than decrease permafrost vulnerability. When we account for blowing-snow redistribution from grassy-tundra to shrubs, shifts in snowpack distribution in low versus high shrub area simulations counter the climate warming impact, resulting in a grid cell mean ALT that is unchanged. These results reinforce the need to consider vegetation dynamics and blowing-snow processes in the permafrost thaw model projections.

Keywords: climate change, shrub, Arctic, permafrost, feedbacks

1. Introduction

Arctic climate is changing rapidly, inducing environmental change throughout the terrestrial system (Hinzman *et al* 2005). The impacts and feedbacks of these environmental changes remain poorly understood, which detracts from our ability to make reliable projections of Arctic and global climate change (McGuire *et al* 2006). Among the environmental changes that have been observed is an increase in shrub abundance across much of the Arctic tundra (Sturm *et al* 2001b, Goetz *et al* 2005, Tape *et al* 2006), consistent with experimental warming studies which indicate that both the height and coverage of deciduous shrubs increase in response to climatic warming (Walker *et al* 2006). Permafrost, ground that is at or below 0 °C for at least two consecutive years, is also warming and degrading (Camill 2005, Åkerman and Johansson 2008, Thibault and Payette 2009, Romanovsky *et al* 2010). Projecting the amount and rate of future permafrost degradation is important due to the large carbon stocks that are currently frozen in permafrost-affected soils (Tarnocai *et al* 2009) and the possibility that these stocks may be vulnerable to decomposition and release to the atmosphere as carbon dioxide or methane as permafrost thaws (Schuur *et al* 2008). In order for reliable projections of future permafrost degradation to be made, permafrost stability in response to both the direct impacts of warming and other climatic changes (e.g. changes in snowfall and snow season length, Lawrence and Slater 2010) and more indirect impacts related to changes in ecosystem structure, hydrology, and disturbances such as fire, each of which can be positive or negative (Grosse *et al* 2011), need to be understood and represented in models. Vegetation succession, for example, can provide a strong negative feedback that increases permafrost resiliency against climate change (Jorgenson *et al* 2010).

One method to investigate these feedbacks is field manipulation experiments in which an aspect of the ecosystem state is intentionally perturbed and environmental conditions are subsequently monitored over a period of years to study the response (e.g. free-air CO_2 enrichment (FACE) experiments, Hendrey *et al* 1999). Blok *et al* (2010) recently published results from such a study that was designed to isolate the influence of an increase in shrub abundance on permafrost and active layer thickness (ALT). In their experiment, shrubs (*Betula nana*) were removed from a 10 m diameter study plot in northeast Siberia. Thaw depth in these plots was monitored and compared to control plots in which shrub cover dominated. They found that late growing season ALT was ∼9% shallower in the control plot with shrubs than in the experimental plot where the shrubs had been removed, mainly due to the shading of the ground that shrubs provide. Blok *et al* argue that this result implies that shrubs protect permafrost and consequently that an increase in shrub area could partially offset the permafrost degradation induced by Arctic climate change.

However, several studies indicate that a large-scale pan-Arctic expansion of deciduous shrubs is likely to be a positive feedback onto warming. Chapin *et al* (2005) estimate that atmospheric heating due to a complete conversion of Arctic grassy-tundra to shrub-tundra would exceed that due to CO_2 doubling. They conclude that terrestrial amplification of high-latitude warming will likely become more pronounced if shrub area continues to expand. In an idealized climate modeling study in which Arctic shrub area is artificially increased by ∼20%, Bonfils *et al* (2011) found that shrubs warm the Arctic atmosphere through a surface albedo feedback, primarily related to lower surface albedos in spring when shrubs protrude above the snowpack, combined with an evapotranspiration-induced increase in atmospheric moisture content. These land–atmosphere feedbacks are similar in character to those identified in an analogous study of the impact of a northward expansion of temperate deciduous forests (Swann *et al* 2010).

In this study, we utilize a global climate model to evaluate the hypothesis put forth by Blok *et al* (2010) that an increase in shrub abundance could partially offset further warming-induced permafrost degradation against the concept that land–atmosphere feedbacks driven by shrub area increase will amplify Arctic warming. We consider shrub–permafrost interactions for simulations without and with treatments of blowing-snow redistribution from tundra to shrubs, a phenomena that has been observed in Arctic ecosystems (Pomeroy *et al* 2006) and which has consequences for winter soil thermal and biological processes (Sturm *et al* 2005).

2. Description of models and experiments

2.1. Model description

The Community Land Model (CLM4, Lawrence *et al* 2011b) and Community Atmosphere Model (CAM4, Neale *et al* 2011) are the land and atmosphere models used in the Community Climate System Model (CCSM4, Gent *et al* 2011). Biogeophysical processes simulated in CLM4 include solar and longwave radiation interactions with vegetation canopy and soil, momentum and turbulent fluxes from canopy and soil, heat transfer in soil and snow, hydrology of canopy, soil, and snow, and stomatal physiology and photosynthesis. The snow model contains up to five varying thickness layers and represents processes such as accumulation, melt, compaction, water transfer across layers, and snow aging and aerosol deposition which control snow albedo. Surface albedo is prognostic and is a function of vegetation reflectivity and transmissivity (each plant functional type, PFT, has unique specified optical properties), exposed (i.e. proportion of vegetation that is not covered by snow) leaf area and stem area indices (LAI, SAI), ground albedo, the fraction of ground covered by snow, and snow albedo. The ground column is ∼50 m deep and consists of 3.8 m of soil (ten levels) underlain by five layers of bedrock. The thermal and hydrological properties of the soil are determined by a weighted combination of mineral and organic soil content (Lawrence and Slater 2008). Heat conduction through the soil is dependent on the thermal and hydrological properties of each soil layer and is a function of soil liquid and ice water content, soil texture (sand, silt, clay, organic), and soil temperature. A comprehensive technical description of CLM4 is provided in Oleson *et al* (2010).

When forced with observed meteorology, CLM4 reasonably simulates the Northern Hemisphere permafrost distribution, ALT, and deep soil temperatures (Lawrence *et al* 2011a). Deep soil temperatures exhibit a ∼1 °C cold bias in CLM4 due in part to an unrealistically dry active layer. We include several changes to the default CLM4 cold region hydrology parameterization, including the introduction of a stronger ice impedance function, which alleviates the cold bias and generates more realistic active layer hydrological conditions (Swenson and Lawrence 2011). When CLM4 is coupled to CAM4, biases in the climate, especially an excessive snowfall bias that is prevalent across much of the pan-Arctic region, degrade the permafrost simulation resulting in deeper ALT and warmer deep ground temperatures than observed (Lawrence *et al* 2011a). These biases are deemed acceptable for the purpose of this study because we focus on the perturbation, rather than the mean state, of ALT in response to an ecosystem structure forcing.

Table 1. List of experiment names and descriptions.

Experiment name	Experiment description
SB_LOW	CAM4/CLM4 simulation with tundra fraction of pan-Arctic grid cells prescribed at 80% C3 grass/20% boreal shrub PFT distribution, as in figure 1
SB_HIGH	Same as SB_LOW except with 60% C3 grass/40% boreal shrub
SB_LOW_SR	Same as SB_LOW except with grass to shrub snow redistribution
SB_HIGH_SR	Same as SB_LOW_SR except with 60% C3 grass/40% boreal shrub

2.2. Experimental design

In the standard configuration for CLM4, all PFTs share the same soil column, competing for available soil water. Weighted averages of surface energy fluxes across all PFTs are passed to the soil model for use in calculating the vertical soil temperature and moisture profiles. For this study, we need to evaluate soil conditions beneath tundra grasses (Arctic C3 grass PFT) and shrubs (boreal shrub PFT) separately. Therefore, we set up the CLM sub-grid structure so that each PFT exists on its own soil column. This structure has an additional advantage in that we can introduce a simple parameterization for snow redistribution from tundra grass to shrubs (see section below).

The control CAM4/CLM4 experiment is a low shrub area experiment (SB_LOW, see table 1 for experiment descriptions) in which we prescribe a pan-Arctic 80% grass/20% shrub ratio that is meant to be representative of present-day shrub area (figure 1). This ratio only applies to the Arctic C3 grass plus boreal shrub PFT part of the grid cell; the rest of the PFTs within each grid cell maintain the weights specified in the CLM4 surface dataset (PFT fractions are derived from MODIS data). Note that the spatially non-heterogeneous 80%/20% ratio is idealized and is selected based on data presented in Walker *et al* (2005) that erect shrubs make up ~26% of Arctic tundra vegetation. It replaces the unrealistic 37% grass/63% shrub ratio derived from the MODIS vegetation product (Lawrence and Chase 2007), which has difficulty properly distinguishing grasses from shrubs. In the second experiment, we set the grass/shrub ratio at 60%/40% (SB_HIGH), an increase in shrub area that is meant to represent a hypothetical year 2100 shrub area expansion in response to anticipated future climate change. The 20% increase in shrub abundance is arbitrary, but is based on the assumption that the rate of shrub area expansion (~1%/decade over the last 50 yr (Sturm *et al* 2001a, 2001b)) will accelerate along with the projected acceleration of Arctic climate change seen in higher greenhouse gas emission scenarios.

In all experiments, we prescribe monthly LAI and SAI for Arctic C3 grasses and boreal shrubs as shown in figure 1. The seasonality of LAI and SAI corresponds to the grid cell MODIS-derived LAI and SAI annual cycles that are included in the CLM4 surface dataset (Lawrence and Chase 2007). The maximum LAI is adjusted to 0.5 for Arctic C3 grass and 1.5 for boreal shrubs (based on data in Sturm *et al* 2001a). Maximum canopy height of Arctic C3 grass and boreal shrubs is set at 0.1 m and 1.0 m, respectively.

We also conduct a parallel set of experiments that permits us to evaluate how grass to shrub snow redistribution affects the results. In these experiments we very simply impose a snow redistribution by adjusting snowfall rates onto the grass and shrub columns so that a larger fraction of snow falls onto the shrub column according to the following equations:

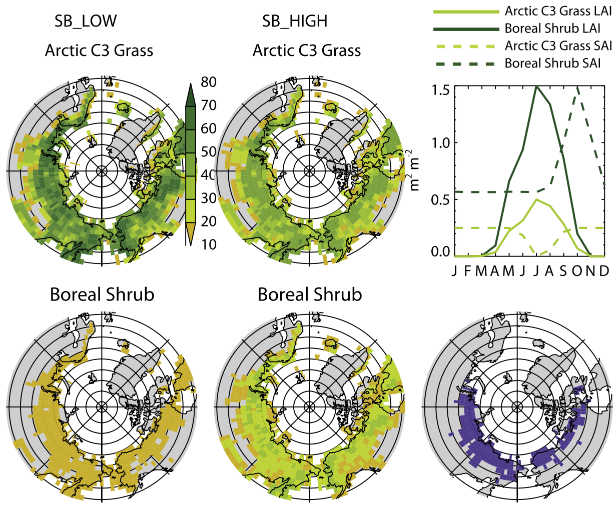

Figure 1. Maps showing Arctic C3 grass and boreal shrub PFT fractions for the SB_LOW and SB_HIGH experiments. The upper right panel shows the prescribed LAI and SAI values for Arctic C3 grass and boreal shrubs that are used for all grid cells in all experiments. The bottom right panel shows the spatial distribution of the 236 grid cells for which the depth to the permafrost table is <2 m for the SB_LOW experiment.

$$S_{\mathrm{shrub}} = S + \alpha S \frac{f_{\mathrm{grass}}}{f_{\mathrm{shrub}}} \qquad S_{\mathrm{grass}} = (1-\alpha)S, \qquad (1)$$

where S (kg m^{-2} s^{-1}) is the grid cell snowfall rate provided by the atmosphere model, S_{shrub} and S_{grass} are the revised snowfall rates on the shrub and grass columns, f_{grass} and f_{shrub} are the grid cell PFT fractions for grasses and shrubs, and $\alpha = 0.17$ is a parameter that determines how much snow is redistributed, chosen such that for the SB_LOW experiment, the shrub column snow depth is approximately twice as deep as that for the grass column (Pomeroy *et al* (2006) report 147% deeper snow in shrubs at a site near Whitehorse in Canada; Sturm *et al* (2005) report 17%–48% deeper snow in shrubs at five sites in Alaska). For higher shrub fractions (SB_HIGH), the amount of redistributed snow decreases, reflecting the smaller grass snow redistribution source area (as in Essery and Pomeroy 2004), and the difference in shrub versus grass snow depth is reduced to $\sim +50\%$. This snow redistribution parameterization is highly simplified and does not take into account, for example, changes in blowing-snow sublimation as shrub area increases, which may affect grid cell mean snow depths (Liston *et al* 2002).

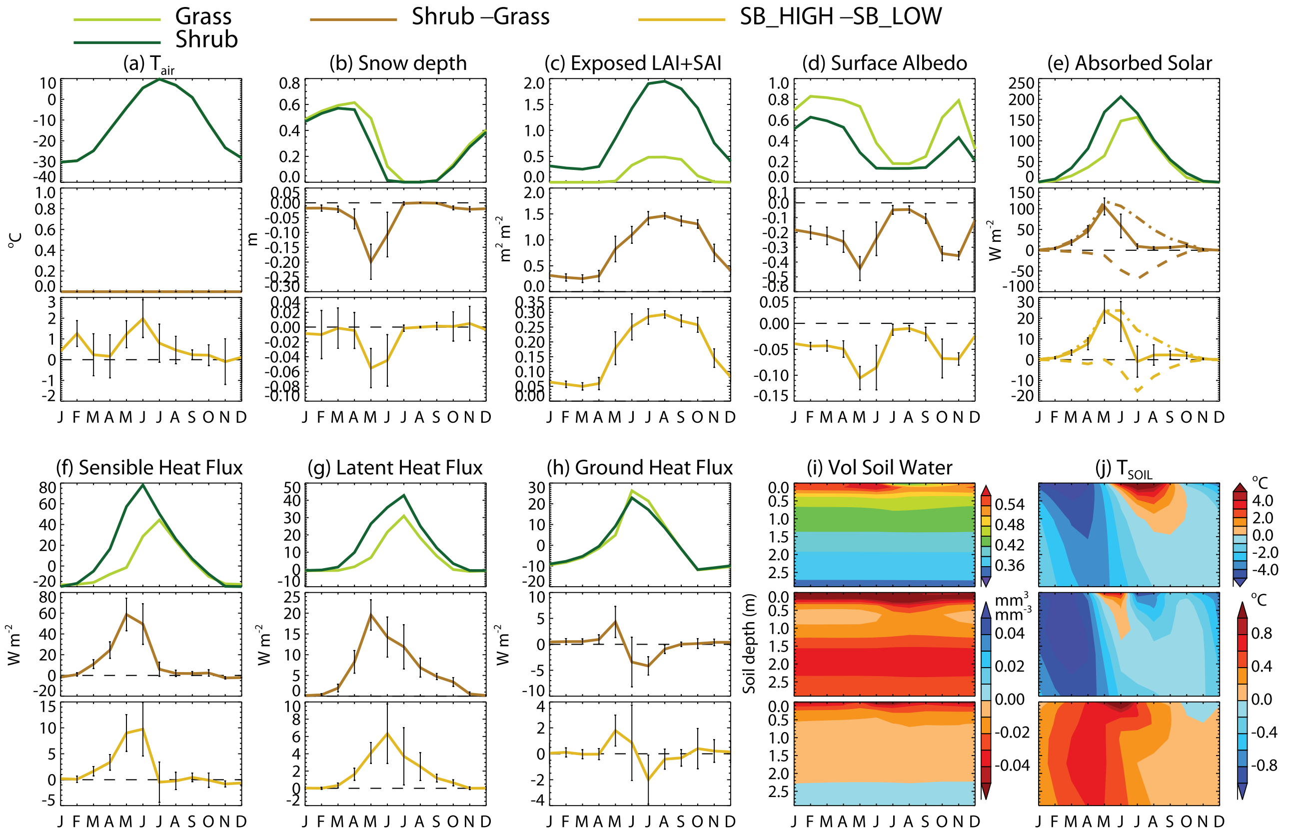

Figure 2. Annual cycle time series of selected variables. For each set of three plots: the upper panel shows data for the Arctic C3 grass and boreal shrub PFT/columns for the SB_LOW experiment, the middle panel shows the difference between shrubs and grasses for the SB_LOW experiment, and the bottom panel shows the average response of the weighted combination of grass and shrub columns for SB_HIGH − SB_LOW. On the absorbed solar difference plots (e), solar radiation absorbed by the ground is shown by a dashed line and solar radiation absorbed by vegetation is a dash-dotted line. For volumetric soil water (i) and T_{SOIL} (j), the upper panel is for the grass columns only, the middle panel is grass minus shrub, and the bottom panel is SB_HIGH − SB_LOW. Data shown are monthly 25 yr climatological averages across the 236 'permafrost' grid cells denoted in figure 1. The range bars indicate the ±1 standard deviation about the mean difference across the 236 points.

All integrations are forced with present-day climatological sea surface temperatures and sea ice distribution. Greenhouse gas concentrations and other forcings such as aerosol deposition onto snow are set at year 2000 values. The land state is initialized from respective offline CLM4 simulations forced with observed meteorology. Each experiment is run for 30 yr. We base our analyses on 25 yr climatological averages (the first five years are thrown out for model spin up).

3. Results

3.1. Simulated differences in surface energy fluxes and soil thermal conditions for grasses versus shrubs

The annual cycles for several illustrative variables are shown for grasses and shrubs separately (upper panel of each set of three figures) and the difference between them (shrubs minus grasses, middle panel) in figure 2 for the SB_LOW experiment. Each curve represents the average across all the permafrost grid cells delineated in figure 1 (bottom right). Since grasses and shrubs share the same land grid cell, they experience the same climate forcing (air temperature, precipitation, incoming solar radiation, downwelling longwave radiation, wind and specific humidity) from the atmosphere model and therefore differences in surface variables between grasses and shrubs are a consequence of the manner in which the two vegetation types partition and utilize the incoming energy. In winter and spring, when the stems of the shrubs can protrude above the snow whereas the grasses typically are completely buried, surface albedo is as much as 0.44 lower for shrubs (figure 2(d)) which is similar to that observed (Pomeroy *et al* 2006). In spring, the lower shrub albedo generates differences of ∼100 W m^{-2} in absorbed solar radiation (figure 2(e)). This leads to earlier and more rapid melting of the shrub column snowpack (figure 2(b)), as observed (Pomeroy *et al* 2006), and to increased heat flux into the ground (figure 2(h)) and warmer soil beneath shrubs during spring (figure 2(j)).

In summer, surface albedo is slightly lower for shrubs due to darker leaves (−0.04 which is slightly larger than the −0.02 difference reported in Eugster *et al* (2000) and Chapin *et al* (2005)). The ground shading effect is captured by the model with ∼70 W m^{-2} less solar radiation absorbed by the ground under shrubs compared to grasses in July (dashed line, figure 2(e)). This shading contributes to an ∼4 W m^{-2} lower summer ground heat flux into the soil under shrubs (figure 2(h)), also consistent with observations (Eugster *et al*

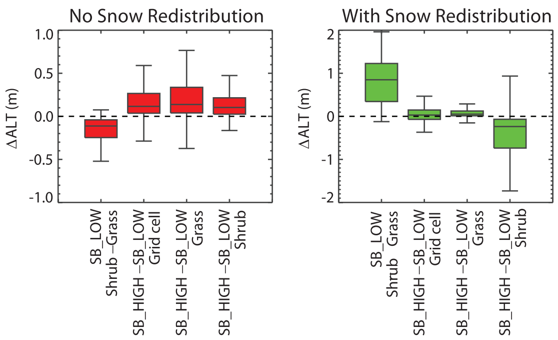

Figure 3. Difference in annual maximum ALT for shrubs minus grasses for SB_LOW and the weighted combination (grid cell) of shrubs and grasses, grasses alone, and shrubs alone for SB_HIGH minus SB_LOW. Results are shown for simulations without snow redistribution on the left and with snow redistribution on the right. Boxes indicate the upper to lower quartile range of ALT response across the 236 permafrost points. The median response is the horizontal bar in the boxes. The range bars indicate the full span of values seen across the 236 grid cells.

2000, Blok *et al* 2010), which limits summer soil warming and reverses the spring warm anomaly (figure 2(j)). The cooler soils translate into shallower active layers with the annual maximum ALT about 2–25 cm shallower under shrubs (figure 3), which is comparable to the ~10 cm shallower ALT reported in Blok *et al* (2010). Note that there is variability about the median ALT response; for a few grid cells the environmental conditions (climate, snow, soil hydrology) result in deeper ALT under shrubs.

Latent heat flux (evapotranspiration) is higher for the more water-consuming shrubs (figure 2(g)), again consistent with observations (Chapin *et al* 2000, Eugster *et al* 2000). Higher shrub transpiration rates dry the active layer/root zone soils (-0.01 to -0.04 mm^3 mm^{-3}, figure 2(i)) which may contribute to colder winter soil temperatures (figure 2(h)) under shrubs as ground loses more heat in the fall and winter due to lower heat capacity and smaller latent heat sink of dry soil.

3.2. Impact of shrub area expansion on Arctic climate and permafrost

Differences between SB_HIGH and SB_LOW, again averaged across all the 'permafrost grid cells' but in this case for weighted combinations of data for grass and shrub columns in each of the permafrost grid cells, are shown in the bottom panels of each set of three figures in figure 2. The grid cell mean response to a 20% increase in shrubs reflects the combined impact of a reweighting of the grass and shrub fractions on each grid cell and the climate change response that is induced by these changing fractions. For most variables, the grid cell average response to a 20% increase in Arctic shrub can primarily be explained as the weighted difference for shrubs relative to grasses. For example, the average May difference in surface albedo for SB_HIGH minus SB_LOW is -0.11, which is close to that which could be estimated based on the changed PFT weights alone ($[\alpha_{gl} f_{gh} + \alpha_{sl} f_{sh}] - [\alpha_{gl} f_{gl} + \alpha_{sl} f_{sl}] = -0.09$ for SB_LOW grass albedo $\alpha_{gl} = 0.73$, shrub albedo $\alpha_{sl} = 0.29$, and $f_{gh} = 0.6$, $f_{sh} = 0.4$, $f_{gl} = 0.8$, $f_{sl} = 0.2$ are the grass/shrub PFT weights in SB_HIGH and SB_LOW). The surface air temperature (T_{air}) adjusts to the surface energy balance perturbations and is warmer in SB_HIGH throughout the year (figure 2(a)). The strongest warming occurs in late spring (~ + 1.5 to +2 °C ± 1 °C across all grid cells in May and June), coincident with the strongest reduction in surface albedo in SB_HIGH (figure 2(d)). The warmer spring and early summer climate leads to higher ground heat flux (figure 2(h)), warming the soil with May and June soil temperatures warmer by about +0.6 to +0.8 °C throughout the upper soil column (figure 2(i)). Later in the summer, the shrub shading effect reduces grid cell ground heat flux in SB_HIGH relative to SB_LOW due to the higher fraction of shrubs (figure 2(h)). This mitigates but does not completely offset the spring/early summer soil warming, yielding late summer near-surface soil temperatures that remain about +0.2 to +0.4 °C warmer in SB_HIGH (figure 2(i)). The warmer late summer soil temperatures correspond to ~10 cm deeper grid cell ALT, though there are grid cells where the local climate and shrub/grass distribution changes lead to ALT changes as high as +65 cm and as low as −30 cm (figure 3). On average, ALT deepens slightly more on the grass column than on the shrub column, reflecting the protection due to shading that shrubs provide.

3.3. Snow redistribution

The impact of shrubs on surface energy partitioning is qualitatively similar in the snow redistribution experiment (SB_LOW_SR, figure 4) with lower surface albedo (figure 4(d)), less solar radiation absorbed by the ground (dashed line, figure 4(e)) and higher latent heat flux seen for shrubs (figure 4(g)). Snow depth, however, is by definition about twice as deep on the shrub column (figure 4(b)). The deeper shrub snowpack yields a weaker maximum surface albedo signal (0.44 in SB_LOW, 0.22 in SB_LOW_SR) since a larger fraction of the shrubs is buried by the deeper snow (figure 4(d)). Soils are warmer under shrubs (figure 4(j)), especially in winter and spring (~+3 to +5 °C) due to stronger snow insulation, which is lower but broadly consistent with observed wintertime T_{soil} differences of > + 5 °C reported for a study in the Kuparak basin in Arctic Alaska (Sturm *et al* 2005). Though shrub ground shading is essentially the same in SB_LOW_SR and SB_LOW, winter soil warming dominates over summer soil cooling and shrub soil temperatures are warmer throughout the year, except very near the surface in summer. ALT is deeper on average by 85 cm under shrubs (figure 3). Shrub soils tend to be drier near the surface (figure 4(i)) despite increased infiltration into the soil (not shown). The shrub surface soils appear to be drier due to the higher water holding capacity associated with the deeper active layer and to greater water transport down and through the warmer and less icy soil column.

Due to the weaker surface albedo response (figure 4(d) compared to 2(d)), the climate warming due to an increase in shrub area is weaker for SB_HIGH_SR–SB_LOW_SR (annual mean = +0.46 °C) compared to SB_HIGH − SB_LOW

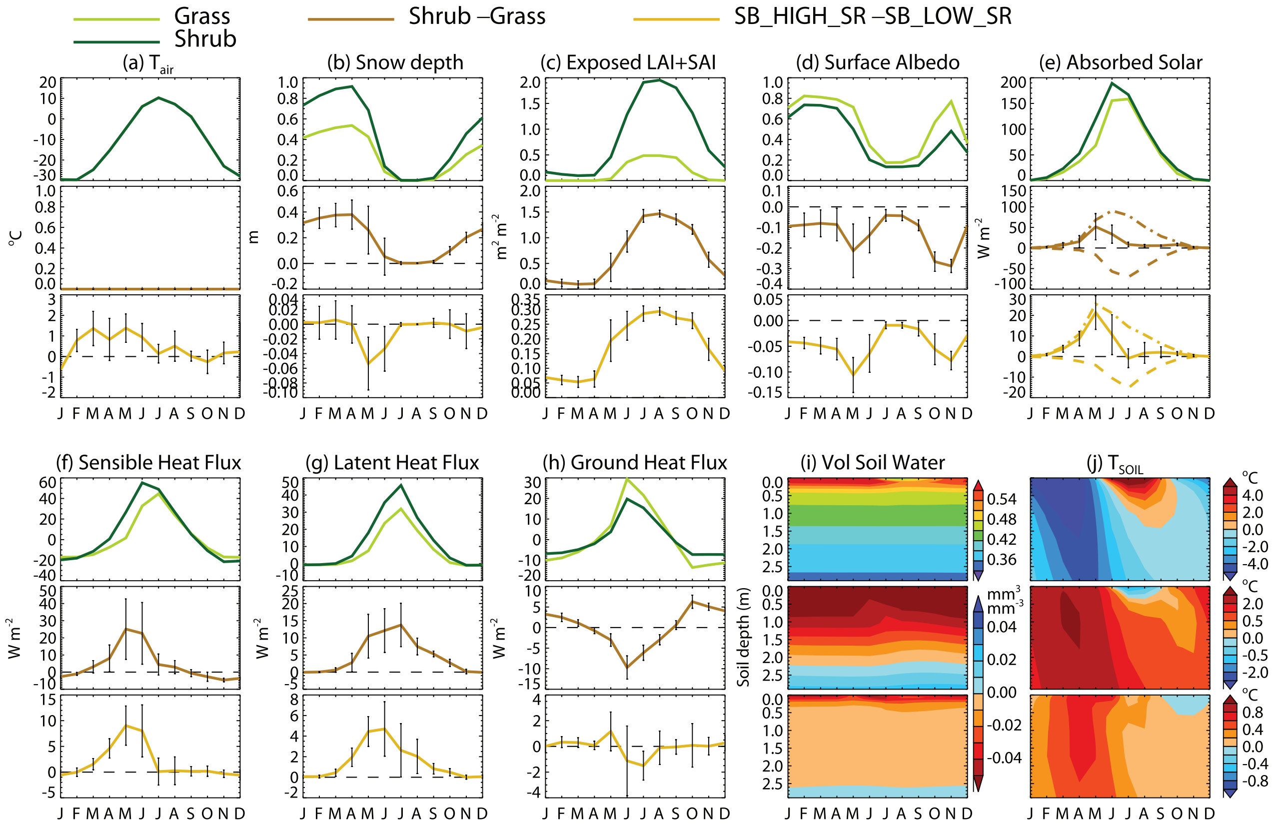

Figure 4. Same as figure 2 except for the snow redistribution experiments (SB_LOW_SR and SB_HIGH_SR).

(+0.59 °C) (figure 4(a) compared to 2(a)). This leads to a weaker and almost negligible ALT response to increasing shrub area (figure 3), under the assumed relatively strong snow redistribution rate used in this study, though T_{soil} is still warmer throughout most of the year (figure 4(i)). Under shrubs, ALT is actually shallower in an increased shrub scenario because a reduction in the grass blowing-snow source area leads to a shallower shrub snowpack in SB_HIGH_SR compared to SB_LOW_SR, thereby providing less winter snow insulation and cooler soil temperatures, despite the warmer climate.

4. Summary and discussion

Deciduous shrub abundance is increasing across the Arctic in response to climatic warming. Blok *et al* (2010) found that ALT under shrubs is shallower than under grassy-tundra, leading them to argue that continued Arctic shrub expansion could to a certain extent mitigate future permafrost thaw. We replicate their field manipulation study by comparing surface energy flux partitioning and soil thermal conditions on shrub and grass columns in CLM, a global land model. We find that the model can capture observed differences, with ground shading by shrubs leading to an ALT that is about 2–25 cm shallower under shrubs than grasses across the Arctic tundra domain. In idealized +20% shrub area experiments in which pan-Arctic tundra shrub extent is increased by 20%, the atmospheric heating, induced by surface albedo changes related to protrusion of shrubs above the spring snowpack and evapotranspiration-induced increase in atmospheric moisture, leads to soil warming and deeper grid cell mean ALT across most of the Arctic. Our conclusion is that although shrubs can protect permafrost through their local cooling influence on soil temperature (in the absence of snow redistribution, which was not observed in the Blok *et al* 2010 study), large-scale climate warming induced by an increase in shrubs can entirely offset this soil cooling. An increase in shrubs, therefore, may actually increase rather than decrease permafrost vulnerability.

In simulations where snow is redistributed from grasses to shrubs, as is often observed, ALT is deeper rather than shallower under shrubs. The impact of a 20% increase in shrubs on grid cell mean ALT is minimal as the weaker albedo and ET induced warming caused by more shrubs is mostly offset by the impact of changes in snow distribution on winter soil insulation and the local summer ground shading effect. Though the ALT is not as strongly impacted in the snow redistribution experiments, grid cell mean soils are still on average warmer throughout the year in a +20% shrub area scenario.

There are several simplifications in this study that should be accounted for when interpreting these results. We have shown, for example, that incorporating a simple snow redistribution parameterization alters the results, with very little change in grid cell ALT seen for a +20% shrub increase scenario when snow redistribution it included. Additionally, the shrub increase that we prescribe here is homogeneous, but in reality the ecosystem response to climate change will vary across the Arctic. Tape *et al* (2006) found that shrub expansion is distributed unevenly across different landforms such as valleys, terraces, and floodplains. The climate response to a more heterogeneous shrub area change would naturally be more complex than that presented here, likely resulting in an even broader range of ALT responses. Another factor that we do not consider is that some species of shrubs have thin and supple stems that bend and are often buried completely by snow during winter, springing up abruptly at some time during snowmelt (Pomeroy *et al* 2006). Incorporating this effect would likely reduce the surface albedo and climate impact of increasing shrubs. On the other hand, an increase in average shrub height could amplify the climate response (Bonfils *et al* 2011). Incorporating sea ice feedbacks (sea ice is prescribed in our experiments) could also amplify the climate response (Bonfils *et al* 2011) resulting in a positive feedback that could induce further shrub growth (Bhatt *et al* 2010) and permafrost thaw (Lawrence *et al* 2008).

The results presented here reinforce the need for vegetation dynamics, as noted in Blok *et al* (2010), and blowing-snow processes to be incorporated and considered in future model projections of Arctic climate change and permafrost thaw. Additionally, our study implies that field manipulation experiments can provide an innovative test of model processes, but also that results from field manipulation experiments cannot always be extrapolated to broader scales due to the potential influence of large-scale feedbacks that cannot readily be measured at the smaller scales of a field experiment.

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