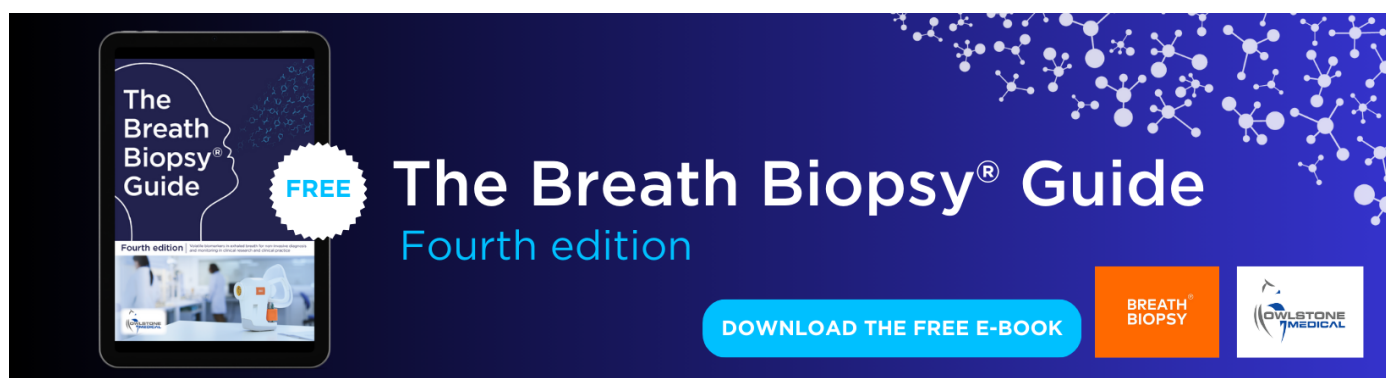**LETTER**

On the influence of shrub height and expansion on northern high latitude climate

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On the influence of shrub height and expansion on northern high latitude climate

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Abstract
There is a growing body of empirical evidence documenting the expansion of shrub vegetation in the circumpolar Arctic in response to climate change. Here, we conduct a series of idealized experiments with the Community Climate System Model to analyze the potential impact on boreal climate of a large-scale tundra-to-shrub conversion. The model responds to an increase in shrub abundance with substantial atmospheric heating arising from two seasonal land–atmosphere feedbacks: a decrease in surface albedo and an evapotranspiration-induced increase in atmospheric moisture content. We demonstrate that the strength and timing of these feedbacks are sensitive to shrub height and the time at which branches and leaves protrude above the snow. Taller and aerodynamically rougher shrubs lower the albedo earlier in the spring and transpire more efficiently than shorter shrubs. These mechanisms increase, in turn, the strength of the indirect sea-ice albedo and ocean evaporation feedbacks contributing to additional regional warming. Finally, we find that an invasion of tall shrubs tends to systematically warm the soil, deepen the active layer, and destabilize the permafrost (with increased formation of taliks under a future scenario) more substantially than an invasion of short shrubs.

Keywords: greening, climate change, shrub, land–atmosphere interactions, Arctic

1. Introduction

In the northern high latitudes (NHL), rapid environmental changes are under way in response to climate change, and are anticipated to continue in the future (Overpeck *et al* 1997, Hinzman *et al* 2005). These changes include a rapid warming rate (Serreze *et al* 2000) attributed to human activities (Gillett *et al* 2008), a sharp decline in sea-ice and terrestrial snow (Parkinson *et al* 1999, Min *et al* 2008), and a progressive thawing of permafrost (Jorgenson *et al* 2006). Initially triggered by the radiative effects of increasing greenhouse gas (GHG) emissions, the warming is amplified by several regional positive feedback mechanisms (e.g., Chapin *et al* 2005, 2008), such as the darkening of the surface caused by the earlier seasonal melting of snow exposing soil, plants, and sea (e.g. Foley 2005, Dye and Tucker 2003).

Changes expected under a warming climate also include the expansion of trees and shrubs into regions currently occupied by tundra (e.g., Chapin *et al* 2005). In anticipation of such changes, a number of global climate model studies have evaluated the feedbacks induced by a tundra-to-forest conversion. In general, these studies indicate that an expansion of the boreal evergreen forest will amplify regional warming through an albedo feedback (Bonan *et al* 1992, Foley *et al* 1994, Levis *et al* 1999), while an expanding temperate deciduous forest (another possible outcome) will additionally

cause a positive transpiration-induced greenhouse feedback (Swann *et al* 2010). However, the invasion of tundra by a tall forest is unlikely to occur in the current century (Chapin *et al* 2005) and is mainly predicted by equilibrium vegetation models (e.g., Kaplan and New 2006) which typically do not account for processes associated with the migration and the succession of plants (Epstein *et al* 2007).

In contrast, no global climate experiments have been conducted thus far to estimate the role of shrub expansion on NHL climate, despite a growing body of empirical evidence (photographs, transect studies, satellite-derived indices, field experiments, and local testimonies) documenting the increase in shrub abundance and size in various locations of the circumpolar arctic (e.g., Tape *et al* 2006, ACIA 2005). For instance, Sturm *et al* (2001b) showed that shrub area has increased by 1.2% decade^{-1} since 1950 in Northern Alaska and satellite data are now used to document the presence of short and tall shrubs across this region (Beck *et al* 2011). Forbes *et al* (2010), using remote sensing evidence, detected an enhanced greening signal likely associated with shrub expansion in the tundra since the early 1980s. This corroborates earlier studies that contrasted consistent greening trends in pan-Arctic tundra areas (with a longer growing season length; e.g. Goetz *et al* 2005, Bunn and Goetz 2006) with the decline in photosynthetic activity found in forest areas (Angert *et al* 2005). Small shrubs are already present in most tundra areas (Chapin *et al* 2005), and therefore can grow in stature and expand further under increasingly favorable environmental conditions, as suggested by field measurements (Sturm *et al* 2005b, Tape *et al* 2006, Forbes *et al* 2010, Hallinger *et al* 2010), experimental warming treatments (Walker *et al* 2006), and warm periods of the past climate (Bret-Harte *et al* 2002). Such changes in ecosystem structure may affect the biogeochemical and biophysical processes regulating the exchanges of energy, water and carbon between the biosphere and atmosphere (Loranty *et al* 2011). Shrubs can also promote their own development by favoring snow accumulation and thereby winter soil warming, which stimulates soil microbial activity and mineralization of nitrogen that could support further shrub growth (Sturm *et al* 2005b). Finally, a plant dynamics model (ArcVeg; Epstein *et al* 2007) estimated that a 2 °C warming can lead to a rapid increase in tall shrubs in regions occupied by low shrub, or increase their abundance where they are already dominant.

Here, we investigate the possible climate feedbacks arising from the biophysical aspects of a tundra-to-shrub conversion. Our analysis is guided by two questions: (1) What are the biophysically induced effects of shrub expansion on the NHL climate? (2) Is this climate response sensitive to the stature of shrubs? As in a forest expansion scenario (Swann *et al* 2010), we expect feedbacks driven primarily by altered albedo and evapotranspiration (ET). However, an increase in shrub height can also affect the timing of those feedbacks, as tall shrubs protruding above the snow and short shrubs buried under the snow affect the surface energy budget during the snow-covered period differently (Sturm *et al* 2001a, 2005a, Loranty *et al* 2011). Through shading of the surface, shrubs can keep soil temperatures cooler than in surrounding tundra,

thereby protecting permafrost (Yi *et al* 2007, Blok *et al* 2010), though a strong climate warming signal associated with the aforementioned land biophysical feedbacks could overwhelm the ground shading cooling effect of shrubs (Lawrence *et al* 2011b).

2. Methods

To investigate the role of a shrub expansion on NHL climate, we performed nine 30 yr steady-state simulations with the Community Climate System Model (CCSM4; Gent *et al* 2011), which includes the Community Land Model (CLM4; Lawrence *et al* 2011c) and the Community Atmosphere Model (CAM4; Neale *et al* 2011). Currently, only one type of shrub is represented in the arctic and sub-arctic regions in CLM4 (the half-meter tall broadleaf deciduous shrub), while some other vegetation models (e.g. Kaplan and New 2006) also represent prostate dwarf shrub, erect dwarf shrub, and low and high shrubs. The simulations were performed using three model configurations (see below) and three idealized representations of the NHL vegetation north of 60°N: (1) the standard present-day vegetation distribution (denoted as CTL); (2) greener NHL where half-meter tall broadleaf deciduous shrubs replace bare ground (denoted as S for short shrubs; figure 1); and (3) greener NHL where 2 m tall shrubs replace bare ground and present-day shrubs (denoted as T for tall shrubs)[5]. In the latter two scenarios, the total shrub fraction was increased from 32 to 51% of the area north of 60°N (figure 1), while the other land cover types were left unchanged (32% for other vegetation types; 13% for glaciers; 3% for wetland; and 1% for lakes). The prescribed leaf and stem area indices (LAI and SAI) were the same for the T and S scenarios.

Following the design strategy of Swann *et al* (2010), we simulated the climate response to short and tall shrub invasions under present-day greenhouse gas conditions in both a fixed ocean (i.e., prescribed climatological monthly sea surface temperatures and sea-ice extents—experiments; FO), and an interactive ocean (sea-ice and slab ocean models—experiments; IO)[6], with each ocean configuration having its own control experiment (CTL^{FO} and CTL^{IO}). It is important to note that unless otherwise specified, we will discuss all the results in terms of changes relative to these control runs (table 1). As a first approximation, the direct atmospheric climate response to the shrub cover change can be estimated from the anomalies (S-CTL)^{FO} and (T-CTL)^{FO},

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[5] These shrub heights, mainly chosen for studying the sensitivity of the boreal climate change to shrub stature, compare closely with field measurements (e.g. see table 1 of Sturm *et al* 2005a and De Groot *et al* 1997 for more detailed descriptions on shrub characteristics).

[6] These configurations are respectively referred to as 'E_2000' and 'F_2000' cases in the CCSM nomenclature. CCSM4 was run with the finite volume dynamical core at 1.9° × 2.5° resolution using year 2000 initial conditions for all components and prescribed aerosol and GHG concentrations. We integrated each simulation for 30 yr but discarded the first 17 yr that were required to reach climate equilibrium. The prescribed land cover changes are designed to study the sensitivity of the boreal climate to a large-scale shrub expansion and are not meant to be realistic representations of the future spatial distribution and/or stature of shrubs in response to global warming.
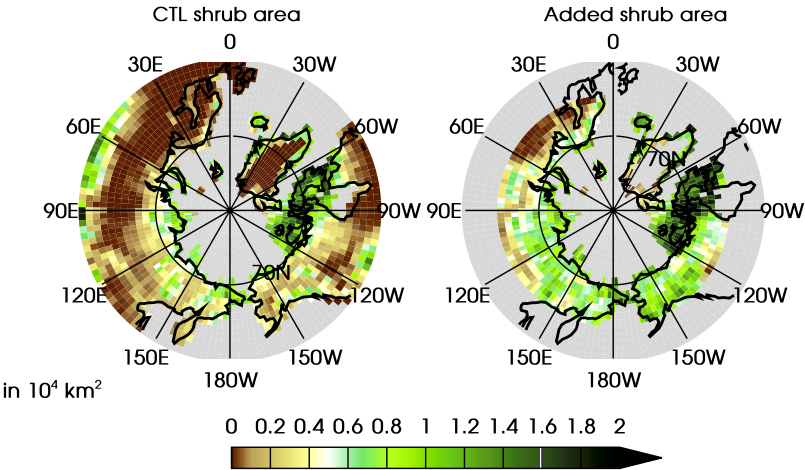
Figure 1. (a) Default deciduous shrub distribution; (b) bare ground area north of 60°N converted to deciduous shrubs (in 10^4 km^2).

Table 1. Experimental design.

Forcings	Short shrubs replace bare ground (S)	Tall shrubs replace bare ground (T)	Objective
$1 \times CO_2$ fixed ocean (FO)	(S-CTL)^{FO}	(T-CTL)^{FO}	Effect of adding shrubs
$1 \times CO_2$ interactive ocean (IO)	(S-CTL)^{IO}	(T-CTL)^{IO}	Added effect from indirect ocean/sea-ice feedbacks
$2 \times CO_2$ interactive ocean (IO)	(S2 $\times$ CO$_2$-CTL)^{IO}	(T2 $\times$ CO$_2$-CTL)^{IO}	Added effect from $2 \times CO_2$

while the climate response to both shrub cover change and indirect ocean and sea-ice feedbacks can be estimated from the anomalies (S-CTL)^{IO} and (T-CTL)^{IO} (Swann *et al* 2010). We also included a pair of $2 \times CO_2$ simulations to estimate the climate response to simultaneous shrub invasion, interactive ocean, and radiative doubling CO$_2$ ((S$_{2 \times CO_2}$-CTL)^{IO} and (T$_{2 \times CO_2}$-CTL)^{IO}) that can be compared to the changes arising from a $2 \times CO_2$ control run (CTL$_{2 \times CO_2}$-CTL)^{IO} performed in the absence of shrub cover change. We analyzed the atmospheric climate and land feedbacks associated with these changes, with an emphasis on local and regional surface and sub-surface energy and moisture fluxes. We employed a two-tailed Student's *t*-test with an estimated total of 13 degrees of freedom for both 13 yr periods (see footnote 6) to test the statistical significance of the mean difference between two experiments at the 99% confidence level (*p* value < 0.01, critical *t* value = 3.012).

3. Results

3.1. Exposed vegetation

Because the exchanges of moisture and energy between the vegetation and the atmosphere are regulated by plant physiology and morphology (Farquhar and Sharkey 1982), it is important to assess the timing and amplitude of exposed vegetation area. In all of our simulations, the snow height averaged over land north of 60°N reaches an annual maximum of about 0.75 m (figure 2). This depth implies that, on average,
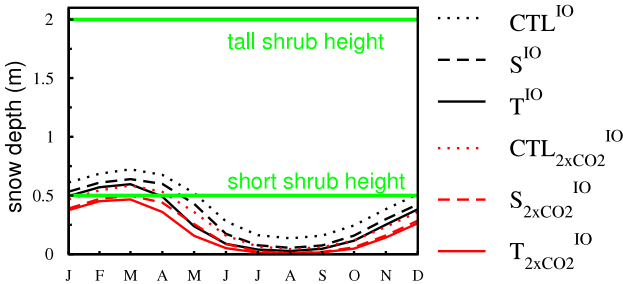

Figure 2. Spatially averaged snow depth over land, north of 60°N.

short shrubs are buried by snow in winter, but protrude above the residual snow layer from spring to fall. The length of time during which the shrubs protrude above the snow varies across our simulations. In contrast, the 2 m tall shrubs remain, on average, above the snow all year long in all our scenarios (for pictures of typical shrub and snow interactions, see figure 3 of Sturm *et al* 2005a). Note that snowfall and snow depths tend to be biased high across much of the northern high latitudes in CCSM4 (Lawrence *et al* 2011a). If these biases were not present the short shrubs would protrude above the snow more frequently than we predict at the end of winter (figure 3 of Sturm *et al* 2005a).

The fraction of vegetation buried by snow (a function of snow depth and canopy height; Lawrence *et al* 2011c, Wang and Zeng 2009) affects exposed leaf and stem area indices in our model (ELAI, ESAI; figures 3(a) and (b)). The amount of exposed leaves and branches is highest in the tall
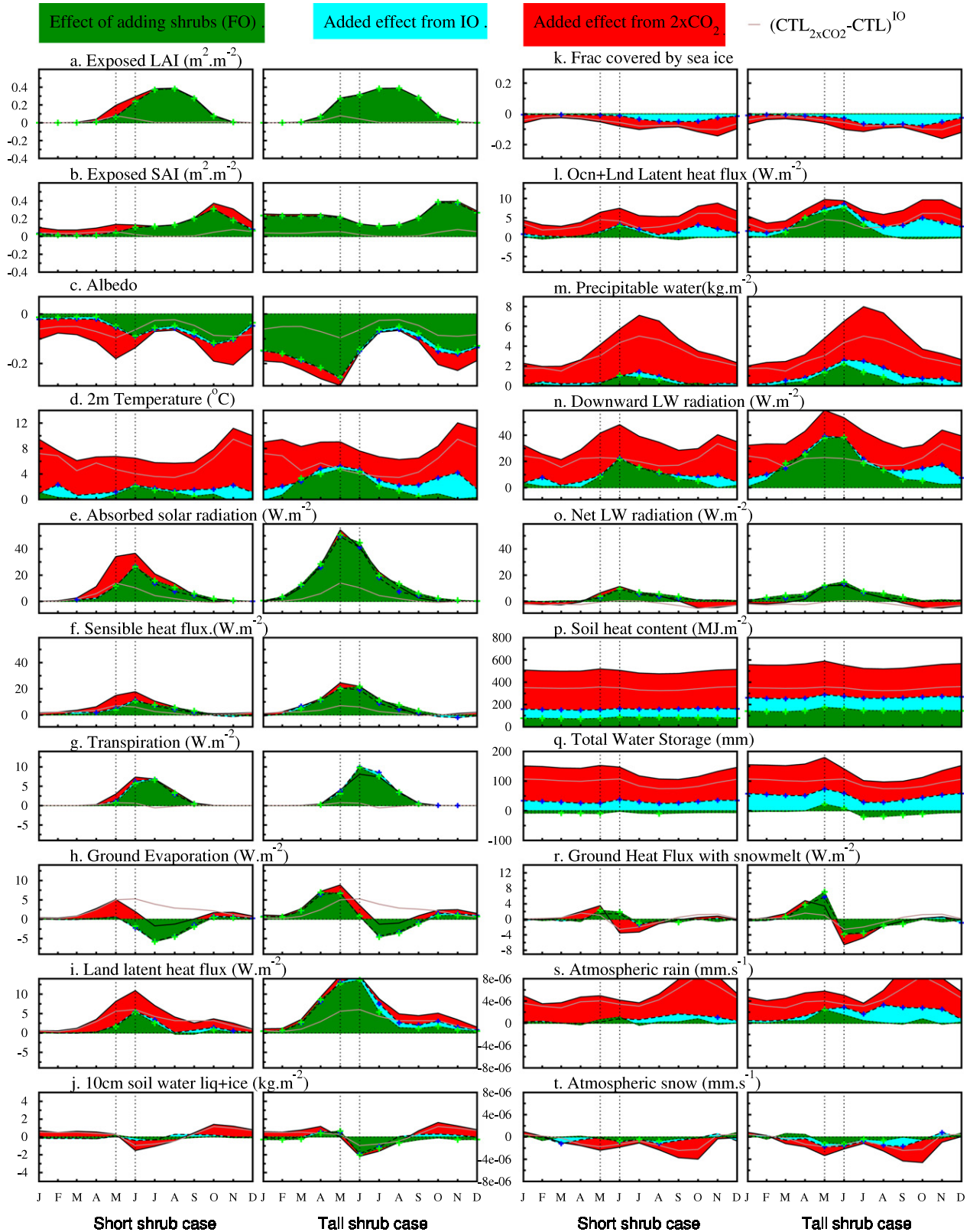
Figure 3. Seasonal evolution of different climate anomalies averaged over land (unless otherwise specified) north of 60°N in response to short (S; left column for each variable) or tall shrub invasion (T; right column for each variable). The green area represents the effect of shrub invasion using a fixed ocean $(S-CTL)^{FO}$ and $(T-CTL)^{FO}$. The cyan areas represent the additional effect (beyond the shrub invasion) induced by the interactive ocean $(S-CTL)^{IO}$ and $(T-CTL)^{IO}$, and red areas represent the effect induced by doubling CO_2 $(S_{2\times CO_2}-CTL)^{IO}$ and $(T_{2\times CO_2}-CTL)^{IO}$. All areas, computed from CTL are overlapped, such as the cyan and red areas appearing as an 'added' effect. The brown line represents the effect arising from doubling CO_2 only $(CTL_{2\times CO_2}-CTL)^{IO}$. Green and blue crosses indicate the statistically significant anomalies at the 99% confidence level. The May–June period is delineated by vertical dotted lines in all panels. The ground heat flux with snowmelt (panel (r)) also includes the shortwave radiation transmitted by the top snow layer.

shrub experiments (T-CTL)$^{FO/IO}$, with no additional changes occurring when CO_2 is doubled. In those runs, leaves are exposed from April to November and branches are visible all year. In contrast, the leaves of short shrubs (S-CTL)$^{FO/IO}$ only begin to be exposed in May, while a comparatively smaller number of branches protrude from May through December. These changes in ELAI and ESAI substantially exceed those induced by doubling CO_2 alone (CTL$_{2 \times CO_2}$-CTL)^{IO}, but the effects are approximately additive when the two forcings are combined (S$_{2 \times CO_2}$-CTL)^{IO}.

3.2. Tall shrub invasion (current climate; fixed ocean)

In the case of tall shrub expansion (and relative to the control run) under the current climate and with a fixed ocean (T-CTL)^{FO}, the annually averaged land temperature poleward of 60N increases by 1.84 °C, with a peak at 4.75 °C in May (figure 3(d), green area). In winter and early spring, only the shrub branches mask the snow (figure 3(c)) and reduce the albedo. The decline in albedo amplifies further as snow melts (exposing more branches), and plants leaf-out[7], and exhibit two troughs in May and November associated with plant phenology (leaf-out and leaf senescence) and the seasonal evolution of snow depth and fractional cover. The decrease in albedo is however the weakest in mid-summer and is a simple function of the difference between the darker shrubs and the brighter tundra. This change in the seasonal evolution of albedo affects the energy balance and temperature anomalies accordingly when sunlight returns after the polar night, with more absorbed solar radiation (ASR) at the surface from February to September (and with a peak in May coinciding with maximum albedo decline between the two simulations; figures 3(e) and (f)). The increase in ASR is then available for increasing the surface sensible heat flux (albedo feedback), evaporation, and transpiration (ET feedback).

Regarding the ET feedback, before leaf-out, the rise in ASR induced by the exposed branches mainly increases ground evaporation (figure 3(h)). As leaves emerge, ground evaporation is progressively replaced by the transpiration process (figure 3(g)), since plants can more readily access soil water and meet atmospheric moisture demand through transpiration. The top soil layer becomes drier (despite more plentiful precipitation owing to local recycling, but accentuated by transpiration and the deeper active layers that increase drainage; figure 3(j)), and ground evaporation decreases. The combined soil evaporation and transpiration changes produce a large increase in latent heat flux in spring and early summer (figure 3(i)), which amplifies the atmospheric water vapor content, and thus the greenhouse

warming of the lower atmosphere during those months (figures 3(m) and (n)). The ratio of rain to snow precipitations increases, as does the ground liquid/ice water fraction near the surface (not shown).

3.3. Short shrub invasion

In this section, we discuss the effects of a short shrub invasion relative to the results presented in section 3.2 for the tall shrub case. In the short shrubs runs (S-CTL)^{FO}, both albedo and ET feedbacks are weaker and delayed until the stems protrude above the snow and leaves appear. The resulting temperature change is much smaller (+0.66 °C) than in the tall shrub case. From January to April, the snow masking mechanism is ineffective because the snow buries both bare and shrub-covered ground. Later, the decline in albedo is weaker and peaks later in the spring when snow has melted down to depths less than the shrub height. The resulting increase in ASR is smaller and occurs later, peaking in June and substantially limiting the increase in sensible heat and the albedo-induced warming response. The ET feedback is also weaker than the tall shrub case throughout the year. Before leaf-out, the small ASR change stimulates less surface evaporation than in the tall shrub case. After leaf-out, the increase in transpiration is limited by the number of exposed leaves, and is primarily offset by a large decline in soil evaporation due to higher shading of the surface. This decline is larger than in the tall shrub case, which is probably related to the effect of vegetation height on surface roughness. Taller shrubs are aerodynamically rougher and therefore favor higher turbulent transfer of latent heat from surface to atmosphere, which limits the impact of soil surface shading on ground evaporation. These results also indicate that the land albedo and ET feedbacks are not independent processes, since the timing and magnitude of the former directly affect the timing and magnitude of the latter.

3.4. Interactive ocean effects

In experiments where the ocean and sea-ice are interactive, the warming and atmospheric moistening over land lead to a significant decrease in sea-ice extent and an associated increase in ocean latent heat flux presumably because the anomalous heat and moisture is advected over the Arctic Ocean. These changes over the Arctic Ocean contribute to further increases in atmospheric water vapor and associated greenhouse warming (Swann *et al* 2010). There are only slight additional feedbacks related to this sea-ice loss over land for fields such as albedo, ASR, transpiration and soil evaporation (figure 3, cyan areas). The sea-ice signal is most distinct from June to December, being larger, and peaking earlier, when tall shrubs are present. The inclusion of interactive sea-ice extends the impact of increasing shrub abundance throughout the year, with the direct shrub-induced feedback dominating during the warm season and instigating the indirect ocean and sea-ice-driven feedbacks that dominate during the cold season.

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[7] In this version of the model, LAI and SAI are prescribed with an annual cycle, which can lead to unrealistic situations where plants can leaf-out before snow melt is complete, with a reduction of albedo too early in the season. The seasonality of LAI and SAI have been improved in Lawrence *et al* (2011b) using data derived from MODIS, but these modifications do not prevent an unrealistic length of the snow season in CAM, with leaf-out possibly occurring prior to the snow-free season. This model limitation could be alleviated by running the land model with inclusion of a carbon–nitrogen (CN) cycle and prognostic phenology; but this will not be a viable option until the model representation of Arctic vegetation is improved.

3.5. Doubled CO_2 effects

As predicted in future climate projections (IPCC), the climate will be much warmer under a doubled CO_2 scenario, accompanied by a large sea-ice loss and a substantial increase in ocean latent heat flux and atmospheric moisture content (Santer *et al* 2007). We find that independently of shrub height, the climate response to doubling CO_2 and shrub invasion is generally similar to the sum of the climate responses arising from the individual forcings (not shown). We also find that the sensitivity of the NHL climate to shrub height is slightly reduced under a doubled CO_2 scenario $((T_{2\times CO_2}-S_{2\times CO_2})^{IO})$ because the GHG-induced reduction of snow depth weakens the distinction between snow masking by short or tall shrubs. One implication of this interaction is that the decline in albedo in the short shrub case $(S_{2\times CO_2}\text{-CTL})^{IO}$ peaks a month earlier (in May) than in the current climate, substantially enhancing the ASR, sensible heat flux, spring ground evaporation and summer transpiration. In these experiments, soil moisture increases and the wetter root-zone soil does not limit ground evaporation during the growing season. Further, the change in surface temperature arising from the tall shrub feedbacks alone $(T_{2\times CO_2}\text{-CTL})^{FO}$ is as large as that imposed by doubling CO_2 $(CTL_{CO_2}\text{-CTL})^{IO}$ without additional shrubs. We show in section 3.6 that in contrast to the surface temperature case, this statement does not hold for atmospheric or soil column temperatures.

3.6. Permafrost vulnerability

Here we extend the analysis of the effects of shrub expansion to the sub-surface climate regime. The representation of soil thermodynamics in the CCSM model has been greatly improved in recent years due to an explicit representation of the thermal and hydrological properties of organic soil as well as a deeper soil column[8] (Nicolsky *et al* 2007); the annual cycle of simulated soil temperature compares reasonably well with observations (Lawrence *et al* 2008a, 2011c).

Figure 4 represents the annual cycle in temperature as a function of atmospheric height and soil depth (down to 5 m), for each individual simulation. The active layer thickness (ALT) deepens with the invasion of shrubs (compare figures 4(b) and (a), and figures 4(c) and (a)), in response to the associated changing climate. When the shrub stature increases and an interactive ocean is used, ALT deepens further, and its below-freezing season shortens (compare figures 4(e) and (a)). In experiments where the shrub expansions are prescribed under a scenario with doubled CO_2 (figures 4(g) and (h)), the refreezing of the soil only occurs in the top meter of soil. Below this level the soil no longer refreezes and this is more likely to favor the formation of taliks (i.e., layers of year-round unfrozen ground that lie in the permafrost zone), which can very efficiently accumulate soil heat content (O'Connor *et al* 2010, Lawrence *et al* 2008b).

While we are aware that the model snow bias (section 3.1) tends to favor warm soil temperature and the formation of taliks in the simulations, we also found that the regions where deep layers of permanent unfrozen ground are found underneath a frozen surface (i.e. the regions of potential talik formation) appear to move poleward in response to introducing shrub and greenhouse warming (not shown).

The difference plots reveal information about the seasonality of such changes. The presence of shrub cover $(S\text{-CTL})^{FO}$ induces a seasonal increase in atmospheric heating which favors summer thawing and reduces winter refreezing (figures 4(i) and (j)). The heat penetrates the ground during May–June for the short shrub case, and April–May in the tall shrub case (figure 3(r)), accumulates greatly (figure 3(p)), and is not fully returned to the atmosphere during the cold months. However, the vertical heat flux to the ground is reduced during June–July, especially in the tall shrub experiment due to the increase in vegetation cover (which prevents the solar radiation from reaching the surface and reduces the air–soil temperature gradient) and the transpiration-induced desiccation of the organic soil (O'Donnell *et al* 2009 have shown that an decrease in moisture in organic soil lowers its thermal conductivity, and therefore the heat transfer). These results suggest that a seasonal atmospheric warming can modify the ground thermal regime all year round.

When tall shrubs and an interactive ocean are imposed simultaneously, the atmosphere becomes warmer (figure 4(l)) and wetter all year (figure 4(s)), which extends the period of ground–atmosphere thermal coupling. With the wetting of the soil, more energy can penetrate the ground at greater depths in spring, while the penetration of summer heating is limited by the increase in dryness of the top soil layer. When the atmospheric CO_2 is doubled, the atmosphere again becomes warmer (figures 4(m)–(o)) and its humidity increases (figures 4(t)–(v)). Meanwhile, as soil ice melts and precipitation increases (figure 3(t)), the ground becomes moister in early spring (figures 4(t)–(v)) and increases its heat conductivity, making its thermal regime more responsive to the atmospheric heating[9]. The increased total liquid groundwater storage (aquifer water and saturated soil water; figure 3(q)), which induces a higher heat content of the soil[10], and the formation of taliks both favor the accumulation of heat in the ground. Overall, the hydrological response due to permafrost thaw remains complex and poorly represented in large-scale models.

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[8] The model's total soil depth is 43 m. If there is permafrost near the surface, the entire soil column is very likely frozen, since geothermal heat flow is not represented.

[9] In fall, in contrast, because water conducts less heat than ice, the delayed freeze-up of the soil can potentially slow the heat release to the atmosphere (assuming that the air–soil temperature gradient is unchanged). Interactions may also occur with changed timing and presence of snow insulation and the changes in heat of fusion released by the soil freezing water; additional experiments would be required to disentangle these effects.

[10] The soil heat content is a diagnostic variable calculated in CLM4, which includes in its calculation the sum over all soil layers of the heat capacities of mineral soil, liquid water, and ice water multiplied by the temperature. In this version of the CLM4, this diagnostic quantity does not precisely account for the time-integrated absorbed energy fluxes required to change the soil state, as it does not include the heat of fusion, and the total heat capacity itself changes during phase change or when the total mass of soil water changes. Discussions among CLM modelers are under way in efforts to develop a more physically precise definition in the updated version of the model. The implications for the interpretation of figure 3(p) should be minor.
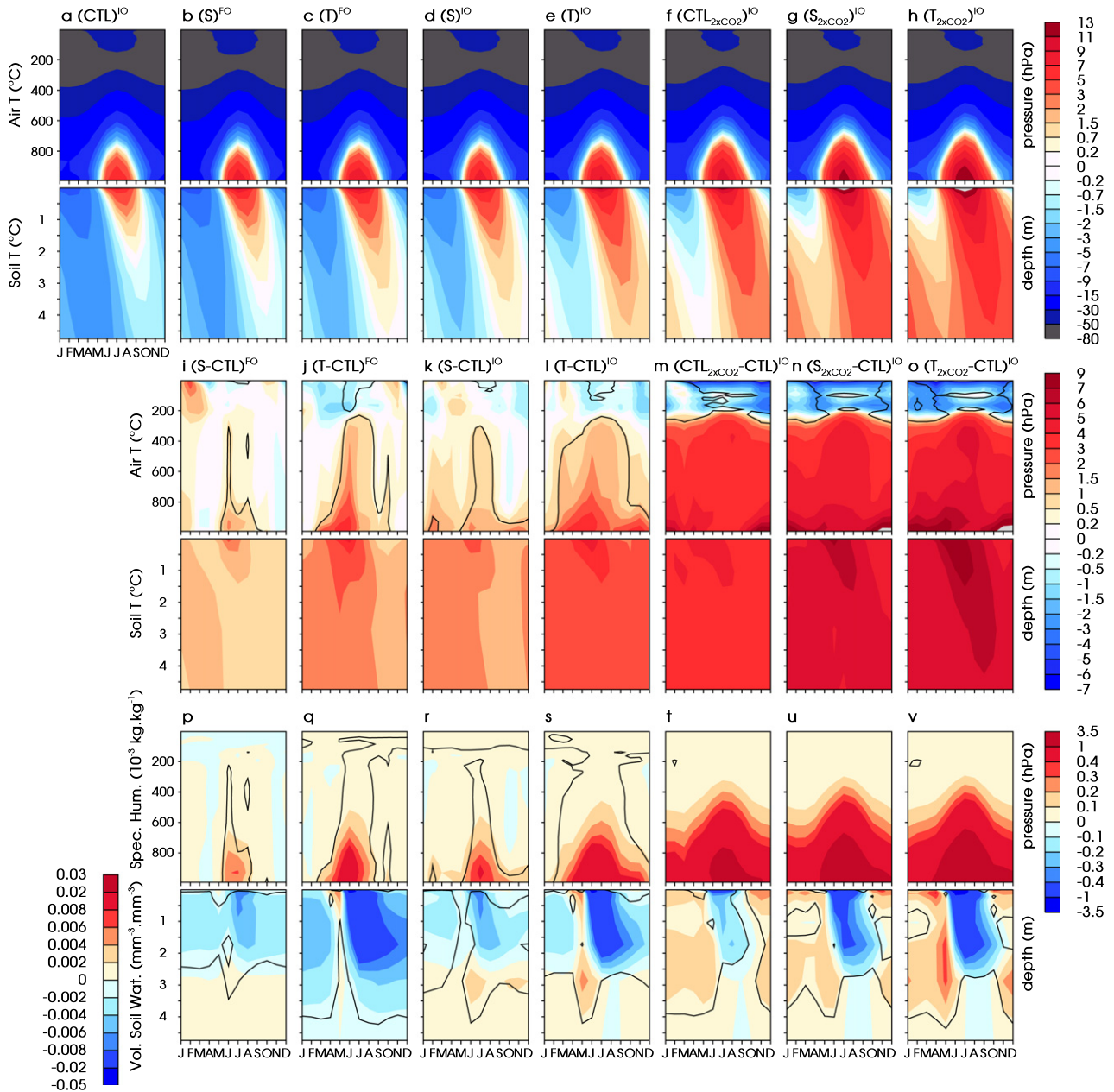
Figure 4. Climatological annual cycle in air and soil temperature (in °C) as a function of height and depth for each simulation ((a)–(h)) and the difference relative to the CTL for each simulation ((i)–(o)). Annual cycle in soil water content (mm^3 mm^{-3}) and atmospheric specific humidity (in 10^{-3} kg kg^{-1}) for different anomalies ((p)–(v)). The black line outlines statistically significant anomalies at the 99% confidence level.

4. Discussion and conclusion

This study is the first to investigate the biophysical effects of deciduous shrub expansion and height on NHL climate. The idealized simulations have been designed to separate the effects of shrub expansion (short or tall) from the effects arising from an active ocean and sea-ice, or from doubling CO_2 (table 1).

As in a previous analysis of increased tree cover at high latitudes, we found that the large-scale shrub expansion triggered substantial regional atmospheric warming in spring and summer through direct albedo and ET feedbacks. We also found that the strength and timing of these two feedbacks

are very sensitive to the stature of the expanding shrubs: when tall shrubs (instead of short shrubs) are prescribed, the sensible heat flux, pre-leaf-out soil evaporation and post-leaf-out transpiration increase sooner. These effects, in turn, impact the strength of the contributions of the indirect sea-ice albedo and ocean evaporation feedbacks to additional regional warming during the winter months. Comparatively, the imposed shrub expansion has a stronger albedo feedback, but a weaker ET feedback than doubling CO_2 (cyan and brown lines of figures 3(f) and (m)). Finally, we found that the invasion of tall shrubs systematically increases sub-surface soil temperature, deepens the active layer, shortens the length of the sub-freezing season, and

triggers permafrost degradation more substantially than do short shrubs. The active soil layer deepens further with inclusion of an interactive ocean. In summary, we found that the amplitudes of the warming and other climatic changes are highly dependent on the stature of the invading shrubs, with all feedbacks being more intense for taller shrubs.

We caution that several pertinent mechanisms are not fully represented in this modeling study. For example, LAI and SAI are prescribed, so the effect of CO_2 fertilization of plants, which can alter plant photosynthesis rates and therefore ET through LAI and SAI (if they were prognostic), was not taken into account with respect to vegetation structure (e.g., canopy height or LAI) or phenology (i.e., timing of leaf-out and senescence). Furthermore, bending of thin and supple stems has been observed for some short shrubs and in this situation could keep those shrubs buried and protected by snow (Sturm *et al* 2001a, 2005a), thereby reducing their estimated impact on climate. We also did not consider the 'snow fence effect'. Some previous observational studies have found that snow preferentially accumulates around shrubs, thus producing a more effective insulating snow layer which can potentially affect the permafrost and stimulate soil microbial activity (Sturm *et al* 2005b).

This study, and that of Lawrence *et al* (2011b), prescribed substantially different distributions of hypothetical shrub area increase. Despite the differences, both studies indicate that the warming response to a large-scale expansion of shrubs in the NHL could overwhelm the soil cooling effect due to shading (Blok *et al* 2010, Yi *et al* 2007), leading to increased rather than decreased vulnerability of permafrost. Although not analyzed here, these physical feedbacks would likely impact ecosystem biogeochemical processes (e.g., soil decomposition, plant growth) controlling the exchanges of carbon between soil and atmosphere.

To summarize, our study highlights the need to account for the expansion, stature, and phenology of invading vegetation to improve climate prediction in the NHL regions. This study also highlights the need of augmenting the number of CCSM arctic and sub-arctic shrub types, improving their representation of fractional cover and height, and treating the shrub expansion more realistically with a dynamic vegetation component in the model.

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