Effects of shrub and tree cover increase on the near surface atmosphere in northern Fennoscandia

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Abstract. Increased shrub and tree cover in high latitudes is a widely observed response to climate change that can lead to positive feedbacks to the regional climate. In this study we evaluate the sensitivity of the near surface atmosphere to a potential increase in shrub and tree cover in the northern Fennoscandia region. We have applied the Weather Research and Forecasting model (WRF) with the Noah-UA land surface module in evaluating biophysical effects of increased shrub cover on the near surface atmosphere on a fine resolution (5.4 km x 5.4 km). Perturbation experiments are performed in which we prescribe a gradual increase of vegetation height in the alpine shrub and tree cover according to empirically established bioclimatic zones within the study region. We focus on the spring and summer atmospheric response. To evaluate the sensitivity of the atmospheric response to inter-annual variability in climate, simulations were conducted for two contrasting years, one warm and one cold. We find that shrub and tree cover increase leads to a general increase in near surface temperatures with the highest influence seen during the snow melting season, and a more moderate effect during summer. We find that the warming effect is sensitive to an enhancement of shrub and tree heights, which decreases the surface albedo, resulting in taller vegetation having a stronger influence on both spring and summer temperatures. Counteracting effects include increased evapotranspiration which can lead to increased cloud cover, precipitation and snow cover. We find that the strength of the atmospheric feedback is sensitive to snow cover variations, and to a lesser extent to summer temperatures. Our results show that the positive feedback to high latitudes warming induced by increased shrub and tree cover is a robust feature across inter-annual differences in meteorological conditions, and will play an important role in land-atmosphere feedback processes in the future.

Keywords. Climate change, Arctic amplification, vegetation perturbations, Arctic greening, Fennoscandia, WRF, land-atmosphere feedback

1 Introduction

Arctic warming is occurring at about twice the rate as the global mean warming (IPCC, 2013;Pithan and Mauritsen, 2014). This is partly owing to land-atmosphere feedback mechanisms in high latitude ecosystems (Beringer et al., 2001;Chapin et al., 2005;Serreze and Barry, 2011;Pearson et al., 2013), such as Arctic greening (Myneni et al., 1997;Piao et al., 2011;Snyder, 2013). Arctic greening refers to the observed increase in high latitude biomass resulting mainly from increased temperature (Walker et al., 2006;Forbes et al., 2010;Elmendorf et al., 2012). The observed increase in biomass includes extensive increase in shrub and tree cover in areas previously covered by tundra (Tape et al., 2006;Sturm et al., 2001b;Forbes et al., 2010) and northward migrating tree lines (Soja et al., 2007;Tommervik et al., 2009;Hofgaard et al., 2013;Chapin et al., 2005).

Increased tree and shrub cover alters the biophysical properties of the surface, inducing land-atmosphere feedbacks (e.g. Bonan, 2008). With increasing canopy height and complexity, the overall surface albedo decreases and more incoming radiation is absorbed. Sturm et al. (2005a) observed the impact of shrub cover on wintertime albedo in snow covered regions and its implications for the winter surface energy balance. They concluded that increased shrub cover caused a positive feedback to warming through lowered surface albedo. The absorbed radiation heated the canopy itself and increased the sensible heat flux to the atmosphere. They also found that an increase of shrub canopies protruding the snow cover shaded the snow beneath the canopy from radiation. This further led to decreased melt and sublimation, as higher shrub and tree cover increased the winter snow cover beneath the shrubs and the soil temperature in winter. Other studies have shown that more shrubs act to speed both the onset and advance of the melting season through its effect on surface albedo (McFadden et al., 2001;Sturm et al., 2001a).

Enhanced leaf area index (LAI) associated with an increase in shrub and tree cover can lead to higher evapotranspiration (ET). This subsequently leads to more latent heat (LH) being transferred into the atmosphere, and acts to increase air temperature (Chapin et al., 2005). The increase in LH may also lead to more cloudiness and precipitation (Bonfils et al., 2012;Liess et al., 2011). Increased cloud cover may in turn limit the effect of an albedo decrease through lowering the short wave (SW) radiation reaching the surface.

The height of the shrubs and trees influences the strength of the land-atmosphere feedbacks, as studied specifically by Bonfils et al. (2012). By modelling an increase in the shrub cover by 20% in areas north of 60^{o}N, they found a higher increase in the regional temperature for taller shrubs as compared to lower ones. They explained the temperature increase by the additional lowering of albedo and increase in LH corresponding to taller and more complex canopies.

In summer, increased shrub cover may also act to shade the soil beneath the shrubs, thereby lowering the temperature of the soil and thus, decrease summer permafrost thaw as observed by Blok et al. (2010). This effect was also modelled in a study by Lawrence and Swenson (2011) who applied an increase in shrub cover by ~20% in the Arctic region. Their findings suggest, however, that increased temperatures due to albedo decrease more than offset the cooling of the soil by the shading effect, resulting in a net increase in soil temperatures.

The studies of Bonfils et al. (2012) and Lawrence and Swenson (2011) both prescribe a 20% increase in shrub by expanding existing shrub cover into areas of tundra or bare ground. Based on circumpolar dendroecological data and several future emission scenarios, Pearson et al. (2013) concluded that the warming effect of increased shrub cover found in these two studies were realistic, however, a shrub expansion of 20% may be substantially underestimated. They predicted by applying various climate scenarios, that about half of the regions defined as tundra could be covered by shrubs by 2050.

The actual extent of shrub expansion into tundra regions and the predicted increase in shrub height in coming decades are highly uncertain, and determined by numerous and complex mechanisms and environmental forcers. As highlighted by Myers-Smith et al. (2011), climatic forcers (e.g. air temperature, incoming solar radiation, precipitation), and soil properties (e.g. soil moisture, soil temperature and active layer depth), coupled with biochemical factors such as the availability of soil nutrients and atmospheric CO_2 concentrations, all influence the rate of shrub growth. In addition, disturbances, such as fires, heavy snow pack and biotic interactions including herbivory, make accurate estimates of future shrub distribution challenging (Milbau et al., 2013). Tape et al. (2012) highlighted the importance of soil properties in estimating likely areas of shrub expansion and shrub-climate sensitivity, and argued that this factor increases the geographic heterogeneity of shrub expansion. In addition, increased shrub cover has also been suggested to trigger feedback loops that further induce shrub growth by e.g., shrub-snow interactions (Sturm et al., 2005a;Sturm et al., 2001a;Sturm et al., 2005b). Positive feedbacks include lowering of spring albedo causing earlier snowmelt, longer growing seasons and increased soil temperatures, all favorable for growth. Also, thicker wintertime snow pack in shrub areas acts to insulate the ground during winter and increase the soil temperatures (Sturm et al., 2001a).

Several of the controlling factors regulating shrub growth and expansion have been investigated using dynamic vegetation models. Miller and Smith (2012) simulated an increase in shrub cover caused by mainly warmer temperatures and longer growing seasons. They found that the shrub cover increase was in part enhanced by shrub-atmosphere feedbacks, particularly related to a reduction in albedo with an increase in canopies protruding the snow cover. In agreement with observations, several other modelling studies have also found increased biomass production and LAI related to shrub invasion and replacement of low shrubs by taller shrubs and trees in response to increased temperatures in tundra regions (e.g. Zhang et al., 2013;Miller and Smith, 2012;Wolf et al., 2008).

Several recent studies have aimed at isolating a few of the dominating environmental drivers of shrub expansion. Myers-Smith et al. (2015) investigated climate-shrub growth relationships and found that mean summer temperatures and soil moisture content are particularly important forcers. By examining circumpolar dendroecological data from Arctic and alpine sites, they demonstrated that the sensitivity of shrub growth to increased summer temperatures was higher at European than American sites. Furthermore, they found a higher sensitivity to climate forcing for taller shrubs at the upper or northern edges of their present domain and at sites with higher soil moisture. Based on dendroecological observations, Hallinger et al. (2010) concluded that the mean summer temperature and winter snow cover are the main climatic drivers correlated with shrub growth in sub-alpine areas in northern Scandinavia. Based on tundra vegetation surveys covering 30 years in 158 plant communities spread across 46 high latitude locations, Elmendorf et al. (2012) demonstrated a biome-wide link between high latitude vegetation increase and local summer warming.

The changes in biophysical properties associated with increased shrub cover in tundra areas are more moderate compared for example to an expansion of forest ecosystems, and a rather modest effect on the overlying atmosphere is expected (Beringer et al., 2005;Chapin et al., 2005;Rydsaa et al., 2015). Still, aforementioned observational and modelling studies have demonstrated notable feedbacks to the regional climate. However, large uncertainties still exist concerning the estimated extent of shrub and tree advance in response to warming, and to the corresponding feedback to climate resulting in response to these ecosystem changes (Myers-Smith et al., 2015;Pearson et al., 2013).

In this study we investigate the regional atmospheric response related to biophysical changes resulting from enhanced vegetation cover in high latitudes. Our investigations are carried out on a domain covering northern Fennoscandia and north-west Russia. This is a sensitive region for shrub expansion in response to climate forcing (Myers-Smith et al., 2015). Extensive increase in the shrub covered area, as well as shifts in the tree line towards higher latitudes and altitudes have been observed in this region over the past decades (Tommervik et al., 2004;Hallinger et al., 2010;Tommervik et al., 2009;Rannow, 2013). The study addresses the atmospheric response to an increase in the area covered by shrubs and low deciduous trees in northern Fennoscandia, and the sensitivity to their height. The primary research questions are:

a. How will the feedback be influenced by increased shrub and tree cover and height?
b. Which season will be more affected and experience the strongest feedback?
c. How sensitive is the feedback to varying climatic conditions, such as snow cover and temperatures?
d. How sensitive are the atmospheric feedbacks to the amount of shrub and tree increase?

Details of the methodology, experimental design, model used and development of bioclimatic envelopes for re-distributing shrubs and trees across the study domain are presented in Section 2. The atmospheric response for spring and summer are presented in Section 3 (Results), including differences in response under various climatic conditions and for varying degree of shrub and tree cover. Finally, discussion and conclusions follow in Section 4 and Section 5.

2 Methodology and study design

2.1 Study design

Model simulations were conducted on a limited region with a state-of-the-art high spatial resolution (5.4 km x 5.4 km). This enabled us to investigate finer scale features of vegetation changes, and corresponding finer scale atmospheric responses. To investigate the effects of increased shrub and tree cover (referring to both areal expansion and increased height) (Research question a), we conducted six simulations; reference simulations for two seasons (Research questions b) and two climatically contrasting years (Research question c), and for each year, two separate simulations in which the vegetation cover was manually altered to represent increased shrub and tree cover (using two different vegetation redistributions) (Research questions d). By comparing the reference and perturbed simulations, we can isolate the effect of shrub and tree cover changes on the overlying atmosphere and evaluate the feedback sensitivity to the degree of shrub and tree increase, since the simulations are otherwise identical.

The spring season has been identified as the season with the strongest feedback to temperatures from increased shrub cover in previous studies due to surface albedo changes (Bonfils et al., 2012;Lawrence and Swenson, 2011). Furthermore, a large potential for growth feedbacks lies with the warming response of the atmosphere during summer. For these reasons we have chosen to focus on the atmospheric response during spring and summer seasons.

As the atmospheric response may vary under different climatic conditions (e.g. warm vs. cold, snow rich vs. snow poor, present vs. future), we chose to run experiments for two contrasting years, spanning the natural variability across a 10-year period with respect to temperature and snow cover in the study region. By averaging the response across two climatically contrasting years, we achieve a robust result representing the meteorological variability across this period, without simulating many years. Secondly, by investigating the contrasting response between the two years, this setup provides us with valuable information of how the contrasting climatic conditions influence the atmospheric feedbacks (Research question c). The two years were selected based on a ten-year (2001-2010) long simulation by Rydsaa et al., (2015), who performed a dynamical downscaling of ERA Interim using the Weather Research and Forecasting (WRF) model. The reason for using this dataset, instead of a global dataset, was the ability to search through relevant variables to identify suitable years. Furthermore, it provided consistency in model setup and boundary conditions with this study. The year 2003 was chosen as it represented a low snow cover spring season and a warm summer season in this region (hereafter referred to as the warm spring and summer season). The year 2008 represented a snow-rich spring season and a cold summer season in this region (hereafter referred to as the cold spring and summer season).

Two different vegetation redistributions were applied to account for some of the uncertainties inherited in the shrubs' response to summer temperatures. They are based on the concept of bioclimatic zones (ref. Section 2.3), and the two distributions allows the sensitivity of the atmospheric feedback to the variability in shrub cover change to be assessed. The more drastic vegetation change (i.e. the one based on a 1 K temperature increase) may represent a scenario in which the response of the shrub cover to warmer conditions is faster, or alternatively represent some future distribution of shrubs.

Combining findings of the atmospheric response in two different vegetation distributions, and contrasting years (warm and cold), further allow us to identify potential responses under various future climate conditions.

2.2 Land cover and re-distribution

The land cover data in the reference simulations (RefVeg) is based on the newly available 20 class MODIS 15 sec resolution dataset (Broxton et al., 2014). In this dataset most of the Arctic and alpine part of our study area is covered by the dominant vegetation category "open shrubland", consisting of low shrubs of less than 0.5 m height. This land use category was split into three shrub categories to distinguish the atmospheric sensitivity to shrubs and low deciduous trees of various heights. The study domain was divided into bioclimatic zones based on mean JJA temperatures and re-distributed shrubs and low trees following the approach of Bakkestuen et al. (2008). The shrub and tree vegetation was re-distributed across the study domain by applying bioclimatic envelopes, which were derived from empirically determined vegetation-climate relationships for the region. In order to prevent shrubs from being distributed in areas unsuitable for growth despite favorable climatic conditions, the area extent of other vegetation categories than "open shrubland" was kept unaltered. In this way, the heterogeneity in the vegetation distribution across the domain was kept similar to the original dataset.

The bioclimatic zones for each shrub category were derived using some general features of vegetation distribution that have been determined for this area. Gottfried et al. (2012) defined various alpine zones as altitudinal dependent belts of vegetation above the forest line, where each alpine zone represents a bioclimatic envelope in this study. Although the altitudinal extent of each alpine zone is determined by the local mean temperature lapse rate, in addition to various geographical and climatic features, the altitudinal extent of each zone remains rather constant across the domain, as illustrated in Fig. 1. The altitudinal extent of each alpine zone used in this study is based on Moen et al. (1999), but also confirmed by a new dataset from the region (Bjørklund et al., 2015).

Following the vegetation categorization of Moen et al. (1999) and Bakkestuen et al. (2008), we defined tall shrubs and boreal deciduous trees with a height from 2 to 5 m (Aune et al., 2011) to belong to the sub-alpine zone, shrubs with height from 0.5-2 m to belong to the low-alpine zone, and low shrubs with height up to 0.5 meters to belong to the mid-alpine zone (Fig. 1). The high-alpine zone contains no shrubs and is characterized by barren ground, boulder fields or scattered vegetation (Moen et al., 1999). High mountain tops were regarded as high-alpine (largely in agreement with the defined climatic limits), and vegetation cover in these areas were adjusted accordingly (e.g. see Karlsen et al. (2005)).

The climatic forest line was used to separate the boreal forest from the sub-alpine region characterized by scattered mountain birch (Aas and Faarlund, 2000). The last mountain birches stretching towards higher elevations are approximately 2 m tall, and define the so-called boreal-tundra or tree line ecotone (Hofgaard, 1997;Bryn et al., 2013;de Wit et al., 2014). This ecotone was determined here to be above the line where the fraction of boreal tree exceeds 25% in each grid cell. This line furthermore defines the base line temperature used to derive the alpine vegetation zones at higher elevations, and was found to correspond well with the mean summer 12^{o}C isotherm (in our domain). This is slightly higher than what is found in southern parts of mountainous Scandinavia (Aas and Faarlund, 2000;Bryn, 2008). The sub-alpine zone was then determined based on an average altitudinal extent of 100 m (Aas and Faarlund, 2000), the low-alpine and mid-alpine zones were both estimated to be on average 300 m in altitudinal extent, and vegetation cover at higher elevations defined as high-alpine zone (Moen et al., 1999).

Based on temperature simulations by Rydsaa et al. (2015), the mean tropospheric JJA lapse rate for the area was found to be 6.0 K km^{-1}. This value was used together with the average zone-heights to find the summer temperature ranges for each vegetation zone (Fig. 2). The interpolated mean JJA 2 m temperature was then used to distribute each shrub category across the domain in accordance with their climatic envelope (Fig. 2). This vegetation distribution is referred to as Veg0K.

Revised bioclimatic zones with the same relative altitudinal extent, but with a 1 K increase in JJA 2 m temperatures, were calculated and vegetation categories re-distributed, resulting in a shift in the distribution of shrub categories across the domain. This distribution is referred to as Veg1K (Fig. 2). The reference vegetation distribution (RefVeg) and the two perturbed distributions (Veg0K and Veg1K) are shown in Fig. 3.

To represent each alpine shrub type in the model, we chose suitable vegetation categories (and corresponding parameter values) from the ones already defined within the satellite dataset provided and thus tested within the framework of the model system. The categories were chosen based on vegetation types already present in the domain. Special emphasis was given to decreasing LAI and canopy height for vegetation distributed towards higher altitudes and latitudes, and further based on a recent mapping of vegetation types in the region (Bjørklund et al., 2015). A list of the shrub categories and their corresponding parameter values is presented in Table S1, supplementary material. With two exceptions (see supplementary material, Table S1, bold), parameter values were left unaltered to keep consistency between and within each vegetation category.

The only alteration between the reference simulations (RefVeg) and perturbed simulations (Veg0K, Veg1K) is the land cover. Any differences in atmospheric and soil variable values result from the land cover changes, as simulations are otherwise identical with respect to setup and meteorological forcing. The difference between Veg0K and RefVeg shows the effects of an increase in shrub and tree cover where shrub heights are in equilibrium with the climatic potential (as defined by the bioclimatic zones and 10-year mean JJA temperatures). The difference between Veg1K and RefVeg, in comparison, shows the sensitivity to a potential vegetation shift derived from a 1 K increase in mean JJA temperatures.

2.3 Model

WRF V3.7.1 (Skamarock et al., 2008) is a non-hydrostatic weather prediction system with a wide variety of applications ranging from local scale domains of a few hundred meters in resolution to global simulations. With a range of physical parameterization schemes, the setup may be adjusted to simulate case-specific short-term weather events, or decadal long climate simulations. The current setup is based on available literature (ref. the NCAR choices for physical parametrizations for high latitude domains), and a consideration of the polar WRF setup and validation studies (Hines and Bromwich, 2008;Hines et al., 2011). A summary of key physical schemes applied is presented in Table 1.

As initial and boundary conditions we used the ERA Interim 6-hour reanalysis. The model was run for two domains, where the outer domain with a resolution 27 km x 27 km (90 x 49 grid cells) serves purely as a bridge between the coarse resolution boundary conditions and the finer inner domain with resolution 5.4 km x 5.4 km used for analysis. The model was run with 42 vertical layers and 3 hourly outputs. Each simulation spans the snow accumulation season (starting in November), however, only the spring (MAM) and summer (JJA) seasons are included in the analyses.

The model was run with the Noah-UA land surface model (LSM), which is the widely used Noah LSM (Tewari et al., 2004), with added parameterization for snow-vegetation interactions by Wang et al. (2010), including vegetation shading effect on snow sublimation and snowmelt, under-canopy resistance, improvements to the ground heat flux computation when snow is deep, and revision of the momentum roughness length computation when snow is present. The soil is divided into four layers of varying thickness, in total 2 m. The LSM controls the soil and surface energy and water budgets, and computes the water and energy fluxes to the atmosphere, depending on air temperature and moisture, wind speed and surface properties. The dominant vegetation category in a given grid cell determines a range of biophysical parameters that controls its interaction with the atmosphere. These parameters include the height and density of the canopy, the number of soil layers available to the plants' roots, minimum canopy resistance, snow depth water equivalent required for total snow cover, and ranges for values of leaf area index, albedo, emissivity and surface roughness length. A list of parameter values used to represent the relevant vegetation categories in our simulation is presented in Table S1, supplementary material. The value within each range is scaled according to the vegetation greenness factor, which is based on a prescribed monthly dataset provided with the WRF model.

This model setup is able to capture changes in surface properties following a redistribution of vegetation classes and the corresponding atmospheric response. It will not simulate the vegetation's response to environmental forcing, such as changes in surface temperature or soil moisture. Only prescribed changes to the vegetation as described in the next section differ in reference versus perturbed simulations. Differences in the atmosphere result from the biophysical changes accompanying the applied vegetation changes only.

3 Results

Sections 3.1 -3.3 present the seasonal effects on the overlying atmosphere of increased shrub and tree cover. Results are presented as mean anomalies between the reference and perturbed simulations (Veg0K-RefVeg), as averaged over the warm and the cold year. Special emphasis is on how the increased shrub and tree cover alters the feedback to atmospheric near surface temperatures. Changes in other variables are presented largely to explain variations in temperature. We start presenting the results as averages over the two spring (MAM) seasons, and the two summer (JJA) seasons (Section 3.1). This gives an estimate of the mean response of the atmosphere across a wide range in meteorological conditions and thus represents a robust estimate of shrub induced effects across inter-annual variations. To show the sensitivity in the atmospheric response to differing meteorological conditions, results comparing the response in the warm versus the cold spring and summer seasons are presented next in Sections 3.2 and 3.3. Section 3.2 focuses on the effect of variation in spring snow cover between the two years, and Section 3.3 on the effect of variation in summer near surface temperatures. Finally, in order to account for the sensitivity of the shrub and tree cover to JJA temperatures, the atmospheric response to the more extensive vegetation re-distribution (Veg1K-RefVeg) are presented in Section 3.4.

3.1 Atmospheric effects of shrub and tree cover increase

Responses in surface fluxes and near surface atmospheric variables as averaged over all areas with vegetation changes and across the warm and cold years (Veg0K-RefVeg), and for each year (in parentheses), are presented in Table 2. Effects of shrub and tree cover increase as averaged over the two spring seasons (Veg0K-RefVeg) are presented in Fig. 4. Fig. 4a shows the spatial distribution in 2 m temperature anomalies (left) and mean values for each bioclimatic zone in the bar plot (right).

In spring, an overall increase in near surface temperatures is seen for all areas where shrub and tree cover increases (Fig. 4a). The higher anomaly values are seen in areas with increase in taller shrubs and trees (as indicated in the bar plots). Average increase in 2 m temperature over the spring season is 0.1 K (Table 2); however, there are large spatial differences (Fig. 4a, bar plot). Values close to 0.6 K are seen in some areas with taller vegetation. There is also large temporal variability within the season, and the increase as averaged over all areas with vegetation changes peaks during the melting season in mid-May with 0.8 K (not shown).

The highest increase in net short wave (SW) radiation is seen during the spring season (Fig. 4b), mainly due to decreased surface albedo caused by increased shrub and tree cover and its effect on earlier snowmelt (Section 3.2). There is a slight decrease in downwelling SW (not shown) caused by enhanced cloud cover (Table 2), but the reduction in downwelling SW is more than compensated by the albedo decrease in areas with sub-alpine vegetation (taller vegetation). The net value is close to zero in areas with low-alpine shrub increase (lower vegetation) due to smaller albedo changes (4b, and bar plot). The long wave (LW) radiation slightly increases (Fig. 4c) in response to enhanced cloud cover and atmospheric humidity (Table 2). The increase in LW is more evenly distributed across the region than changes in SW, as it is not as directly linked to the vegetation changes.

The heating associated with the increase in SW is partly balanced by an increase in evapotranspiration (ET), shown as the latent heat flux (LH) (Fig. 4d). The increased LAI caused by more shrub and tree cover (Table S1, and Fig. S4, supplementary material) results in increased ET, and correspondingly higher LH. The effect is larger in areas with larger LAI increase, i.e. in areas with taller vegetation. The increase is largest towards the end of the spring season (not shown), much owing to larger above-snow canopy fraction due to the canopy height increase associated with more shrubs and trees and reduced snow cover (Fig. S2, S3, supplementary material). An increase in sensible heat flux (SH) (Fig. 4e) from the surface and from canopies protruding the snow cover is seen in areas with taller vegetation, where net SW is positive. This adds to the effect of increasing LH in balancing the surplus of SW energy at the surface.

In the summer season (Fig. 5) the 2 m temperature increases in areas with taller vegetation, and decreases in areas with low-alpine shrub increase (lower vegetation) (Fig. 5a). The latter areas are characterized by a lowering of net SW radiation in this season, which results in a decreased sensible heat flux and less warming of the lower atmosphere. The negative net SW (Fig. 5b) is related to a slight albedo increase in early summer (early to mid-June, not shown) caused by enhanced snow cover in these areas (Fig. S3 and S4, in the supplementary material). The enhanced snow cover is a result of increased precipitation (including snow fall; Table 2). In addition, the summer season SW downwelling is decreased due to an increase in cloud cover (Table 2), as confirmed by the increased LW to the surface (Fig. 5c). On the other hand, in areas with taller shrubs and trees, the stronger albedo decrease dominates, leading to a decrease in snow cover throughout the spring and summer (albedo changes are shown in Fig. S4, supplementary material).

The increased SH mainly acts to heat the planetary boundary layer (PBL), while the LH is mainly released above the PBL height. The LH therefore does not affect the 2 m temperature to the same degree as the SH, as the heat is released as the water condenses, which may well be higher up in the atmosphere. The vertical structure of the lower atmosphere heating along a cross section is shown in Fig. S6 in the supplementary material, along with changes in PBL height and turbulent fluxes of SH and LH. The atmospheric humidity increase associated with increased shrub cover results in more clouds and total precipitation in both seasons (Table 2).

The spatial distribution of mean changes in the low cloud fraction (here defined as below 3 km) and precipitation anomalies in the two seasons is shown in Fig. 6. The top panels show the relative change in low cloud cover resulting from increased shrub and tree cover. Here the change in cloud cover is shown as the difference in fractional cloud cover averaged over the lower 3 km of the atmosphere (further details about this variable in the supplementary material). The increased cloud cover acts to decrease the SW radiation reaching the surface in both seasons (shown only as net SW, Fig. 4 and 5) and increase the amount of LW radiation towards the surface (shown only as net LW, Fig. 4 and 5). The effect is largest in areas where the humidity increases the most through enhanced LH, i.e. in areas with an increase in taller vegetation.

The most prominent increase in low cloud cover is occurring in spring (Fig. 6, upper left panel) largely covering areas with vegetation changes. The summer season's response is patchier, although a tendency towards increased cloud cover in areas with vegetation change (ref Fig. 3) is recognizable. The second row shows the relative increase in precipitation (in percent), as accumulated over the season. For both variables only areas with significant changes are shown. The relative change in precipitation is based on daily accumulated values. As with the cloud cover, the spatial distribution of (significant) precipitation changes is somewhat patchy, particularly for the summer season. However, the significance is higher in areas with vegetation changes, as compared to the total area (cells with significant differences in areas with vegetation changes is 8.3%, versus 5.7% in the total domain). The increase in accumulated precipitation is most prominent in summer, amounting to 186 mm in areas with vegetation changes, corresponding to a 2.2% increase (*p*-value based on the Mann-Whitney significance test is $1.2\ 10^{-5}$). For spring, the increase in precipitation is 1.07%, and for precipitation in the form of snow and ice, 1.4%.

3.2 **Sensitivity to snow cover**

The two contrasting spring seasons are characterized by large differences in snow cover, albedo and near surface temperatures. In the reference simulations, the warm spring season ($RefVeg_{warm}$) has 16% less snow cover than the cold one ($RefVeg_{cold}$), resulting in a decreased albedo of 12% and an average 3.1 K warmer 2 m temperature (numbers are averages over the land area of the total study domain). Total precipitation is similar for the two years, although the rain-to-snow ratio is larger in the warm spring due to higher temperatures. The snowmelt lso starts earlier in the warm spring season ($RefVeg_{warm}$) (more than two weeks) and a faster rate of snowmelt is seen as compared to the cold spring season ($RefVeg_{cold}$), with the largest difference in snow cover in May (Fig. 7). It is worth noting that the most pronounced effects of increased shrub cover on the atmosphere are during the melting season, i.e. May-June.

The warm spring season experiences up to 0.38 K higher increases in 2 m temperature in response to shrub and tree cover increase as compared to the cold one (Fig. 8). As seen in the right panel of Fig. 8, the anomaly distribution is shifted towards overall higher values in the warm season. The shrubs act to enhance warming more in the warm than in the cold spring season. This represents a positive feedback to warm conditions and early snowmelt.

The increased shrub and tree cover leads to a reduction in snow depth in spring as averaged over all areas with vegetation changes, as seen in Fig. 9a (the spatial distribution of snow cover is shown in Fig. S3, in the supplementary material). An exception is seen in late spring (and early cold summer, not shown). This is related to the late spring and early summer increase in snow cover found in areas with low-alpine shrub increase. These areas experienced an increase in snow fall in the cold summer season and subsequently, a shortening of the snow free season (a grid cell is considered snow free if the fraction of ground covered by snow is less than 0.1) (Fig. 9b). In the cold season the shortening is only about half a day averaged over the areas with vegetation changes. The warming effect of shrub cover in the warm season on the other hand, acts to prolong the snow free season by just over one day, however, it speeds the onset of melting by several days.

Also, increased shrub and tree cover acts to enhance soil temperature (Fig. 9c), with maximum impact in the upper layers of the soil (not shown). The increased precipitation during both spring and summer also influences the soil moisture. Soil moisture (Fig. 9d) increases in areas with increased shrub and tree cover throughout the warm spring. A notable increase in soil moisture, and corresponding decrease in surface runoff, is seen in mid-May at the time of maximum snow melt (Fig 9e), for both the cold and warm melting seasons. However, before the main snowmelt starts, runoff is slightly higher during the warm spring season, because of the increased snow melt earlier in spring for areas with increased shrub and tree cover.

3.3 **Sensitivity to summer temperatures**

The warm and cold summer seasons encompass a large range in inter-annual temperature variability. For the reference vegetation (RefVeg), the mean JJA 2 m temperature (averaged over land areas in the domain) for the warm summer season ($RefVeg_{warm}$) was 11.7 ^{o}C, while the cold summer ($RefVeg_{cold}$) represents a lower than usual mean temperature of 9.7 ^{o}C. In some areas the difference reached 3.3 ^{o}C. The corresponding increase in atmospheric absolute humidity at 2 m is 6.9%. The warm summer also represents drier conditions with less precipitation (Table 2).

The difference in atmospheric temperature response to increased shrub and tree cover between the two summers is shown in Fig. 10. The response of the atmosphere to increased shrub cover (Veg0K-RefVeg) shows more similarity across the warm and cold summer seasons as compared to the warm and cold spring seasons. For the summer seasons, the mean difference in 2 m temperature response is smaller and rather evenly distributed around zero (Fig. 10, right panel). Positive values over areas with low-alpine shrub expansion indicate less cooling in the warm as compared with the cold summer season, during which these areas were partially covered by snow. The tall vegetation changes contribute to similar warming in the summer seasons. The temperature response in the warm season is slightly shifted towards warmer anomalies (Fig 10, right panel), indicating a slightly larger vegetation feedback to warmer summer temperatures in the warm summer season when compared with the cold.

The difference in atmospheric temperature response is larger between the warm and cold spring season than between the warm and cold summer season. Thus, it seems that the shrub cover feedback is more sensitive to meteorological conditions in spring than summer. This is likely due to the feedback being closely linked to albedo changes, which are heavily dependent on snow cover. Therefore, the feedback is more sensitive to temperature in the melting season.

3.4 Sensitivity to the degree of vegetation changes

The shift in shrub and tree distribution according to the theoretical 1 K increase in summer temperature (Veg1K vegetation distribution) results largely in a northward shift in the boreal tree line ecotone, replacing low-alpine shrubs with small trees across most of the shrub covered areas, as compared to the Veg0K distribution. It also acts to increase the low-alpine shrub cover in higher latitudes and altitudes (Fig. 3). The increased cover of trees at the expense of shrubs, with corresponding strong decrease in albedo and increase in LAI, enhances the net SW absorbed by the surface. This is balanced by strong increases in SH and LH (Table 2, and Fig. S5 in the supplementary material). In addition, the vegetation changes result in increasing precipitation and cloud cover (Table 2).

The mean seasonal response in 2 m temperature caused by this vegetation shift (Veg1K-RefVeg) is shown in Figure 11. The warming at 2 m is on average more than doubled as compared to that of the more moderate shrub and tree cover distribution (Veg0K-RefVeg), in both seasons (Table 2). This is due to the more extensive changes in biophysical properties related to the shift towards taller vegetation. The warming is most prominent in the spring season, particularly in late spring when the increased vegetation cover notably affects the snow melt and corresponding albedo and surface heat fluxes. The average spring warming is therefore strongest in areas with the tallest vegetation. However, although highly localized the highest peak values, up to 0.71 K, are found in summer (Fig. 11). Increased LH also leads to enhanced atmospheric moisture and more summer precipitation (Table 2) and corresponding greenhouse effect of up to 5 W m^{-2} (not shown). The response of the Veg1K vegetation change also differs between the warm and cold summer and spring seasons. In contrast to the response of Veg0K, the strongest warming is found in the cold summer in most areas.

4 Discussion

The spring albedo effect is often regarded as the most important effect of increased vegetation cover in high latitudes (Arora and Montenegro, 2011;Bonan, 2008), and our results confirm this as the main cause of warming during the spring season. Our findings show that the net SW is highly sensitive to the vegetation properties such as the height of the vegetation. We find that competing effects of increased ET (resulting in more cloud cover, precipitation and snowfall, less downward SW), versus the effect of albedo decrease (more absorbed SW), determine the net SW and corresponding near surface temperatures.

In the most moderate vegetation re-distribution case (Veg0K-RefVeg) the seasonal average spring temperature increase reached 0.59 K in in the areas with the tallest vegetation. The warming as averaged over the entire area with vegetation changes reached 1.0 K during the melting season in the warmest of the two years studied, due to the strong impact of shrubs and trees under snow free conditions. These peak values represent the warming potential of the vegetation changes applied in this experiment. The albedo decrease related to more complex canopies and enhanced snowmelt dominate over competing effects and cause warming in spring in areas with increased tall vegetation, but this dominance is smaller and sometimes reversed in areas with increased low shrub cover. In the large areas with increased low-alpine shrub cover, the average summer warming was only 0.1 K, reflecting an increased early summer snow cover and albedo in these areas caused by increased snowfall. This, combined with the weak counteracting effect of small albedo decreases associated with the low-alpine shrubs, resulted in a decrease in the net SW and 2 m temperatures. In areas with taller vegetation, the summer maximum increase in near surface temperature reached 0.39 K. This contrasting pattern in summer warming, confirms the strong dependence of the atmospheric response on vegetation height as was also found by Bonfils et al. (2012). They applied a 20% increase in shrub cover in bare ground areas north of 60^{o}N in order to simulate the influence of shrubs on climate. They found a regional annual mean temperature increase of 0.66 K for shrubs up to 0.5 m high, which was most prominent during the spring melting season. To investigate the sensitivity of height and stature of shrubs, they performed a second experiment, increasing the shrub heights to 2 m. This caused the regional annual warming to increase to 1.84 K by 2100. Furthermore, they found increases in both SH and LH, the latter mainly resulting from an increase in ET. Similarly to our results, they also found an increase in summer precipitation, particularly in the case of tall shrubs.

Lawrence and Swenson (2011) also applied a 20% increase in shrub cover north of 60^{o}N. In their case this led to a moderate increase in mean annual temperatures of 0.49-0.59 K, with a peak during the melting season in May of 1-2 K. They also found an increase in soil temperatures of 3-5 K in winter and spring following added shrub cover and re-distributed snow cover. Although not directly comparable, we note that their results were substantially larger than the soil temperature response in our results, with maximum values reaching up to 1.5 K in the top soil layer during the warm melting season. This difference is probably related to inter-model differences in soil and vegetation properties, and particularly to differences in simulation domain and extension of shrub and snow cover increase. Their analyses did not include effects on cloud cover and precipitation. Also Swann et al. (2010) applied a 20% increase in shrub cover north of 60^{o}N and found an annual warming of 0.2 K and a decrease in low level clouds despite increased vapor content due to increased ET. Similarly to our study, they also found increase in summer precipitation, but not in spring.

The atmospheric response to shrub cover increase in our simulations was larger in the warm than in the cold year, both in the spring and summer seasons. However, the difference in response between warm and cold summers was more moderate as compared to the warm and cold spring. Based on these results, we might expect that in a warmer climate, shrub expansion would increase spring surface temperatures more than summer temperatures. The areas with strongest feedback to the summer season warming were related to increase in taller vegetation (sub-alpine and boreal).

The sensitivity of shrub expansion to summer temperatures is not well known, and for this reason, we applied a second set of simulations with vegetation distribution based on a 1 K increase in JJA temperatures (Veg1K). When interpreted with care, the atmospheric response to this vegetation change as compared to the more moderate on may serve as a simplified proxy as a future vegetation re-distribution scenario. However, precautions should be made, as the time delay related to such a vegetation shift could be substantial (Corlett and Westcott, 2013), and because the actual vegetation re-distribution according to such a shift in summer temperatures could be limited by other environmental and ecological factors, as mentioned in the introduction and discussed by Svenning and Sandel (2013) and Myers-Smith et al. (2011). Also, the warmer climate might influence the response itself, with responses even falling outside the range of climatic conditions represented by the two contrasting years in this study. Keeping all this is in mind, a careful interpretation of the results as representing some future state can still be interesting. The Veg1K re-distribution was largely dominated by extended areas of sub-alpine and boreal deciduous vegetation cover, consisting of tall shrubs and low trees. The northward migration of taller trees and the sub-alpine ecotone more than doubled the warming in both seasons, but to a larger degree in summer (on average 0.16 K in Veg1K-RefVeg, as compared to 0.05 in Veg0K-RefVeg, Table 2). Peak seasonal anomalies in this experiment were also higher in the summer season as compared to the spring season.

Combining our findings, we find that the main summer temperature feedbacks are mainly related to increases in taller vegetation. The surface albedo decrease is largest in summer in areas with boreal and sub-alpine deciduous trees, despite the snow masking effect of snow-protruding canopies in spring. This is mostly owing to the deciduous nature of the northward expanding shrubs and trees in this study, which is based on what is observed in the study region (Hofgaard et al., 2013;Aune et al., 2011). This would be different if we allowed for expansion of evergreen needle leaved trees (Rydsaa et al., 2015;Arora and Montenegro, 2011;Betts and Ball, 1997), which would more strongly affect the albedo across all seasons. Allowing for such a vegetation change could certainly be interesting in this type of investigation. However, in this study, the main focus has been on the relatively "fast" shrub and (deciduous) tree cover increase.

As the mean summer temperature is assumed here to be the main environmental driver of shrub expansion, our results lead us to conclude that a warming effect on summer temperature strong enough to lead to a positive feedback to shrub and tree growth, would depend on establishment of taller shrubs and sub-alpine trees in tundra areas, rather than an increase in lower shrub types. This also supports the findings by de Wit et al. (2014).
As the differences in atmospheric response between the warm and cold summer in these experiments are rather small, a positive feedback to summer warming seems to be a robust feature across inter-annual variations. Given the strong impact of the northward migrating sub-alpine ecotone on the summer temperature shown here, we find the possibility for a future ecological "tipping point" in this area possible, and this would be an interesting topic to investigate further. The term refers to the level of vegetation response, where the atmospheric warming resulting from increased shrub and tree cover feedbacks enhances the further growth to such a degree that the response becomes nonlinear in relation to the initial warming (Brook et al., 2013).

The temperature increases in our results, both for the peak melting seasons and in seasonal means, are below the seasonal estimates of some similar studies. This was expected given the comparatively more moderate vegetation shifts (both on areal scale and partly in vegetation properties) in our simulations. Also, large variations in the atmospheric response with regard to cloud cover and precipitation were found among other modelling studies, despite qualitatively similar responses of enhanced ET and LH related to increased shrub cover. The vegetation perturbations applied to represent shrub and tree cover increase in this study are moderate in both areal extent and in vegetation property changes, as compared to other studies with similar purpose (e.g. Bonfils et al., 2012;Lawrence and Swenson, 2011). We have altered shrub properties only in areas already covered by tundra and low shrubs, and only within empirically based suitable climatic zones (Fig. 1 and 3). Shrub properties were selected from predefined vegetation categories within the modelling system employed to represent high latitude vegetation. Only minimal alterations were made to the existing categories in order to keep consistency within and between the vegetation categories applied in the modelling domain. This approach does inherit some uncertainty regarding the suitability of single parameter values. However, we judged that further alterations might lead to unintended biases within the modelling system. A complete review of the parameter values applied for each vegetation category within the modelling system is beyond the scope of this study.

Since we have chosen to focus on biophysical aspects of the effects of increased shrub and tree cover, there has been no atmospheric or soil chemistry changes included, nor effects of aerosols. These factors may substantially alter atmospheric composition and possibly impact on the response to vegetation changes. However, other studies have concluded that the main impact of changes in the high latitudes ecosystems results from biophysical effects (Pearson et al., 2013;Bonan, 2008).

Our investigations are based on simulations using a relatively fine spatial resolution. This has enabled a more realistic representation of finer scale features of the shrub-atmosphere feedbacks as compared to previous modelling studies. However, this comes with the price of having to reduce the size of the domain. Due to its limited size, and the proximity to warm waters along the coast of Norway, our domain is largely influenced by the incoming marine air from the west. This advection of weather into the domain acts to diffuse the effects of shrubs' and trees' on the atmosphere. As such, our results for impacts on upper atmospheric features, such as cloud cover and precipitation, are heavily influenced by the meteorological boundary conditions and not only near surface variables. This effect could influence our results for atmospheric response to be more modest when compared to results of similar studies on circumpolar domains (e.g. Bonfils et al., 2012;Liess et al., 2011).

Vegetation dynamics were not included in this study to account for the vegetation's response to the changing environmental conditions. This represents a limitation in our simulations, particularly with regard to differing responses among the cold and warm seasons. However, it is hard to predict whether this represents an over or underestimation of our results. In this model version, the daily interpolated greenness factor (based on monthly values), acts to scale between maximum and minimum parameter values representing each vegetation category (such as the LAI and vegetation albedo etc.). This gives rise to the seasonal variation in vegetation in these simulations. The greenness fraction describes the vegetation density distribution within each grid cell. Since we have made no assumptions about changes in the density of vegetation, only about the type of dominant vegetation, this variable was left unaltered in our perturbations. Although it can be argued that an assumption of enhanced vegetation density (i.e. greenness) is reasonable, we considered it beyond the scope of this study to estimate scales and predictions regarding such changes. In addition, recent reports on arctic browning suggest high uncertainty related to enhanced vegetation density (Phoenix and Bjerke, 2016). Also, limiting the perturbations to affecting only the vegetation types and heights, not the density, is beneficial for the interpretation of the results. We do however acknowledge that this choice might influence the results for the atmospheric response. Particularly the partitioning between latent and sensible heat flux could be affected by the choice of perturbations applied.

5 Summary and conclusions

We have applied the weather, research and forecasting model (WRF) coupled with the Noah-UA land surface model to evaluate biophysical effects of shrub expansion and increase in shrub height on the near surface atmosphere on a state-of-the-art fine resolution. We first applied an increase in shrub and deciduous tree cover with heights varying in line with the present climate potential according to empirical temperature-vegetation limits for the region (bioclimatic envelopes). To evaluate the sensitivity of the atmospheric response to climatic variations, simulations were conducted for two contrasting years, one with warmer and one with colder spring and summer conditions. The response across the different years represents an atmospheric response across a broad range in temperature and snow cover conditions. To evaluate the sensitivity to a potential further expansion in shrub and tree cover, we conducted additional simulations for each year, applying a second vegetation cover shifted according to bioclimatic envelopes corresponding to a 1 K increase in mean summer temperature.

Our results show that shrub and tree cover increase leads to a general increase in near surface temperatues, enhanced surface fluxes of heat and moisture, increase in precipitation and cloud cover across both warm and cold years and seasons. A noteable exception is areas with sub-alpine shrubs, where increased atmospheric moisture resulting from shrub expansion leads to increased snowfall and surface albedo, early in the colder summer season. This highlights that the net SW absorbed by the surface strongly depends on the strength of the albedo decrease due to enhanced canopies, versus albedo changes related to increased ET causing enhanced cloud cover and precipitation (including snow fall). The atmospheric responses in all variables strongly depend on the shrub and tree heights. However; increased LAI leads to a persistent increase in LH in all areas with shrub expansion, in all seasons investigated.

We find that the effects of increased shrub and tree cover are more sensitive towards snow cover variations than summer temperatures. Increased shrub cover has the largest effect in spring, leading to an earlier onset of the melting season, particularly in the warmer spring season. This represents a positive feedback to warm spring temperatures. Taller vegetation influences summer temperatures more than spring temperatures in most areas. The response is not affected by variations in summer temperatures to any large degree, but rather seems to be a robust signal across inter-annual variations.

Summer temperatures have been estimated to be one of the strongest drivers of vegetation expansion in high latitudes. Here, we find that the strongest feedbacks to the summer temperatures are related to the expansion of taller vegetation rather than shorter shrubs. Due to large areas with small elevation gradients within this domain as well as the rest of the circumpolar tundra covered areas, the temperature zones as derived here are highly sensitive to increases in summer temperatures. Small increases in mean temperatures will as such make vast areas climatically available for shrubs and tree growth. Our results show that the positive feedback to summer temperatures induced by increased tall shrub and tree cover is a consistent feature across inter-annual variability in summer temperatures. In combination with the vast area that is made available for taller shrubs and trees by relatively small increases in temperature, this represents a potential for a so-called vegetation-feedback tipping point. This is a possibility which we find to be an interesting subject for further research.

Competing interests

The authors declare that they have no conflict of interest.

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6 Tables and figures

Table 1: Key parameterizations used in the model setup.

Parameterization scheme	*Reference*
Mellor–Yamada–Janjić planetary boundary	(Janjic, 1994)
Morrison two moment microphysics	(Morrison et al., 2009)
RRTMG short- and longwave radiation options	(Iacono et al., 2008)
Noah-UA land surface model	(Wang et al., 2010)

Table 2. Mean response in surface fluxes and near surface atmospheric variables as averaged over all areas with vegetation changes.

	RefVeg mean value		**Δ Veg0K-RefVeg**		**Δ Veg1K-RefVeg**	
	MAM *(Warm,Cold)*	JJA *(Warm,Cold)*	MAM *(Warm,Cold)*	JJA *(Warm,Cold)*	MAM *(Warm,Cold)*	JJA *(Warm Cold)*
Near surface temperature [K]	-5.77 (-4.28 , -7.25)	10.02 (11.0, 9.06)	0.10 (0.13,0.07)	0.05 (0.06, 0.03)	0.23 (0.28, 0.18)	0.16 (0.16, 0.15)
Upward sensible heat flux [W m^{-2}]	0.3 (0.1, 0.5)	52.3 (59.2, 45.5)	0.8 (1.1, 0.6)	1.8 (2.2, 1.5)	1.9 (2.4, 1.3)	4.2 (4.5, 3.8)
Upward latent heat flux [W m^{-2}]	6.1 (7.7, 4.5`)	33.7 (34.7, 32.7)	2.3 (2.3, 2,3)	2.5 (2.8, 2.2)	3.7 (3.7, 3.7)	3.8 (4.2, 3.5)
Net short wave down [W m^{-2}]	54.2 (60.2, 48.3)	153.2 (165.4, 141.0)	2.45 (3.18, 1.73)	3.6 (4.26, 2.99)	4.93 (5.98, 3.88)	7.22 (7.86, 6.58)
Net Long wave down [W m^{-2}]	-38.0 (-40.3, -35.7)	-55.45 (-60.8, -50.1)	0.35 (0.09, 0.60)	0.64 (0.59, 0.69)	0.60 (0.16, 1.04)	0.47 (0.53, 0.42)
Precipitation* [mm day^{-1}]	5865 (6496, 5234)	8446 (8090, 8801)	1.07% (1.1%,1.01%)	2.2% (2.4%, 2.06%)	2.5% (2.7%, 1.6%)	4.3% (5.0, 3.7)%
Snowfall* [mm day^{-1}]	4477 (4289, 4666)	274 (328, 220)	1.4% (1.5%, 1.3%)	2.3 %** (3.04%, 1.4%)**	2.8% (3.0%, 2.4%)	3.0%** (3.5%, 1.2%)**
Low cloud coverage (<3km) [fraction]†	0.31 (0.29,0.29)	0.16 (0.14, 0.19)	1.92% (2.06%, 1.85%)	0.81% (1.0%, 0.7%)	3.2% (3.3%, 3.4%)	0.71% (1.0%, 0.5%)
Vegetation buried by snow [fraction]	0.87 (0.78, 0.95)	0.01 (0.00, 0.02)	-0.42 (-0.43, -0.42)	-	-0.52 (-0.49, -0.55)	-

**accumulated values over areas with vegetation changes, **not statistically significant ,†average fraction over model layers below 3km*

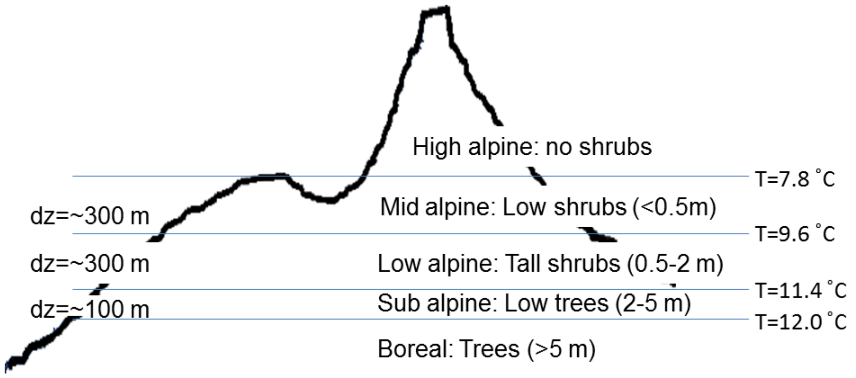

Figure 1: Illustration of alpine zones and corresponding dominating shrub vegetation. The altitudinal extent of each alpine zone is indicated by the values of elevation differences (dz), and corresponding mean JJA temperatures dividing the zones based on mean summer lapse rates in the area.

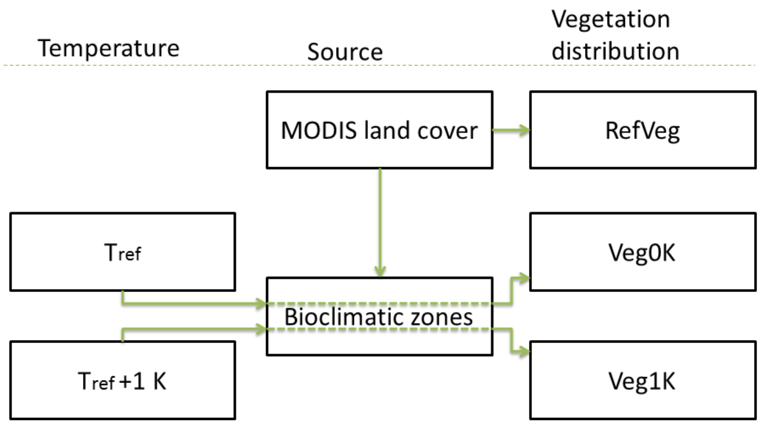

Figure 2. Illustration of the procedure applied to derive the vegetation distributions used in each simulation. T_{ref} is the mean summer (JJA) temperature distribution in the area as averaged across 2001-2010 (from Rydsaa et al. (2015)). T_{ref}+1K is the same temperature distribution, with a 1 K increase. Each of the three distributions has been simulated for two climatically contrasting years (cold and warm), yielding in total six simulations.

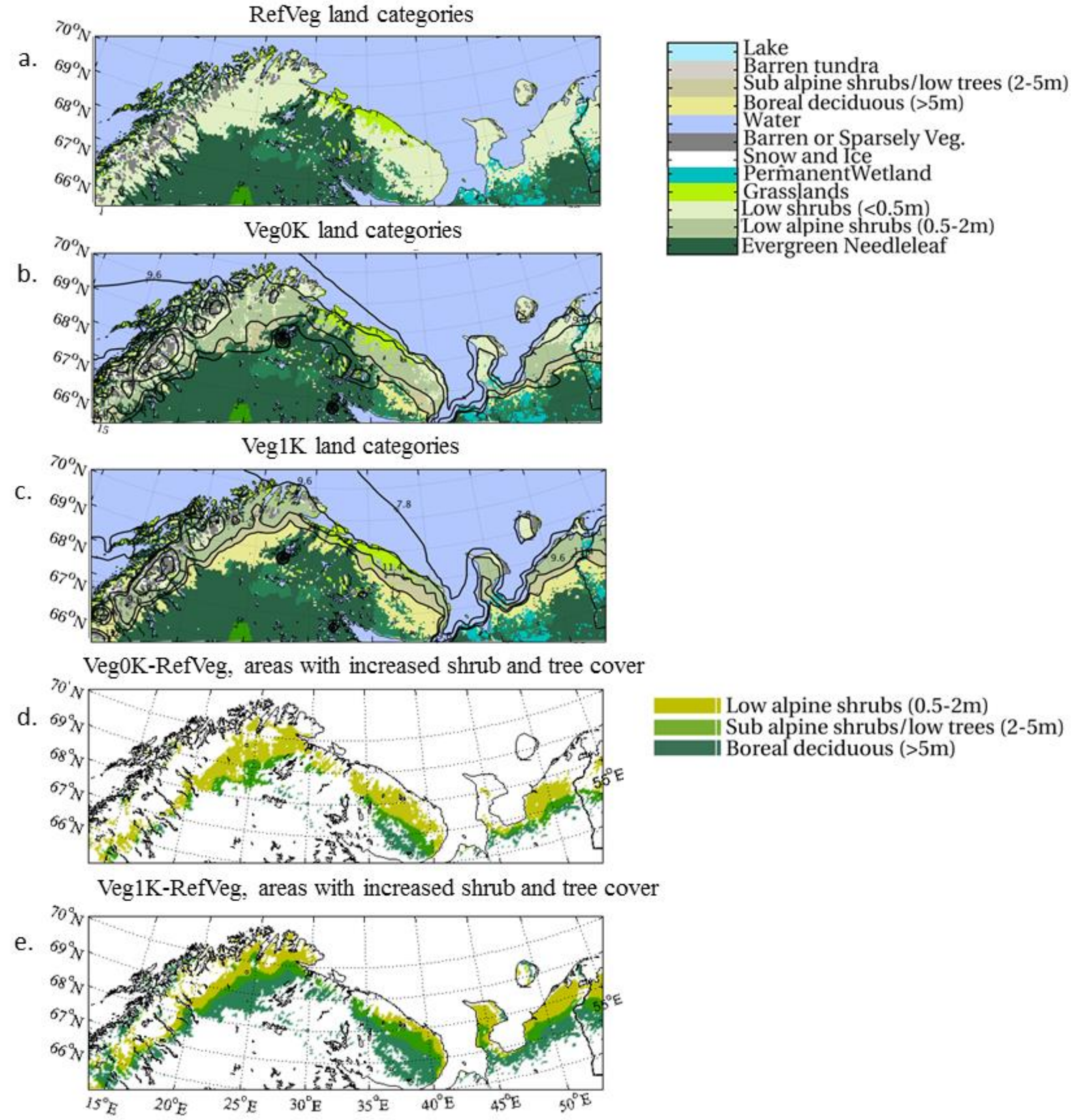

Figure 3: Dominant land use categories (colors) in the a. reference simulations (RefVeg), and as distributed according to the derived bioclimatic zones (indicated by contour lines) in each of the perturbed simulations. Panel b. shows Veg0K distribution, and c. Veg1K vegetation distribution. Only the temperature contour lines calculated to distinguish between the various alpine zones are shown. In the bottom panels only areas with increased shrub and tree cover are colored, to show the difference in vegetation cover between the perturbed and the reference simulations. Panel d. shows Veg0K-RefVeg vegetation changes, e. shows Veg1K-RefVeg vegetation changes.

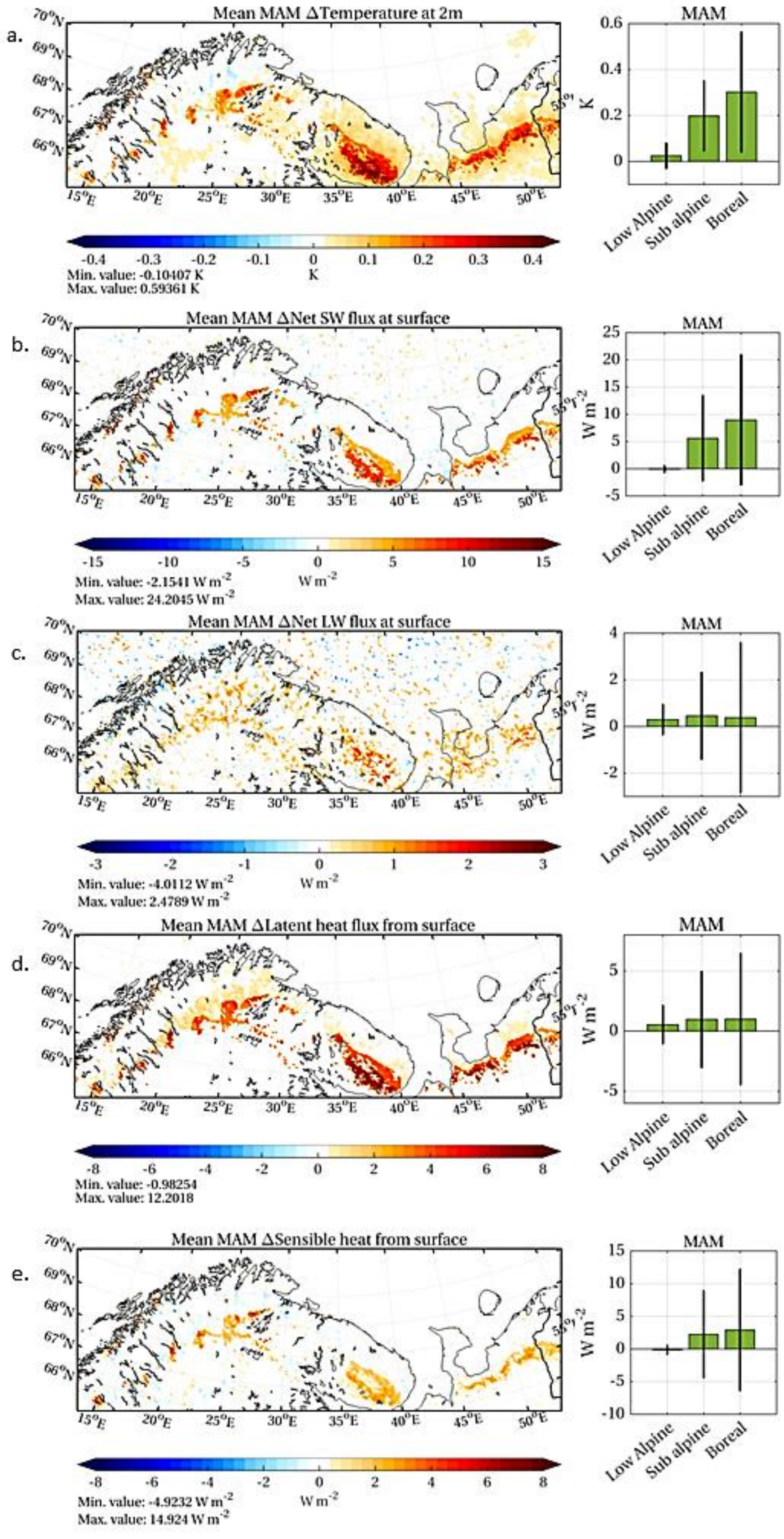

Figure 4: Effects of increased shrub cover (Veg0K-RefVeg) on the MAM season a. 2 m temperature, surface fluxes of b. net SW, and c. LW radiation (both direction downward). Fluxes of d. LH and e. SH (direction upward from surface). The minimum and maximum in mean seasonal values are shown below each map to present the full spatial variation in the average seasonal response. Colors only show significant results at the 95% confidence level based on a Mann-Whitney test of equal medians. Bar plots indicate the mean response as averaged over the separate areas with vegetation changes (black lines indicate one σ range about the mean). Note that scales differ among variables.

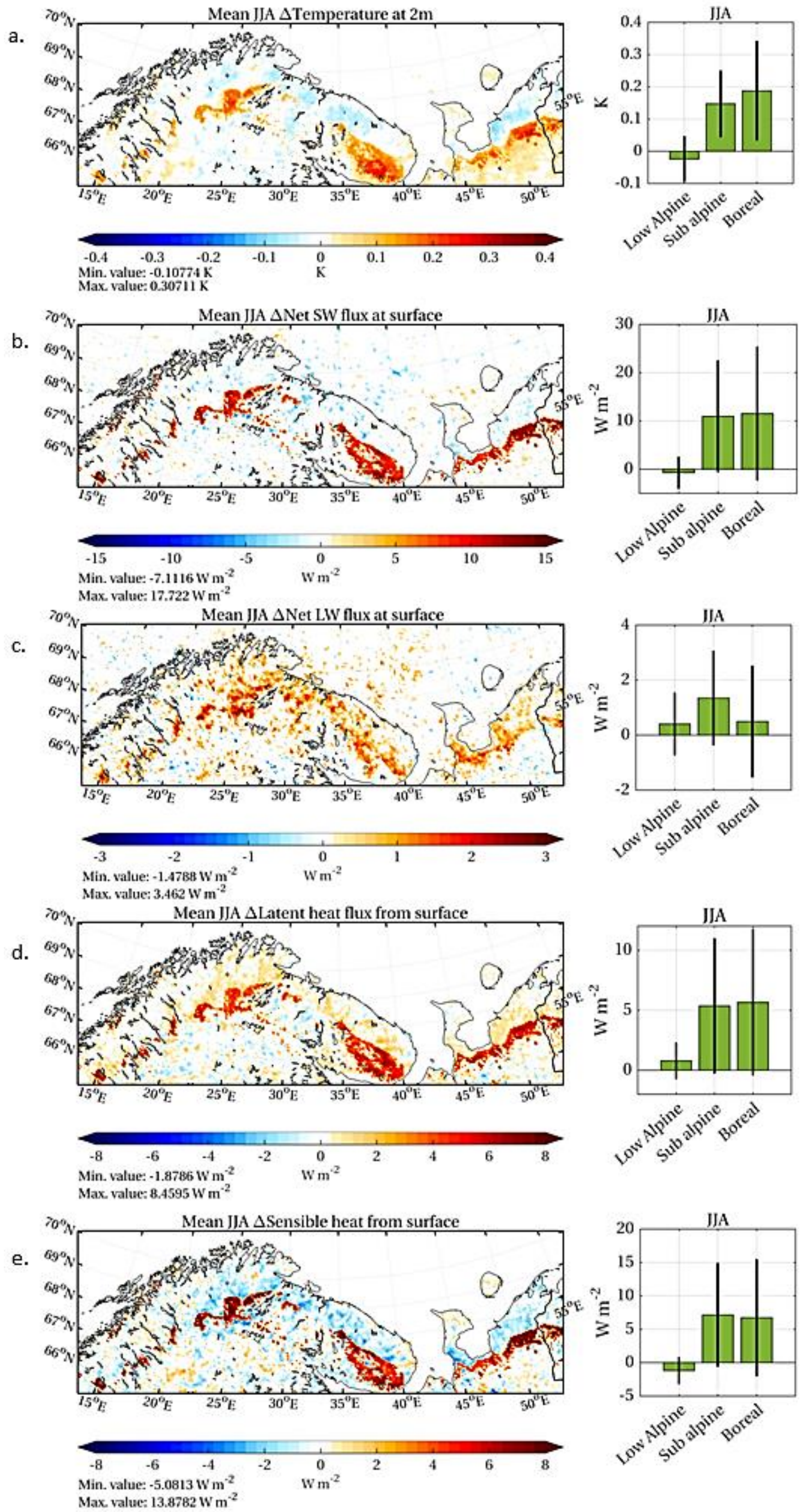

Figure 5. Effects of increased shrub cover (Veg0K-RefVeg) on the JJA season. Variables as in Fig. 4. Note that scales differ among variables.

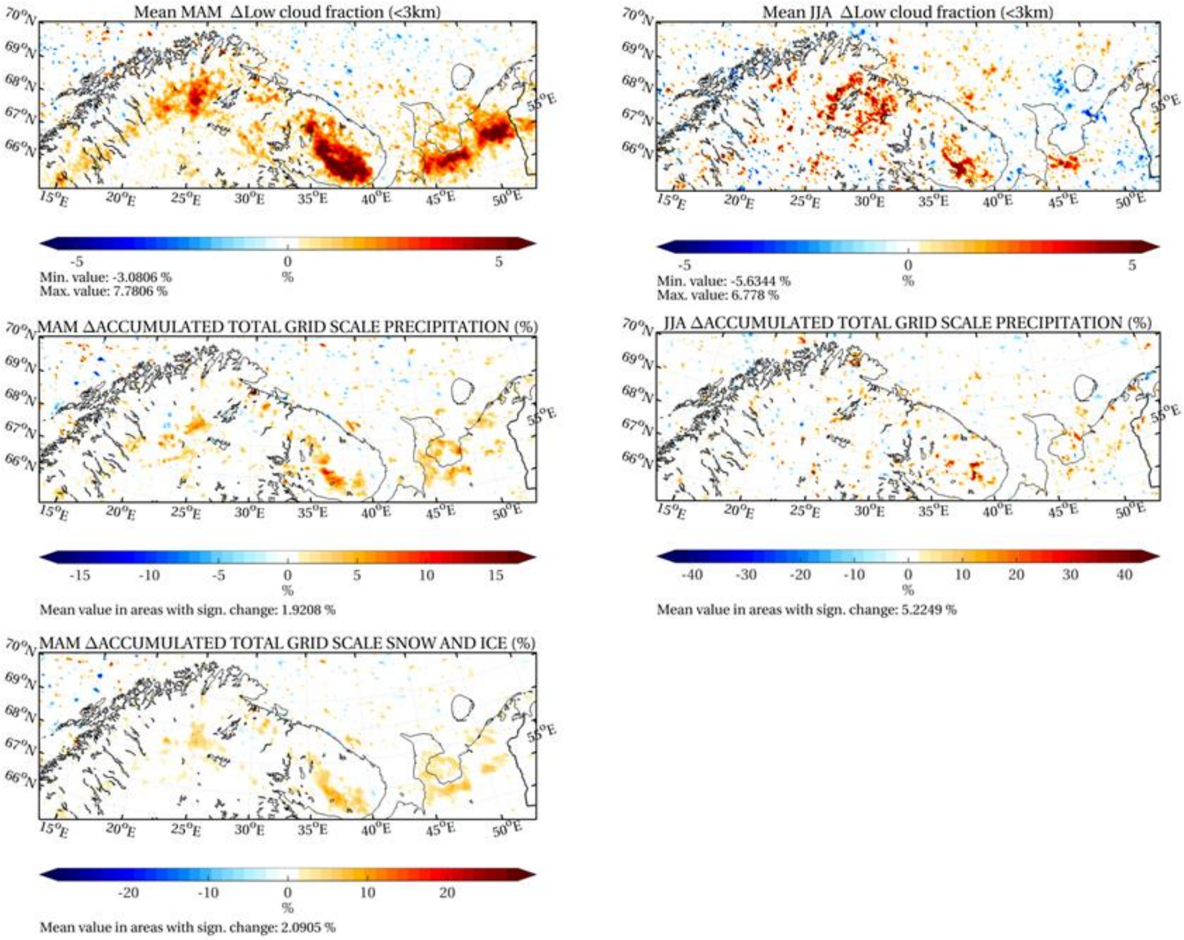

Figure 6. Effects of increased shrub cover (Veg0K-RefVeg) on low level (< 3 km) cloud cover fraction (top row), relative change in accumulated seasonal precipitation (middle row) and spring season snow and ice precipitation (bottom panel). (Only showing significant changes at the 95% confidence level, as in Fig. 4). For precipitation, significance tests are conducted on daily values of accumulated precipitation, rather than three-hourly values. Mean over spring seasons in left column, and summer seasons in right column. Note that scales differ among panels.

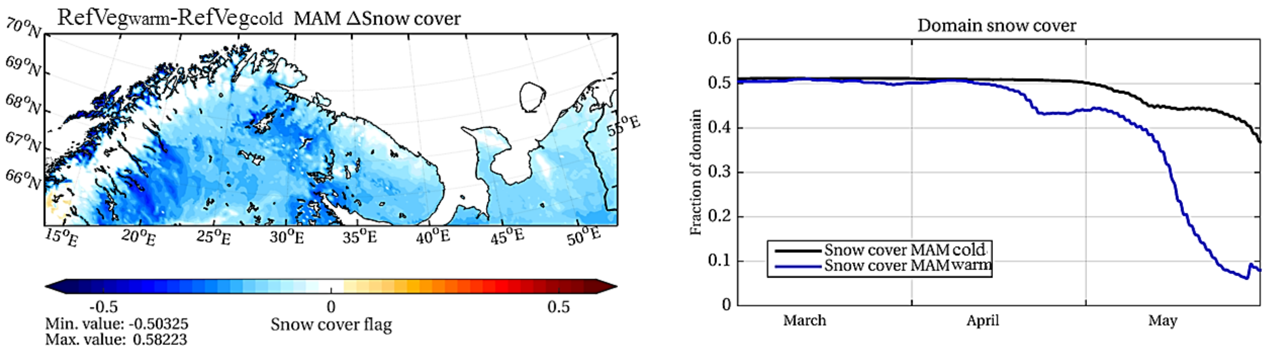

Figure 7: Difference in mean seasonal snow cover between the warm and cold spring season ($RefVeg_{warm}$ –$RefVeg_{cold}$). Mean seasonal spatial differences are shown in the left panel, and the temporal development over the seasons in the right.

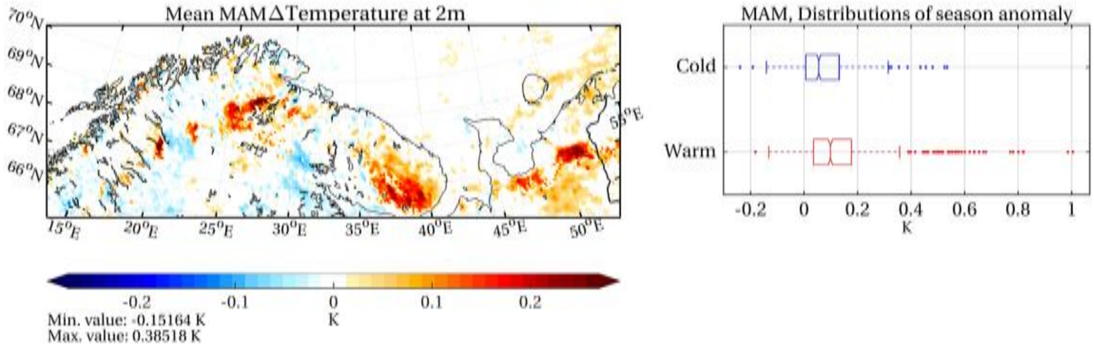

Figure 8: Difference in temperature response due to increased shrub cover (Veg0K-RefVeg) between the warm and cold year (only showing significant results at the 95% confidence level). The distributions of shrub induced anomaly values are shown in box plots, the red box shows warm season anomalies and blue box cold season anomalies in areas with vegetation changes.

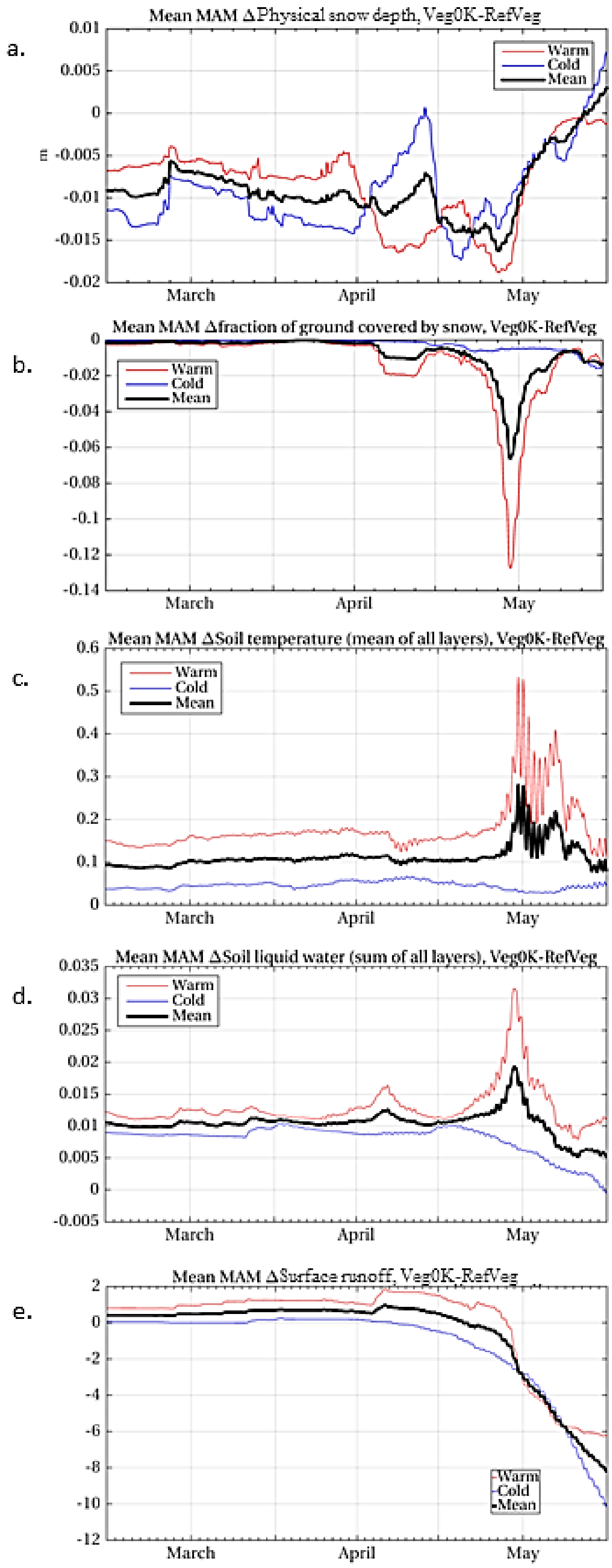

Figure 9: Effect of increased shrub cover (Veg0K-RefVeg) on spring snow depth and cover, soil temperatures and moisture content and surface runoff, as averaged over all areas with vegetation changes. Red and blue lines indicate warm and cold season response, respectively. Black lines indicate inter-seasonal means.

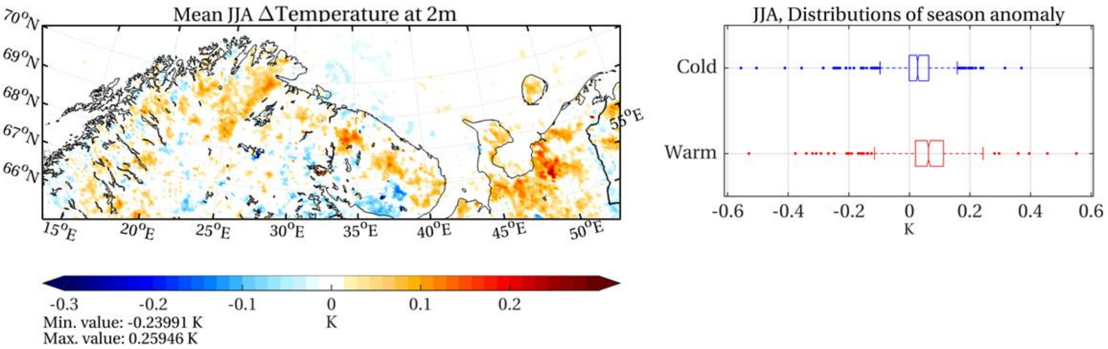

Figure 10: Difference (ΔT2mwarm-ΔT2m cold) in temperature response due to increased shrub cover (Veg0K-RefVeg) (only showing significant results at the 95% confidence level, as in Fig. 4). The anomaly distribution across the domain is shown (right panel), red box shows warm season anomalies and blue box cold season anomalies in areas with vegetation changes.

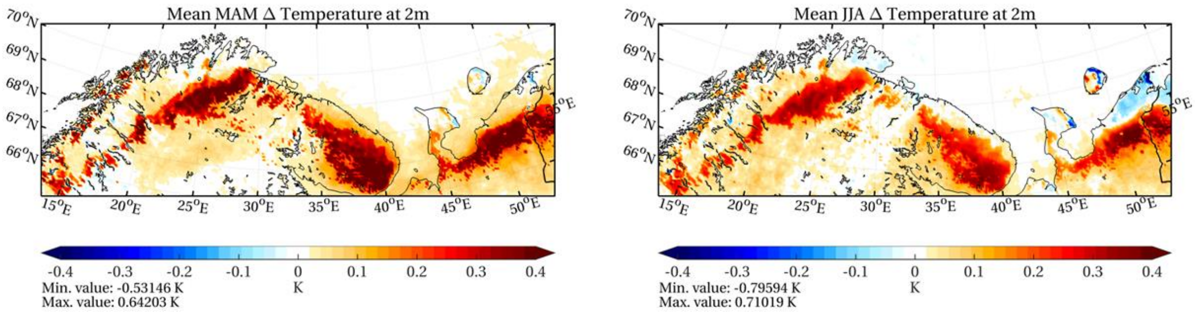

Figure 11: Effects of increased shrub cover (Veg1K-RefVeg) on the 2 m temperature resulting from a shrub and tree cover increase corresponding to a 1 K warming of JJA temperatures (only showing significant results at the 95% confidence level, as in Fig. 4). Mean spring season response is shown in the left panel and mean summer season response in the right.