

5 *Firstly, we would like to express our sincere gratitude towards the two anonymous referees for taking the time to review our study, and for the constructive suggestions and comments to improve the manuscript. See point-by-point replies to the comment below, answers are given below each cited comment in italics.*

Answers for anonymous Referee #1

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10 “Rydsaa et al. present an interesting investigation into changes to the near-surface atmosphere resulting from vegetation change, with a particular focus on near-surface temperatures. They use the WRF model to compare simulations where the vegetation extent is (i) based on present day climate distributions, and (ii) relating to a 1K increase
15 in summer temperatures, relative to the current vegetation distribution. The authors also considered the sensitivity of this response to inter-annual variability. Based on the results presented in this manuscript, the authors suggest that tall shrubs are key to a summer warming feedback but that the main impact of shrub expansion is on advancing the onset of snowmelt in the spring, thus inducing a positive feedback to
20 spring temperatures. In terms of inter-annual differences, the authors propose that their results show that the warm summer-tall shrubs feedback is consistent across warm and cold seasons. They finish by proposing that their findings show “a clear potential for a so-called vegetation-feedback tipping point”.”

25 *We are glad that the reviewer finds the study interesting. The reviewer has clearly taken the time and effort to get to know our study very well, and we truly appreciate this and the following thorough review of the manuscript.*

30 “In order for this paper to be acceptable for publication in Biogeosciences, the following major revisions are required:

1. Ideas are not always introduced in a logical manner, and the text is frequently hard to follow. Moreover the writing style needs to be more concise to improve clarity and flow of ideas (See detailed line-by-line comments for examples). It would also be nice
35 to see some hypothesis or specific research questions clearly stated in the introduction and these used to structure the subsequent results and discussion. This would greatly facilitate the overall readability and coherence of the work, but will require some major structural changes to the manuscript to be achieved.”

40 *The text has now undergone a thorough revision for the purpose of increased readability. We have also adjusted and re-organized the manuscript to further clarify the focus and ideas behind the study, by 1. rewriting the introduction to better introduce the main research questions, and 2. change the headers in the methods section and re-organize the text, 3. changed order of figures in methods section and 4. change the flowchart in what is now
45 Figure 2. Furthermore, we have re-arranged parts of the results presentation and discussion to follow up on the structure presented in the research questions and methods section.*

50 *The language has been examined and clarified throughout the manuscript, and certain sections have been substantially shortened in the process. We sincerely hope the reviewer agrees that the revised manuscript improved and more easily accessible.*

5 “2. Central to this work is the assumption that published climate envelopes for vegetation
types in Norway are sufficient to predict changes in future vegetation when
mean summer temperatures are 1K warmer. However, the authors show significant
discrepancies between the present-day vegetation distribution and that expected from
the climate envelopes based on present day climate. This suggests that either (i) the
climate envelopes are inappropriate, or (ii) the present-day vegetation is out of equilibrium
with the present climate – perhaps due to warming that has already occurred. The
10 former case presents obvious difficulties for the use of these climate envelopes. In the
second case, it seems somewhat unrealistic that the vegetation will have had time to
adjust to the scenario indicated by the climatic envelopes under 1K warming, given the
timeframe over which 1K warmer summer temperatures will be achieved. As it stands,
this study is limited in how much can be drawn from the ‘future’ distribution based on
15 the climatic envelopes associated with a 1K increase. There needs to be significantly
more discussion of the limitations of using climatic envelopes and justification of their
use.”

20 *As pointed out by the reviewer, we realize that our use of bioclimatic envelopes in this work
has not been properly introduced and explained, and the background for each of the
vegetation distributions not well enough distinguished. As mentioned in the original
manuscript (but not adequately emphasized), the vegetation distribution in the reference
simulations are based on the MODIS land use dataset (Broxton, 2014), which represents
present day vegetation distribution (which one can only speculate to which degree is in total
25 equilibrium with present day climate or not, as several other factors are also influencing the
shrub cover, as explained in the introduction). As a satellite based dataset, it is not
specifically linked to summer temperatures or bioclimatic envelopes and cannot be expected
to be in complete equilibrium to the 10 year mean summer temperature based bioclimatic
zones developed for the purpose of this study. Although this vegetation distribution in our
opinion serves well as a reference point for our vegetation perturbations, one original
30 limitation to this dataset with respect to our study, is that it has only one shrub vegetation
category representing the tundra area of interest here (with shrub heights of <0.5m). To study
the effects of different shrub heights on the atmospheric response (research question 1.a), we
found it necessary to split this shrub class into three sub-classes with different heights; sub
35 alpine, low alpine and mid alpine shrubs. In order to distribute these across the shrub
covered area as defined by the MODIS dataset, we applied the simplified “bioclimatic
envelopes” based on the key criteria of mean summer temperatures, in combination with
empirically derived temperature-vegetation relationships from the region (as further
explained in the Methodology section).*

40 *We realize that the distinction between the use of the MODIS dataset (which is not based on
bioclimatic envelopes) and the vegetation perturbations applied to it (which are based on a
key bioclimatic criteria; summer temperatures which represents a simplified bioclimatic
envelope) was not properly introduced in the manuscript, and appeared confusing.*

45 *This has been clarified in the revised manuscript, both in the new “Study design” section
(2.1) and by adding a further explanation of this in the “Land use and re-distribution” section
2.3. Furthermore, it is illustrated in the flowchart figure (now Figure 2.)*

5 *We hope the reviewers agree that given this distinction, there is no discrepancy in the use of bioclimatic envelopes between the reference simulation and the perturbed simulations, rather bioclimatic envelopes are used as a refinement on the original, satellite-based dataset. However, following the reviewer's suggestion, this side of the study and its potential limitations has been discussed further in the revised manuscript.*

10 *With respect to the original 1K "future" scenario, we do agree with the reviewer in that results from this experiment should be interpreted with care (as highlighted in the Discussion section).*

15 *The manuscript has been rewritten to emphasize this, and to more clearly highlight the actual purpose of this experiment; The vegetation perturbation produced from the 1K perturbation to the mean summer temperatures were applied as a sensitivity experiment, rather than to represent a pseudo-realistic future scenario for vegetation distribution in the area. As such, we have made no assumptions of a specific timeframe for this vegetation distribution. However, as a temperature increase is a very likely part of future climate conditions in this area, the loose term "future scenario" was used to describe it, yet the aim was rather to take into account an assumption of uncertainty in the shrubs' response to summer temperatures as a key environmental condition. However, we argue that valuable information about potential future feedbacks can be inferred by interpreting the results from the two different experiments.*

25 *The description of this experiment in the introduction and in the study design sections has been clarified and rewritten to better reflect this purpose, rather than emphasizing the "future" aspect. In addition, the results and the discussion sections have been rewritten (both headers and text) to better present the experiment in the proper context.*

30 "3. It is stated that only the vegetation distributions are altered and that the simulations are identical in all other respects. This suggests that your model is being forced with present day climate for both the reference and 1K runs, i.e. you are measuring the strength of the vegetation feedback under today's climate. However, of interest is the strength of the vegetation feedback in a 1K warmer climate. To assess this, surely the driving meteorological data need to reflect this 1K warming (and associated changes in winter climate and snow cover)? I suggest that you run a new 1K reference simulation with the present-day vegetation distribution and met data reflecting the 1K warming. This would still allow you to isolate the vegetation feedback, under a more meaningful scenario."

40 *We agree with the reviewer's opinion that the strength of the atmospheric feedback might vary under different climatic conditions. This was exactly our reason for choosing to simulate our reference and perturbed vegetation distribution under varying climatic conditions, by choosing two contrasting years with respect to snow cover and summer temperatures. The contrasting response between the two years will give an indication of how sensitive the feedback strength is to variations in the climatic conditions, whether they arise as part of the natural present climate variability, or represent some future mean state or condition.*

50 *Although the perturbations to the vegetation distribution in the two sensitivity experiments are based on a shift in the bioclimatic envelopes corresponding to a 1K difference in mean summer temperatures, the goal of investigating feedbacks under varying climatic conditions is not particularly linked to a 1K general warming of the climate. The temperature difference*

5 between the two contrasting years chosen here more than covers the 1K temperature difference chosen to perturb the vegetation cover (as shown in the results section). Rather than representing a particular shift in temperature, it represents the natural variability in temperature in this area over a 10 year period. However, our motivation is that the difference in response particularly across the warmer versus the colder year, may serve as an indicator of potential differences in feedback mechanisms that dominate in a warmer versus a colder climate.

10 The reviewer suggests an approach to investigate this aspect of the feedback sensitivity, by making another reference simulation with met data reflecting a 1K warming. It is not clear whether the suggestion inherits a perturbation of met data (which could prove problematic in comparison with the other simulations in principle, as this would force the regional model with “unrealistic” meteorological conditions), or if the reviewer in fact suggests a similar approach as the one we have chosen yet apparently failed to properly communicate.

15 We acknowledge that this side of the setup/approach was not introduced clearly enough in the original manuscript, and in the revised manuscript, more emphasis has been put on this aspect of the setup in both the introduction, study design section, results section and in the discussion. The different response across the two contrasting years has been more emphasized, and the context/meaning of this investigation has been highlighted. We hope the reviewer agrees that this is a sound approach to answer this research question.

25 “4. The introduction highlights the importance of soil properties in determining the distribution of shrubs and their response to changes in climate, in particular drawing attention to soil moisture content, in addition to mean summer temperatures, as key drivers of shrub expansion. This study explores the effects of increased summer temperatures (by 1K). However, it is not clear that the influence of soil properties is taken into account regarding the perturbed vegetation simulations, although this will surely be an important constraint on future distributions. “

30 As referred to in the introduction, both soil moisture content and summer temperatures have been shown to be important factors in regulating shrub expansion. In this study we have chosen to use only mean summer temperatures to derive our “simplified bioclimatic envelopes” used to perturb the vegetation distribution. This has been clarified in the revised manuscript, particularly under the section “study design”. The effect of soil moisture in the system is taken into account in the model simulations, and feedback to the soil moisture is briefly shown in the results. However, in the “simplified bioclimatic envelopes” as defined and used here, the soil moisture content is not a determining factor. We completely agree with the reviewer (and cited literature) that in a more realistic future scenario it would certainly be an interesting factor to include. Also, in the study region of interest here, other factors such as herbivory by reindeers could possibly play an equally important role, however a further investigation into these factors is not the aim of the present study (as also noted in point 1 by Reviewer#2).

45

Detailed comments

Abstract

We agree and the abstract has been rewritten in accordance with the reviewer's suggestions. The abstract has also been revised to better fit with the restructuring of the rest of the manuscript.

5 "P1L11 Specify that you are evaluating the sensitivity of near surface atmosphere /
Temperatures

Corrected

10 P1L12 Specify that these are model experiments

Corrected.

P1L21 Shortwave radiation instead of SW would be clearer

Corrected

15

P1L22 "shrub and tree heights, which lower the surface albedo"

Revised in accordance with the reviewer's suggestion

P1L28 Be more specific –a role in what?"

20 *We agree that this was vague and have adjusted the abstract accordingly. Added; "...role in land-atmosphere feedback processes..."*

Introduction

25 "P1 L34-6 Writing style needs to be more concise"

The section has been revised, and a thorough review of the language has been conducted throughout the manuscript.

30 "P2 L6 You mention biochemical effects here but nowhere else. Can you provide some references for this opening sentence?"

As the biochemical effects are not addressed in this manuscript, the phrase has been removed to avoid confusion.

35

P2 L7-8 The increase in radiation absorption is due to the decrease in surface albedo –please structure the sentence to reflect this.

Corrected

40 P2 L12 "influence the melt and sublimation" this sentence is quite vague –can you specify what this influence is (i.e. does it enhance or reduce melting/sublimation)

Re-phrased for clarity

45 P2L15-16 Provide a reference for this.

The paragraph is rewritten for clarity, showing that this statement is referring to the findings in the Sturm paper cited.

P2 L16 Missing punctuation.

50 *Corrected*

P2 L21 “speed the melting season” –this is unclear, do you mean that the onset of melting is advanced or that the melting season is shorter and more intense?

5 *Both the onset and rate of snowmelt is meant, and clarified in the revised manuscript.*

P2 L24-39 Provide more information regarding the climate scenarios these vegetation increases related to (i.e. how many degrees increase in temperature) –this will provide better context for your own study

10

The mentioned modelling studies do not put their shrub expansion experiments in relation to a specified climate scenario or temperature increase, rather that the shrub expansion is a result of some hypothetical future climatic state (the year 2100 is mentioned in one of the studies). In this respect, their approach is similar to ours, and therefore, in our opinion, these studies serve as excellent studies for comparison to ours.

15

P3 L4 coupled “with” not “to”
Corrected

20 P3 L9-12 Please provide a reference(s) to support/illustrate this”

References inserted

25 “P3 L31 “Also based on dendroecological observations in northern Scandinavia” is misleading as the study discussed just previously (Myers-Smith 2015) was based on data from across the circumpolar region, not just northern Scandinavia.”

This is a good point, and we acknowledge that this was not made clear. It has been adjusted as suggested.

30

“P4 L 6-7 This spatial resolution cannot resolve “fine scale features of vegetation change”, which will be occurring on much smaller scales than the model grid size”

35 *This is of course a valid objection, and this statement was written in comparison with previous, coarser scale studies in mind. However, the sentence has been rewritten for clarity and the role of resolution more appropriately addressed to reflect the comparison.*

40 “P4 L12-18 This paragraph could be clearer in its presentation of the main aims of the study. In the methodology you state that differences between seasons are of particular interest, but this is not mentioned in this paragraph. You should list the hypotheses that are tested in the manuscript here (this will also help provide a structure to your discussion section, relating yours results to the research questions).”

45 *We agree with the reviewer that a more clear presentation in this paragraph greatly benefitted the total readability and re-structuring of the manuscript. As mentioned in point 1. above, the more clear structure in the presentation of both the purpose and corresponding setup presented above has been added to the revised manuscript, and followed up throughout the methodology section and in the presentation and discussion of the results.*

50

Methodology

“P4 L22-24 This needs to be explained more clearly, i.e. how do the vegetation change simulations differ from one another

5 *The difference between vegetation distributions have been more clearly presented and ideas behind them more appropriately introduced in both the introduction and in the study design section.*

P4 L36 Requires references to said studies”

10

P.4, Line 38: References inserted.

“P6 L10-11 “Alterations in the atmosphere results from the biophysical changes related to the applied vegetation perturbations alone” –does this mean that in simulations where the vegetation is prescribed based on a 1k increase in summer temperature, you do not adjust the forcing met data to reflect this?”

15

As discussed in the points above, yes, the reference and perturbed simulations are run with the same meteorological forcing to isolate the effect of vegetation perturbations on the atmosphere. However, the sensitivity of the feedbacks related to variations in climatic conditions such as the temperature are investigated by choosing two contrasting years (2003 and 2008) with respect to temperature and snow cover.

20

“P6 L19-23 This is not clear”

25

P6, line 35-38: Rewritten for improved clarity.

“P6 L19 The authors define vegetation categories according to “empirically derived climatic vegetation zones” –they cite Bakkestuen et al 2008 who develop a model for vegetation variation in Norway. It is not clear during the methodology section whether the “empirically derived climatic vegetation zones” are from Bakkestuen et al. 2008 or are derived by the authors.”

30

It will be clarified in the revised manuscript that we have followed a comparable approach as Bakkestuen et al, in deriving our simplified bioclimatic zones. However, whereas Bakkestuen et al. derived their bioclimatic zones from a multitude of climatic and other variables (temperature, precipitation, snow cover, geology, topography etc.), the presented zones were purely based on summer temperature.

35

“P7 L4 Should be “e.g. see”
Corrected

40

P7 L23 Specify the increase in JJA 2 m temperatures applied”

45

Clarification added,

“P7 L34 I’m not sure what you mean here

The sentence was unclear and unnecessary and has been removed from the revised manuscript

50

P7 L36-38 Shouldn't the forcing met data reflect the temperature increase in the Veg1K simulation?"

5 *As explained above, the feedback sensitivity to temperature is investigated using the two contrasting years of met forcing data.*

Results

"P8 L2-3 This should be explained properly in the methodology
Section has been moved up to methods section.

10

P8 L8-10 Refer to table 2 here
The section has been rewritten for clarity, and reference to Table2 inserted below.

P8 L25 Remove "also"

15

Corrected

P8 L27 Refer to specific plots, e.g. using lettered plots
Lettered plots incerted, and references updated accordingly

20

P8 L35 Reference to Fig. 7 not Fig. 6
Corrected

P9 L4 Reference to Fig. 4 not Fig. 3"

Corrected

25

"P9 L14 "These areas" –do you mean areas with low alpine shrub expansion?"
Yes, and clarification has been added, in addition to other adjustments to the section.

"P9 L22-23 ". . . the small albedo decrease associated with the low-alpine shrub increase.

30

The areas with taller shrubs and trees on the other hand, are characterized
by a decrease in snow cover throughout the spring and summer seasons due to a
stronger albedo decrease (Fig. S4)" –I can't see how this figure specifically shows the
different albedo effects associated with these vegetation types (i.e. low-alpine shrub
vs. tall shrub and tree)"

35

*The spatial distribution in mean seasonal albedo changes are shown in the bottom panels.
Each area with vegetation changes can be recognized by comparing with e.g. Fig. 3.*

"P9 L27 Add parenthesis"

40

Corrected

"P9 L29-30 "The increased SH mainly acts to heat the lower atmosphere within the
boundary layer, while the LH is also released above the PBL height" –it's not clear
where this result comes from"

45

*This is not specifically shown here, but more a reference to general meteorological processes.
The sentence has been rewritten for clarity:*

P. 9, lines 38-40 “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.”

5 “P9 L37-39 The figures you refer to do not show the results you present in the manuscript text here (net not incoming SW and LW)”

P.10, Lines 10-12: This is not specifically shown here, but provided as additional information to explain the results. This is clarified in the revised manuscript.

10

“P10 L3 You refer to “increased shrub cover”, do you also mean increased tree cover here too? Later on in this paragraph you refer to “vegetation changes” and on L38 you talk about “increased shrub and tree cover” –are you using these three phrases interchangeably or do you mean something different in these instances? It is not clear. Also, please specify which simulation these results are from (I presume Veg0K – RefVeg).”

15

Yes, the three phrases are, somewhat confusingly used interchangeably, as the reviewer points out. The revised manuscript has been rewritten towards a more coherent presentation of the vegetation changes applied.

20

“P10 L 5-6 It is not clear from just looking at Fig. 7 that the low cloud cover increase is predominantly occurring over areas of vegetation change –you should at least refer to the bottom panel in Fig. 1 that shows this or include it again in the empty plot of Fig. 7 for easy reference.

25

A reference to the maps in Fig. 3 has been inserted in the revised manuscript.

“P10 L13-14 “This indicates”. If the only thing that you changed between the two simulations was the vegetation cover, then surely then all the precipitation change must be attributable to this? What else would have caused it if all other variables were kept constant?”

30

We acknowledge that this is vague, as the referee correctly points out, the changes are caused by vegetation changes and feedback mechanisms related to these. The sentence has been omitted from the revised manuscript as it was misleading.

35

“P10 L15-18 What do you mean by “summarized”? Looking at Table 2, the 2.2% increase is the averaged change over all areas with vegetation changes and over both cold and warm summer seasons.

40

By “summarized”, we refer to the fact that rather than averaging over the areas with vegetation changes, as with the other variables, it was more informative to summarize over these areas for this particular, accumulated variable. The sentence has been rewritten for clarity in the revised manuscript.

45

You only provide the warm spring increase in precipitation (1.1%), why not the change averaged over both warm and cold seasons in this case? This is not consistent with your presentation of the summer result.

The number has been changed for the mean value, as suggested for consistency.

50

The 1.4% increase in snow and ice appears to be from the cold summer season (looking

at Table 2), why did you select this specific value? Per Table 2 this is not a statistically significant finding, yet the p value you present in this paragraph is ($p = 3.19 \times 10^{-9}$).”

5 *The 1.4% was referring to the increase in spring average snowfall, however, Table 2 said 1.3%, due to a round-off error, which is now corrected. P-values for some of these numbers have been omitted in the revised manuscript, for improved readability, as they were not necessary.*

10 “P10 L20-25 Be clear that you are discussing the RefVeg simulations here

Clarification in the form of simulation abbreviations have been added.

15 P10 L 22 “and a 3.1K warmer 2 m temperature, on average.” Looking at Table 2, the difference seems to be 2.97K ?

These are numbers that are based on the domain as a whole (as they are not linked to the experiments as such) which has been clarified in the revised manuscript.

20 P10 L27-28 Be clear that you are discussing the RefVeg simulations here

Clarifying references to simulation names have been inserted for clarity.

25 P10 L28 Be more specific –how many days earlier?

We refer the reader to the figure for more exact numbers.

P10 L39 Spatial pattern of snow cover shown by Fig. S3 not the spatial pattern of snow Depth

This is an excellent point, we have revised the manuscript to account for this.

30 P11 L11 Please indicate the subplots of interest here, e.g. Fig. 10 c & d”

Figure and references have been adjusted in accordance with the reviewer’s suggestion.

35 “P11 L21-26 The temperature values presented here do not match those given in Table 2. I presume this is because the Table values are means over areas with vegetation change only whereas in this paragraph you are presenting values for the entire model domain –is this correct? It is not clear why you are not consistent here, particularly as for precipitation you refer to Table 2 rather than continue with giving whole-domain values.”

40 *The numbers presented here are not particularly related to the experiments or the areas with vegetation changes, as they are given as a summary of the mean differences in the climatic conditions between the two contrasting years in the area as a whole. Therefore, they are given as domain averages (only land areas) and not related to areas with vegetation changes specifically, as the case in the previous section. We have clarified this in the revised manuscript, following the reviewer’s constructive comment.*

50 “P11 L 36-38 If snow conditions are important then surely you need to take into account

that temperature increases during the winter months are projected to be much greater than 1K in your Veg1K simulations.”

5 *The differing snow conditions are a direct result of the differing temperatures between the warm and cold years selected here. The simulations span the whole snow accumulation season (from November), even though only spring and summer are in focus here, and is as such taken into account. The span in temperatures between the two spring seasons are greater than 1K, as explained in the first paragraph in Section .3.2. This sentence is only meant to summarize the findings in 3.2 and 3.3 by highlighting which meteorological condition that seems to have the greater effect on the atmospheric response and is further explained in the revised manuscript (P.12, lines 1-5).*

15 “P12 L2-4 This would benefit from a figure illustrating this change in the vegetation, i.e. such as in the bottom row of Fig. 1

An additional panel is added to Fig 1(which is now Fig.3) to more clearly show the areas referred to in this section. A reference to this figure is also added.

20 P12 L11-12 This is confusing as both vegetation simulations (Veg0K and Veg1K) represent a “future” scenario? Or at least, Veg0K does not reflect the present-day vegetation distribution but the distribution that one would expect given our present-day climate.”

25 *We acknowledge that this side of the study design was not properly explained in the original manuscript, and a thorough revision has been made to better explain this in the revised manuscript (see also above, points 1 and 3).*

30 “P12 L14-16 The second sentence (“Therefore average spring season heating is therefore strongest in areas with the tallest vegetation”) does not logically follow on from the sentence preceding it. Also, over-use of “therefore”.

The sentence has been rewritten for clarity. (P.12, lines 20-22)

35 P12 L16-18 But what about the spread of temperatures. So, the highest temperature is found in Summer but in Fig 12 it looks as though this is very localized and that during the Spring more of the domain experiences higher temperatures.”

We completely agree with the reviewers point, and have clarified this in the revised manuscript. (P.12, lines 18-25)

40 “P12 L20 Why is this not included in the supplementary material?
We found that the figure was very similar to the one with the net LW, and as such contributed little to the manuscript.

45 P12 L28 Start your discussion off with a summary of your major findings in the order they were presented as hypotheses in the methods section.”

We appreciate the reviewer’s suggestion and have re-organized and rewritten the entire discussion in accordance with the revised introduction, as suggested.

50 “P13 L 17-19 Needs re-wording

Corrected

P13 L21 The authors don't change the greenness factor of each grid cell between the simulations, this seems strange as you would expect a 'greening' effect with the 1K increase?"

5

The reviewer makes a good point, and we acknowledge that there are many possible ways to make perturbations to the vegetation cover within this model framework. Here, our choice of only altering the type of vegetation is that this will indirectly lead to a modelled alteration of vegetation properties related to greenness (i.e. LAI, height, shading factor etc.), all properties that we through a thorough review of the literature have sound scientific basis for changing. Also, the perturbations made here are sufficient to give answers to the research questions in focus here. The "greenness factor" variable in this model setup is related to the overall density of vegetation in a grid cell, i.e. is based on an entirely different satellite dataset and also has a monthly varying distribution, and is used to scale other vegetation-type specific variables in time. We found it difficult to base any alterations to this distribution on empirical or theoretical arguments. Although, as the reviewer points out, one could expect a change in what this variable represents, it is hard to estimate to which the degree this would occur, and whether it would be in addition to, or instead of, the changes already taken into account. Also, another reason for making the perturbations as simple and concise as possible is the interpretability of the results, and as such, we found that changing the vegetation type (and corresponding properties) was more beneficial. However, the results are carefully interpreted with the model setup and its possible limitations to this in mind. A short discussion of this issue has been included in the revised manuscript, and a consideration of both greening and the opposite; a browning is inserted.

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"P13 L30 ". . . areas with increased tall vegetation"

Corrected

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P13 L31 ". . . related to increased low shrub cover. . ."

Corrected

P13 L32 "enhanced" rather than "added". What is the balance between these two factors during the spring season?"

35

Corrected, and a clarification and further explanation of the balance is added and lifted up to the first paragraph in the Discussion section.

"P13 L 36 What do you mean by "despite the snow masking effect in winter"? Also, you did not analyze winter months in this study. The final part of this sentence doesn't make sense: "the deciduous nature of the northward expanding shrubs and trees in this study, which is based on what is observed in the study region""

40

This paragraph has been rephrased for clarity. See also point below.

45

"P13 L38-40 They haven't allowed for expansion of needle leaved trees –is this reasonable?"

In this study the aim was to look at vegetation changes related to the expansion of shrubs (area and height) and low trees in the tundra region specifically. Also, the northern Fennoscandia region is dominated by mountain birch forest, which is deciduous. Whether the simultaneous northward migration of evergreen needle leaved trees would give a more

50

realistic vegetation distribution given our climatic conditions would certainly be interesting to look at, but is besides the aim of this study. This choice of limitation has been added to the discussion in the revised manuscript. (P 14, lines 15-25)

5 “P14 L18 Clarify that you are talking about changes in SW and 2 m temperature, i.e. a reduction in early summer

Clarified in the revised manuscript.

10 P14 L21 Remove “also”
Corrected

P14 L26 “we note that they observed a substantially larger response in soils temperatures than was shown in our results””

15 *Suggestions are appreciated and adjustments to the manuscript added.*

“P14 L36-37 Can you provide the equivalent percentage shrub increases for your simulations to aid comparison with the studies discussed here?”

20 *We could add an area extent or a percentage number for comparison as the reviewer suggests, however we are reluctant to do so for the following reason; The papers cited here have looked at the entire circumpolar area, and made adjustments to the vegetation cover that differ substantially in nature from the ones applied in our study. A percentage number relating the areal extent of changes to the entire study domains would as such aid little in comparing the studies, and on the contrary give rise to an unfounded expectation of similarities in the results. As the studies share a similar aim (i.e. to study the feedback effects of high latitude vegetation changes on the atmosphere), an overall comparison of the atmospheric effects are defensible. However, a more close and qualitative comparison of the applied changes in vegetation distribution between the studies could potentially be more misleading than beneficial, in our opinion.*

35 “P15 L1 “The response of shrub expansion” –this doesn’t make sense; the response of what to shrub expansion?

P. 13, line 32: Added: “The atmospheric response to shrub cover increase”

P15 L2-3 More moderate than what?

The paragraph has been rewritten for clarity (P. 13, Lines 32-37)

40 P15 L6 Remove “were related to” and change to “are occupied by””
Rephrased for clarity.

“P15 L18 Change 0.04 to 0.05 as per Table 2

45 *Corrected*

P15 L14 “we find” This is the first time a time lag is mentioned. What sort of time-lag –provide an estimate.

The sentence has been omitted during rewriting of the Discussion section for the revised manuscript.

5 P15 L33 Remove “have”
Corrected

P15 L34 Change “in evaluating” to “to evaluate”
Corrected

10 P15 L35 Remove “have”
Corrected

15 P16 L12 You stated in your results that this increased snow cover was due to “increased snow fall in the cold season and possibly the increased shading effect of the shrubs” whereas here you are implying it is entirely down to shrub expansion –this seems to be a contradiction.”

This is rewritten for clarity and coherence, mainly in the results section, where the speculation with regard to the shrubs shading is omitted.

20 “P16 L35-36 Repetition of P15 L31-33”
Corrected

Figures

25 “Figure 1. The following changes would improve the clarity of this figure:
Labelling sub-plots (e.g. a, b, c, d) would be beneficial for clearer linking between the text and the figure (this comment applies for further figures also).
The temperature limits shown by the contour lines are unclear.
The axis labelling of the fourth subplot is slightly inconsistent with the others.
30 Why does the vegetation classification change in the final subplot? For instance in the top panels, Tall shrubs are 0.5-2m whereas shrubs of this height are classed as Low alpine shrubs in the bottom panel.
It would be helpful to see a subplot like the one at the bottom of this figure for the other vegetation perturbation, i.e. Veg1K – RefVeg. Why have you not included this?”

35 *The figure has been revised in accordance with the reviewer’s suggestions.*

40 Figure 2. You have shown temperatures in degrees Celsius here but throughout the manuscript you refer to temperature changes in Kelvin, this should be kept consistent.
Although the Kelvin formulation is used in the text, where temperature differences are presented (SI units are encouraged in most journals), the figures have temperatures in Celsius for better interpretability.

45 Figure 3. If you re-ordered your figures so that figures 2 and 3 precede Figure 1, this would make Figure 1 clearer as it reflects the order that you present the related concepts in the manuscript text.
The order of the figures has been altered in accordance with the reviewer’s suggestion.

50 Figure 5. Refer to Fig. 4 not Fig. 3
Corrected

Figure 6. This Figure is too small and trying to show too much, which makes it unclear and difficult to extract the key information.

Why did you use that particular cross section?

5 It is hard to see the stippled lines

What is the difference between the inset scale and the main figure scale? Why are they not consistent?

10 *We agree that this figure shows a lot, which was also our intention with it. As the vertical profile of the atmospheric response in various variables has not been the main focus here, we found it beneficial to include only one figure of this, and rather condensed. The particular cross section is chosen so that it intersects areas with all types of vegetation changes, and areas with no changes. The main figure scale shows temperature differences in a vertical cross section, while the inset shows temperatures in the bottom model layer, therefore the scales differ.*

15 *We would like to keep the figure as we think it shows several of the important processes related to shrub cover increase. However, we acknowledge that the figure is not of pivotal importance in presenting the main results of the article, we have chosen to move it to the supplementary material, along with some of the corresponding text.*

Figure 7. The middle row of figures would be easier to interpret if the scales were the same.

25 *Although we do acknowledge the reviewer's point of interpretability, we find that due to the large differences in values in the two seasons, the figures are more informative and show the results more clearly with colors on different scales. We have strived to keep scales similar for several other figures, but find that an exception is necessary for this particular figure.*

Not clear from the figure caption which simulation we are looking at (i.e. Veg0k – RefVeg)

30 *Corrected*

Figure 8. On the right plot, label the two seasons as 'warm' and 'cold' or 'RefVegwarm' and 'RefVegcold' instead of the year, as this is how you refer to them elsewhere in the manuscript.

35 *Corrected*

The title of the left plot is too long and so is hard to read where it overlaps the left axis labels.

40 *Corrected*

Figure 11. In the all other figures showing anomaly distributions across the domain, you state that the figure is "only showing significant results at the 95% confidence level" –why do you not do that here?

45 *Just forgot, it has been corrected in the revised manuscript.*

Figure 12. Inconsistent use of "2 M" and "2m" throughout figures in the manuscript Specify that these are inter-seasonal means

Corrected

50

Table 2. Responses are presented inconsistently: Why are precipitation, snowfall and low cloud coverage changes shown as percentages whereas the actual values are given for the other variables? Why is the mean value for RefVeg MAM Low cloud coverage 0.31 when the mean values for the warm and cold years are 0.29 and 0.29? (this applies to other values presented in the table) Why are you only averaging over areas with vegetation changes? Cloud cover and precipitation effects might not be limited to the atmosphere directly above the vegetation change for instance.”

For precipitation and snowfall we found that accumulated values, and relative changes to these were more informative and gave a better impression than actual values as averaged over the areas, as presented for the other variables. This is in part because of the temporally and spatially scattered pattern in these values, as opposed to the other variables presented. The low cloud fraction is a diagnostic variable more than a direct physical value, and as such, we found it more informative to also present changes in relative numbers. Although these specific variables (precipitation, cloud cover) affect the atmosphere over an area greater than the ones directly covered by shrub cover increase, this is not the case for all variables. To provide informative values of responses to shrub cover increase, and to keep as much consistency as possible, we have chosen to use these specific areas for averaging and accumulation throughout. However, to show the spatial extent of the atmospheric response to the different variables, maps are presented in the figures as additional information to the values in this table. We appreciate this thorough review of the table and constrictive suggestions for improving it. We have made corrections where needed.

Reference list

“P20L1-12 Duplication of reference: Myers-Smith et al. 2015a appears to be the same paper as Myers-Smith et al. 2015b”

Corrected.

Supplementary material

“Figure S1. Consistent scales would be better
Figure S5. In the text preceding this figure, it is not clear why “(Veg0K-RefVeg)” is included at the end. “

Figures and captions have been revised and corrected where appropriate.

Answers for anonymous Referee #2

Received and published: 7 December 2016

“This paper extends prior research into the potential climatic effects of a hypothetical increase in shrub and tree cover (in this case, shrub and tree height) in a region in northern Fennoscandia. My overall impression is that this is a solid paper that provides some interesting new results on the topic of vegetation feedbacks onto climate in the Arctic region. This work does not represent a giant leap forward, but the study is sound and, in my opinion, the paper is worthy of publication.

The paper can be divided into two main parts. The first part focuses on the potential changes in vegetation distribution under a 1K temperature change. The second part focuses on an assessment of the impact of such a shift in vegetation on temperature. From my perspective the first part is fine. One could quibble with aspects of the method and argue whether or not the projected changes in vegetation distribution are completely realistic or not, but I don't feel that the realism is really the point. The main

goal is to generate vegetation distribution changes that are at least quasi-realistic and that can then be applied in the subsequent vegetation change experiment. Perhaps the only recommendation that I would have here is for the authors to be a bit more explicit about this with a statement to the effect that predicting vegetation change based primarily on a climatic envelope should just be treated as a first-order assessment of potential vegetation distribution change. “

Firstly, we appreciate the reviewer’s positive comments. Regarding the use of the bioclimatic envelopes in this study, the reviewer’s assessment is correct in that the aim of the re-distribution of vegetation applied here is mainly aimed at providing a pseudo-realistic experiment for investigating the atmospheric feedback mechanisms, rather than providing an accurate and realistic map of present/future vegetation. We agree with the reviewer’s suggestion of highlighting this and communicating this aim more explicitly in the manuscript (also see our response to comments from Reviewer #1). In the revised manuscript this side of the study has been more appropriately introduced and the ideas and purpose of the use of bioclimatic envelopes has been better explained.

“For the second part, my main recommendation to the authors is that they work to put this study into better context. Prior studies, cited in the paper have looked at the impacts of shrub and tree area expansion in models and concluded, mainly, that these vegetation changes can lead to warming. So, the authors need to clearly establish what is new from this study. I see two main areas where this is new. The first is that this is being done within a regional climate model, which allows a more detailed assessment of the response. The second new result relates to the variability in the impact across high and low snowfall years and warm and cool summers. The authors should strive to emphasize these points.”

We have followed the reviewer’s constructive suggestion and reorganized the manuscript to better emphasize these aspects of the study design in the revised manuscript.

With regard to the variability of the impacts across seasons, part of our goal has been to investigate the sensitivity of the atmospheric response to varying conditions represented here by choosing two contrasting years with respect to temperature and snow cover (as further explained in the answer to point 1 from Reviewer #1). In line with this comment, and with similar comments from Reviewer #1, this aspect of the study has been emphasized and presented more clearly in the revised manuscript.

Minor points:

“1. For the summer feedback, the authors note that the impact of shrubs on summer temperatures is less sensitive to the mean summer temperature (warm or cold summers) than spring temps are to high versus low snow years. That is not surprising. Nonetheless, it would be good to explain why one would think that the summer temperature sensitivity could be related to mean summer temps. “

This is a good point, and we see that this side of the expected feedbacks has not been properly introduced. As further explained in the revised manuscript, several other similar studies have found the strongest impacts in summer as resulting from increased shrub cover. Furthermore, and as highlighted and cited in the revised introduction, such feedbacks are largely driven by increased surface fluxes of heat and water resulting from shrub expansion, besides albedo

changes and the SW/LW fluxes. As such, the mean summer temperature can influence all these variables, and therefore potentially the strength of the feedback as averaged across the season. We hope the reviewer finds this aspect of the study better introduced and discussed in the revised manuscript.

5

“2. p. 12, line 26. 0.16K versus 0.15K is essentially the same. Shouldn’t say that one season has a slightly larger response when they are effectively identical. “

10

We acknowledge that the sentence is placing too much emphasis on the second decimal number here, and have adjusted this statement in accordance with the reviewer’s comment.

15

“3. Figure 11 and other figures. It would be clearer to be specific that you are talking about warm summer seasons and cool summer seasons. Just writing cold seasons and warm seasons can lead to ambiguity about whether referring to different seasons (spring versus summer, for example).”

This has been amended in the revised manuscript, and figures adjusted where needed for clarity.

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Interactive comment on Biogeosciences Discuss., doi:10.5194/bg-2016-373, 2016.

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

Johanne H. Rydsaa¹, Frode Stordal¹, Anders Bryn,² Lena M. Tallaksen¹

[1] Department of Geosciences, University of Oslo, Oslo, Norway

[2] Natural History Museum, University of Oslo, Oslo, Norway

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Correspondence to: Johanne H. Rydsaa (j.h.rydsaa@geo.uio.no)

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Abstract. ~~Shrub expansion~~ Increased shrub and tree cover in high latitudes ~~is~~ a widely observed response to climate change. ~~Extensive evidence has shown that shrub expansion that~~ can lead to positive feedbacks to the regional climate. In this study we evaluate the sensitivity of the near surface atmosphere of the near surface atmosphere to a potential expansion-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). ~~Using a state-of-the-art atmospheric model, two perturbation~~ 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. ~~The first experiment is based on present-day climate, and the second is based on a future +1 K increase in temperature. We focus on the spring and summer atmospheric response.~~ To evaluate the sensitivity of the atmospheric response to inter-annual variations ~~variability in climatic conditions~~, simulations were conducted for two different-contrasting years, one ~~with~~

40

Comment [LMT1]:

warmer and one with cold ~~yearer~~ spring and summer conditions. 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). We find that shrub and tree cover increase leads to a general increase in near surface temperatures with the peak-highest influence seen occurring during the snow melting season. It has the largest effect in spring, by advancing the onset of the melting season, and has a more moderate effect on during summer temperatures. We find that the net short wave radiation absorbed by the surface warming effect is sensitive to anthe enhancement of shrub and tree heights, which lower-decreases the surface albedo, resulting in ~~-C~~ taller vegetation having a stronger influence on both spring and summer temperatures. Counteracting effects include increased evapotranspiration ~~increased snow cover and enhanced evapotranspiration which can causing lead to~~ increased cloud cover, ~~and~~ precipitation and snow cover. We find that the strength of the atmospheric feedback effects resulting from increased shrub cover is more sensitive to snow cover variations, ~~and to a lesser extent to than~~ summer temperatures. ~~Taller vegetation has a stronger influence on both spring and summer temperatures. However, Oe~~ 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 likely play an important role in land-atmosphere feedback processes in land atmosphere feedback processes ~~land atmosphere feedback processes in~~ the future. ~~{can you be more specific here? — potentially delete this part}~~

Keywords. Climate change, Arctic amplification, ~~V~~vegetation perturbations ~~Shrubs, shrub expansion,~~ Arctic greening, Fennoscandia, 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 partly due to~~ land-atmosphere feedback mechanisms in the high latitude ecosystems (Beringer et al., 2001; Chapin et al., 2005; Serreze and Barry, 2011; Pearson et al., 2013), such as. ~~Some of these feedbacks are related to the observed a~~ Arctic greening (Myneni et al., 1997; Piao et al., 2011; Snyder, 2013). ~~This Arctic greening term~~ refers to the observed increase in high latitude biomass mainly resulting mainly from increased temperatures (Walker et al., 2006; Forbes et al., 2010; Elmendorf et al., 2012). ~~While present across arctic ecosystems, t~~ The observed increase in biomass ~~is largely related to~~ includes the extensive expansion-increase in shrub and tree cover in areas previously ~~tundra~~ covered by tundra areas (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 ~~as well as the biochemical~~ properties of the surface, leading to inducing ~~This changes~~ changes in land-atmosphere feedbacks (e.g. Bonan, 2008). With increasing canopy height and complexity, the overall surface albedo is decreased, ~~and~~ more incoming radiation is absorbed, ~~and the overall surface albedo is decreased~~. This is known as the albedo effect of increased vegetation. Sturm et al. (2005a) observed the importance-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 due to higher temperatures caused a positive feedback to warming through lowered surface albedo. The absorbed radiation

5 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~~ ~~cover~~ ~~also~~ shaded the snow beneath the canopy from radiation. This further led to ~~and decreased~~ ~~decreased~~ ~~—melt and sublimation.~~ ~~as increased~~ ~~higher shrub and tree cover enhanced~~ ~~increased the winter snow cover beneath the shrubs and increased the soil temperatures 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).

10 ~~Increase~~ ~~Enhanced~~ in leaf area index (LAI) associated with an increase in shrub and tree cover can ~~cause enhanced~~ ~~more~~ ~~lead to higher~~ evapotranspiration (ET). This ~~subsequently~~ leads to more latent heat (LH) ~~being~~ transferred into the atmosphere, ~~and which may also~~ ~~acts~~ to increase ~~air the~~ ~~temperatures~~ (Chapin et al., 2005). The ~~enhanced~~ ~~increase in~~ LH ~~may~~ ~~ight~~ also lead to ~~enhanced~~ ~~more~~ cloudiness and precipitation (Bonfils et al., 2012; Liess et al., 2011). Increased cloud cover may in turn ~~act to~~ limit the effect of ~~an~~ ~~the~~ albedo decrease through lowering ~~of~~ the short wave (SW) radiation reaching the surface. ~~In addition, increased shrub and tree cover has been observed to increase the soil temperatures in winter, enhance the winter snow cover and speed the melting season through its effect on surface albedo (McFadden et al., 2001; Sturm et al., 2001a).~~

20 The height of the shrubs and trees ~~height is also important for~~ ~~influences~~ the strength of the atmospheric response and atmosphere feedbacks, ~~and this was~~ studied specifically by Bonfils et al. (2012). By modelling an increase in the shrub cover by 20% in areas north of 60°N, they found ~~that a higher increase in~~ the regional temperature ~~increased more~~ for taller shrubs as compared to lower ones. They explained the temperature increase by the additional lowering of albedo and increase in ~~ET-LH~~ corresponding to taller and more complex canopies.

25 In summer, ~~if~~ increased shrub cover may also act to shade the soil beneath the shrubs, thereby lowering the temperature of the soil ~~and~~ ~~This thus~~ ~~acted to~~ 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, ~~found~~ 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. In both these

30 The studies of ~~In both of the mentioned~~ Bonfils et al. (2012) and Lawrence and Swenson (2011) both prescribe modelling studies, a 20% increase in shrub cover was prescribed, based ~~only a procedure of~~ 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 effects of increased shrub cover found in these two studies by Bonfils et al. (2012) and Lawrence and Swenson (2011) were realistic, ~~however,~~ ~~but that~~ ~~at the applied~~ shrub expansion of ~~a~~ 20% ~~increase in land cover may~~ ~~ight~~ 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, ~~by applying various climate scenarios.~~

40 The actual extent of shrub expansion into tundra regions ~~as well as~~ ~~and~~ the predicted increase in shrub ~~density and~~ height in coming decades, ~~are~~ ~~is~~ ~~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 CO₂ concentrations, all influence the rate of shrub growth. In addition, disturbances, such as fires, heavy snow pack and biotic interactions including herbivory, makes accurate estimates of future shrub distribution challenging (Milbau et al., 2013). Tape et al. (2012) ~~also 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 ~~to these determining mechanisms~~, 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 ~~winter spring~~ albedo ~~which causes~~ earlier snowmelt, longer growing seasons and increased soil temperatures, ~~all~~ favorable for growth. Also, thicker wintertime snow packs 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 ~~further~~ investigated using dynamic vegetation models. Miller and Smith (2012) ~~found~~ simulated ~~an~~ increase in shrub cover caused by ~~mainly~~ warmer temperatures and longer growing seasons. They ~~explained~~ ~~found~~ that the shrub cover increase was in part enhanced by ~~shrub-atmosphere~~ feedbacks, ~~particularly~~ related to ~~a reduction in the~~ albedo effect of ~~covering tundra with shrubs, related to~~ ~~leading to with an~~ increase in ~~canopies heights~~ protruding the snow cover. In agreement with observations, several other modelling studies have also ~~reported~~ ~~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, ~~resulting partly from shrub invasion and replacement of low shrubs by taller shrubs and trees~~ (e.g. Zhang et al., 2013; Miller and Smith, 2012; Wolf et al., 2008).

Comment [JHR2]: Dette afsnittet kan muligens kattes.

Several recent studies have aimed at isolating ~~a few of~~ the dominating environmental drivers of shrub expansion. Myers-Smith et al. (2015a) 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 ~~that the~~ ~~higher~~ sensitivity to climate forcing ~~was higher~~ for taller shrubs at the upper or northern edges of their present domain and at sites with ~~greater~~ ~~higher~~ soil moisture. ~~Also b~~Based on dendroecological observations ~~in northern Scandinavia~~, Hallinger et al. (2010) concluded that the mean summer temperatures 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) ~~also~~ demonstrated a biome-wide link between high latitude vegetation increase and local summer warming, ~~based on tundra vegetation surveys covering 30 years in 158 plant communities spread across 46 high latitude locations.~~

~~T~~Compared to e.g. an expansion of forest ecosystems, ~~Since~~ the changes in biophysical properties ~~related~~ ~~associated with~~ increased shrub cover in tundra areas ~~are~~ more moderate ~~compared for example to an~~

expansion of forest ecosystems, ~~and as compared to changes resulting from e.g. a comparable expansion of forest ecosystems,~~ a comparatively ~~more~~ rather modest effect on the overlying atmosphere is ~~to be~~ expected (Beringer et al., 2005;Chapin et al., 2005;Rydsaa et al., 2015). ~~Still, afore-mentioned observational and modelling studies have shown considerable~~ demonstrated notable feedbacks to the regional climate. ~~Considerable~~ However, large uncertainties still exist ~~concerning within the~~ estimated ~~s of both the~~ extent of shrub and tree advance in ~~relation-response~~ to ~~elimate-warming~~ forcing, and to the corresponding feedback ~~to climate resulting of-in response to~~ these ecosystem changes (Myers-Smith et al., 2015a;Pearson et al., 2013).

1. 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 according to (Myers-Smith et al., 2015a). Extensive increase in the shrub covered area, in addition to as well as shifts in the tree lines 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). We The study focus addresses the atmospheric response to on both an expansion of the areal extension increase in the areal covered by shrubs and low deciduous trees in northern Fennoscandia ~~area and and the sensitivity effects of to their increased height when it comes to feedback strength~~ height of shrubs and trees. For this purpose, simulations are conducted for a limited region on high temporal and spatial resolution (5.4 km x 5.4 km), using a state of the art regional atmospheric model. This enables us to investigate fine scale features of vegetation changes and the corresponding atmospheric response. The shrub and tree vegetation is redistributed across the study domain by applying three types of shrub and tree classes according to their climatic envelope. These are derived from empirically determined vegetation climate relationships for the region. The primary research questions motivating in this study, and the corresponding experimental setup is presented below are:

The warmer climate is causing more shrubs and low trees to grow in the northern Fennoscandia area, how does this feed back to the atmosphere in the region? More specifically:

- a. How will the feedback be influenced by increased shrub and tree cover and heights?
- 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?

The spring season has been identified as the season with the strongest feedback to temperatures from increased shrub cover in previous studies (!!! INVALID CITATION !!! (Bonfils et al., 2012;Lawrence and Swenson, 2011)). This is due to the effects on snowmelt and corresponding surface albedo changes. As the mean summer temperature has been identified as one of the main environmental drivers for future shrub expansion by several studies, a large potential for growth feedbacks lies with the warming response of the atmosphere during this season. For these reasons we have chosen to focus on the atmospheric response during spring and summer seasons.

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~~The details of the methodology, and the experimental design, is presented in section 2.1, the model used in 2.2 and the development of bioclimatic envelopes for re-distributing shrubs and trees across the study domain in accordance with empirical vegetation-climate relationships for the region is presented in Section 2.3. The results for the atmospheric response for spring and summer is presented in Section 3 (Results), and including the differences in response under various climatic conditions and for varying amounts degree of shrub and tree cover are presented in Sections 3.2-3.4. Finally, followed by a discussion and conclusions follow in Sections 4 and Section 5.~~

~~We focus on the response of the atmosphere during the spring and summer seasons. In addition, the sensitivity to inter-annual variation in mean environmental conditions is investigated. Finally, to explore the potential future atmospheric feedbacks to increased shrub and tree cover on high latitudes, an additional experiment representing a simplified future scenario is conducted. In this experiment, we apply a re-distribution of the shrub and tree cover corresponding to a theoretical 1 K increase in summer temperatures. The resulting feedbacks to the atmosphere are assessed and compared to the effect of vegetation changes corresponding to present day climatic envelopes.~~

2 Methodology and ~~model~~ study design

2.1 ~~Methodology~~ Study design

~~Model simulations were conducted on a limited region on with a state-of-the-art high temporal and spatial resolution (5.4 km x 5.4 km), using an atmospheric model. This enabled us to investigate finer scale features of vegetation changes as compared to modelling studies applying coarser grids, and the corresponding finer scale atmospheric responses. To answer research question 1a and investigate the effects of increased shrub and tree cover (referring to both areal expansion and increased height) (Research question a), we have 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 corresponding accompanying sets of simulations in which the vegetation cover has been 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, (Research question d) since the simulations are otherwise identical (i.e. they are driven by the same meteorological forcing and input datasets). Mean summer temperatures were selected as the key environmental criteria used to guide the perturbations applied to the shrub and tree cover.~~

~~In order to answer the research question in point 1b, we chose to focus on spring and summer. 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). This is due to the effects on snowmelt and corresponding surface albedo changes. As the mean summer temperature has been identified as one of the main environmental drivers for future shrub expansion by several studies. Furthermore, a large potential for growth feedbacks lies with the warming response of the atmosphere.~~

during ~~this summer season~~. 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), ~~and we chose to run each season~~ 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 a wide range in the meteorological variability across this period, without ~~having to simulate~~ many years. Secondly, ~~we 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 ~~contrasting~~ years were selected based on a ten-year (2001-2010) long simulation by Rydsaa et al., (2015), ~~who performed which is 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. and the~~ Furthermore, it provides consistency in ~~modelling tool~~ model setup and boundary conditions with this study. The year ~~of~~ 2003 was chosen as it represents a low snow cover spring season and a warm summer season in this region ~~in this the study 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 ~~In order to take into account for some of the uncertainties inherit inherited in the shrubs' response to summer temperatures, one bioclimatic envelope is based on a 10-year average of JJA temperatures, and one based on a 1 K increase in the same JJA temperatures, yielding a new two~~ different vegetation redistributions have been introduced. They are based on the concept of bioclimatic zones (ref. ~~as explained in Section 2.3~~), and the two distributions allows ~~The difference in atmospheric response to these two cases of shrub cover increase provides a measure of the sensitivity of the atmospheric feedback to the variability in shrub cover increase in response to mean JJA temperatures change to be assessed, and is briefly examined.~~ 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.

~~Studying~~ Combining findings of the atmospheric response in two different vegetation distributions, and contrasting years (~~and considering the differing response in the warm versus a wellnd the cold~~) years, further some careful assumptions about the potential changes in atmospheric response under varying climatic conditions and vegetation distributions can be made. Based on this, we can make some careful assumptions regarding ~~what~~ allow us to identify potential responses under various future ~~may be expected under varying (e.g. versus present)~~ climate conditions.

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~~In order to investigate the effects of increased shrub and tree cover (referring to both areal expansion and increased height), we have conducted six simulations; control simulations for two different years, and two corresponding sets of simulations in which the vegetation cover has been manually altered to represent increased shrub and tree cover. By comparing the reference and experiment simulations we can determine the effect of vegetation cover changes, as the simulations are otherwise identical. Our investigations are carried out on a domain covering northern Fennoscandia and north-west Russia (Fig. 1). This is a sensitive region for shrub expansion in response to climate forcing according to (Myers-Smith et al., 2015b). Extensive increase in the shrub covered area, in addition to shifts in tree lines towards higher latitudes and altitudes, has been observed in this region over the past decades (Tommervik et al., 2004; Hallinger et al., 2010; Tommervik et al., 2009; Rannow, 2013).~~

~~In this study, subjects of particular interest include differences in atmospheric feedbacks between seasons. The spring season has been identified as the season with the strongest feedback to temperatures from increased shrub cover in previous studies (Bonfils et al., 2012; Lawrence and Swenson, 2011). This is due to the effects on snowmelt and corresponding surface albedo changes. As the mean summer temperature has been identified as one of the main environmental drivers for future shrub expansion by several studies, a large potential for growth feedbacks lies with the warming response of the atmosphere during this season. For these reasons we have chosen to focus on the atmospheric response during spring and summer seasons.~~

~~The atmospheric response to shrub expansion may also be sensitive to inter-annual variation in mean environmental conditions. Our investigations are conducted for two spring seasons and two summer seasons which represent a wide range in two key environmental conditions; the spring snow cover and the summer temperature. This setup enables us first to investigate the importance of shrub cover increase on the land-atmosphere interactions in both summer and spring seasons. Secondly, we are able to examine how the atmospheric response varies between snow-rich and snow-poor melting seasons, and the sensitivity to temperature on the summer atmospheric response. The two years were selected based on a ten-year (2001-2010) long simulation by Rydsaa et al., (2015), which is 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, and the consistency in modelling tool and boundary conditions with this study. The year of 2003 represents 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 represents a snow-rich spring season and a cold summer season in this region (hereafter referred to as the cold spring and summer season).~~

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.

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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°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.

2.2.3 Model

~~For the purpose of this study, we have used~~ WRF V3.7.1 (Skamarock et al., 2008). ~~WRF~~ 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 wide 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 (aboutref, 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 in this study 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 ~~output written every 3 hourly outputs~~. Each simulation spans the snow accumulation season (starting in November), ~~spring and summer~~, 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). ~~The added parameterizations include~~ consideration of the 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. ~~In the model, t~~The soil is divided into four layers of varying thickness, ~~summing up to a~~ total of 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 ~~related to 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 ~~updated here (how?)~~ based on a prescribed monthly dataset provided with the WRF model.

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~~As such, this~~ ~~model~~ setup is able to capture changes in surface properties ~~related to following a~~ redistribution of vegetation classes and ~~the corresponding~~ atmospheric ~~response effects resulting from these~~. 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 ~~, and corresponding effects on the overlying atmosphere,~~ differ in reference versus perturbed simulations. ~~Any differences~~ ~~Alterations~~ in the atmosphere ~~seen in the comparison of reference to perturbed simulations~~ results from the biophysical changes ~~related accompanying to~~ the applied vegetation ~~changes only perturbations alone.~~

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2.2.1 Land cover and re-distribution

~~For (The land cover input data is based on, we use 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 of "open shrubland", consisting of low shrubs of less than 0.5 m height. This category was further used to as a basis to implement empirically based adjustments aiming 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. For this purpose we divided our study domain into climatic vegetation zones based on mean JJA temperatures, and we defined shrub and low tree categories according to their empirically derived climatic vegetation zones (Bakkestuen et al., 2008). In order to prevent shrubs from being distributed in areas that are unsuitable, despite favorable climatic conditions, the extent of area extents with of other vegetation categories was kept unaltered. In this way, the vegetation was adjusted in accordance with the derived climatic vegetation zones, while keeping the heterogeneity in the vegetation distribution across was kept assimilar to observed in the original dataset.~~

~~The results for the dominant vegetation categories as distributed across the domain for the different simulations, along with mean JJA 2 m temperature limits used to determine the climatic envelopes, are shown in Fig. 1.~~

~~In order to distribute the climatic vegetation zones geographically across the study domain, we utilized were derived using some general features of vegetation distribution among the alpine zones that have been determined for this area. (The various alpine zones are defined as altitudinal dependent belts of vegetation above the forest~~

linewhere (Gottfried et al., 2012). Although the altitudinal extent of each alpine zone is determined by the local mean decline in temperature with elevation (i.e. local mean temperature lapse rate) (Bakkestuen et al., 2008) in addition to various geographical and climatic features, the relative [needed?] altitudinal extent of each alpine zones remains rather constant throughout across the domain in focus here. This altitudinal extent is used here to determine temperature based climatic envelopes for each alpine zone. 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 (Björklund et al., 2015).

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As illustrated in Fig. 2, and following the vegetation categorization of Moen et al. (1999) and Bakkestuen et al. (2008), we defined tall shrubs and boreal deciduous trees reported to be characterized by with a height from 2 to 5 m (Aune et al., 2011) as to belonging to the sub-alpine zone. We defined tall shrubs with height from 0.5-2 m as to belonging to the low alpine zone, and low shrubs with height up to 0.5 meters to belonging 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 (and largely fit in agreement with the defined climatic limits), and vegetation cover in these areas were adjusted accordingly (see e.g. Karlsen et al. (2005)).

The climatic forest line was found and applied 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 cover exceeds 25% in each grid cell. This line furthermore defines the base line temperature used to derive the alpine vegetation zones at higher elevations. The climatic boreal forest line was found to correspond well with the mean summer 12 °C isotherm (in our domain) (Fig. 1), which 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 each, and vegetation cover at higher elevations defined as high alpine zone (Moen et al., 1999). This constitutes the reference vegetation distribution (RefVeg) as illustrated in (Fig. 2).

Based on temperatures from previous simulations covering the area 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 climatic vegetation zone. The interpolated mean JJA 2 m temperature was then used to distribute each shrub category across the domain in accordance with their climatic envelope. In order to simulate a shrub expansion and re-distribution of tall vs. low shrubs in accordance with a theoretical future increase in summer temperatures, revised climatic zones with the same relative altitudinal extent were calculated based on increased JJA 2 m temperatures, and vegetation categories were re-distributed accordingly. is (Fig. 2) For simplicity, the mean lapse rate is assumed to be the same in the new temperatures. The procedure is illustrated in Fig. 3T.

~~the two To represent each alpine vegetation type in the model, we chose suitable vegetation categories (and corresponding parameter values) from the ones already defined within the thus model system. The categories were chosen based on categories types already present in the domain, with Special emphasis was on given to decreasing LAI and canopy height for vegetation applied distributed towards higher altitudes and latitudes, and further based on. The choices were based on a recent mapping of vegetation types in the region (Bjørklund et al., 2015). A list of 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 original usage in the model system is given along with the minor alterations. The only change alteration between the reference simulations (“RefVeg”) and perturbed simulations (“Veg0K”, “Veg1K”) is the land cover. Any other differences in other variable values result from the land cover changes, as simulations are otherwise identical with respect to setup and meteorological forcing data. This methodology aims to isolate the signal in the atmospheric response to land cover changes alone. The difference between Veg0K and RefVeg shows the effects of an increase in shrub and tree cover as having reached the present day climatic potential (as de mean r-fined here). The difference between Veg1K and RefVeg on the other hand, shows the enhanced effect of a potential vegetation shift corresponding to a 1 K shift in surface temperatures and is presented afterwards.~~

3 Results

~~The only change between the reference simulations (“RefVeg”) and perturbed simulations (“Veg0K”, “Veg1K”) is the land cover. Any other differences in other variable values result from the land cover changes, as simulations are otherwise identical with respect to setup and meteorological forcing data. This methodology aims to isolate the signal in the atmospheric response to land cover changes alone. The results are therefore presented largely as anomalies between reference and perturbed simulations when the effects of land cover are of main interest. The difference between Veg0K and RefVeg shows the effects of an increase in shrub and tree cover as having reached the present day climatic potential (as defined here). The difference between Veg1K and RefVeg on the other hand, shows the enhanced effect of a potential vegetation shift corresponding to a 1 K shift in surface temperatures and is presented afterwards.~~

~~In the following Sections 3.1 -3.3 present the the mean seasonal effects on the overlying atmosphere of increased shrub and tree covercover (Veg0K-RefVeg) for each mean season (MAM and JJA) are presented, specifically. The most moderate vegetation re distribution (Veg0K) is focused. 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 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 the variations in temperature. We start presenting the results In Section 3.1 Results are first given as averages over the two spring seasons (MAM) seasons, and the two summer (JJA) seasons (Section 3.1 warm and cold), followed by a spring seasons and two summer seasons. This gives an mean 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, rResults Next we comparingson ofeing the anomalies response between in the warm~~

and versus the cold spring and summer seasons are presented next in Sections 3.2 and 3.3, as it will indicate the sensitivity of the atmospheric response to specific meteorological variations. Section 3.2 focuses on the effect of variation. We focus in Section 3.2 primarily on Here (these effects of are limited to variations in) in spring snow cover between the two years, primarily (in Section 3.1.1) and Section 3.3 on the effect of variation in summer near surface temperatures (in Section 3.1.2). Finally, in order to account for the sensitivity of the shrub and tree cover to JJA temperatures, the atmospheric response to of the most extensive vegetation re-distribution (Veg1K-RefVeg) is are presented in Section 3.4.3. in Section 3.2 a brief analysis of the future scenario with vegetation distributed according to a 1 K increase in temperature is presented. Special emphasis is on how the increased shrub and tree cover alters the feedback to atmospheric temperature. Mean values for the reference simulations, along with mean response as averaged over all areas with vegetation changes for surface fluxes and near surface atmospheric variables, are presented in Table 2.

3.1 Atmospheric effects of shrub and tree cover increase

Mean values for the reference simulations (mean of RefVeg_{cold} and RefVeg_{warm}), along with mean 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 across for both each years (-in parentheses-) years, are presented in Table 2.) for surface fluxes and near surface atmospheric variables, are presented in Table 2. Separate values for the spring seasons are given in Effects of shrub and tree cover increase as averaged over the two spring seasons (Veg0K-RefVeg) by both expansion into areas with lower vegetation, and by increased height of existing shrubs (Veg0K-RefVeg) as averaged over the two spring seasons, are presented in Fig. 4. Top panels Fig. 4a shows the spatial distribution change in 2 m temperature anomalies averaged over the spring seasons (left) and mean values for each separate bioclimatic zone area with vegetation changes for each vegetation type (corresponding areas are indicated in Fig. 14, bottom panel) in the bar plot (right) (right).

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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 vegetation shrubs and trees (as also 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 appear (Fig. 4a, bar plot). Values close to The mean response reaches up to 0.6 K are seen in some areas with taller vegetation (Fig. 4). There is also large temporal differences variability within the seasonal response, 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).

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The second row of panels in Fig. 4b shows changes in fluxes of net short wave (SW) radiation (towards the surface). The main strongest highest increase in net short wave (SW) radiation fluxes is seen during the spring season (Fig. 4b), mainly due to decreased surface albedo caused by both the increased shrub and tree cover, and particularly its effect on earlier snowmelt (Section 3.2.1.4). The spring season's net increase in SW radiation occurs despite There is a slight decrease in downwelling SW (not shown) caused by enhanced cloud cover (Fig. 6 and Table 2), but the reduction in downwelling SW is more than compensated by the albedo decrease in areas with sub-alpine vegetation (taller vegetation). T, but the net value is close to zero in areas with low-alpine shrub increase (lower vegetation) due to smaller albedo changes (second row 4b, and bar plot). The long wave (LW)

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radiation ~~is slightly increased~~ (Fig. 4c) in response to enhanced cloud cover and atmospheric humidity (ref. Fig. 7 and 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.

5 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. ~~4d3, row 4~~). The increased LAI ~~due to caused by increased more~~ shrub and tree cover (Table S1, and Fig. S4, supplementary material) ~~causes results in~~ increased ET, and correspondingly ~~increased 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. ~~4c, row 5~~) 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 ~~increased~~ LH in balancing the surplus of SW energy at the surface.

15 In the summer season (Fig. 5) the 2 m temperature ~~is increased~~ in areas with taller vegetation, and ~~decreased~~ in the areas with low-alpine shrub increase (lower vegetation) (Fig. 5a). ~~These 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 the early summer season (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 due to a result of increased precipitation (also including snow fall;) (Table 2). The summer season SW downwelling is decreased due to increased cloud cover (Table 2, Fig. 7 and as confirmed by the increased LW to the surface). In addition, ~~the summer season SW downwelling is decreased due to an increase in cloud cover (Table 2), Fig. 7 and as confirmed by the increased LW to the surface (Fig. 5c).~~ On the other hand, ~~in the negative net SW is caused by a slight albedo increase in the early summer season (early to mid-June, not shown) due to enhanced snow cover in these areas (Fig. S3 and S4, supplementary material). The latter is due to the increased precipitation (also snowfall) (Table 2) and enhanced shading effect by more shrubs, combined with the small albedo decrease associated with the low alpine shrub increase. In the areas with taller shrubs and trees on the other hand, the stronger albedo decrease are characterized dominates by leading to a decrease in snow cover throughout the spring and summer seasons due to a stronger albedo decrease (albedo changes are shown in Fig. S4, supplementary material).~~

35 The increased SH mainly acts to heat the lower atmosphere within the planetary boundary layer (PBL), while the LH is also 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 as the water condenses (Fig. 6). The vertical structure of the lower atmosphere heating along a somewhat arbitrarily chosen cross section across the areas with vegetation changes domain is shown in Fig. S6 in the supplementary material, along with changes in planetary boundary layer PBL height and turbulent fluxes of SH and LH. The values are mean monthly May values from the warm spring season, and as such they represent one of the months with the largest heating anomaly. The increased SH mainly acts to heat the lower atmosphere

within the boundary layer, while the LH is also released above the PBL height. The heating anomaly has a westward tilt with altitude, and the signal extends well beyond the PBL, however the main heating is occurring within the lower 200 meters. The changes in LH and SH fluxes are local to the areas with vegetation changes, as is the increase in PBL height.

The atmospheric humidity increase associated with increased shrub cover results in more clouds and total accumulated precipitation in both seasons (Table 2).

The spatial distribution of mean changes ~~to~~ in the low cloud ~~fractions?~~ (here defined as below 3 km) and precipitation ~~anomalies for~~ in the two seasons is shown in Fig. ~~76?~~ 76. 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 atmospheric humidity increase associated with increased shrub cover results in more clouds and accumulated precipitation in both seasons (Table 2).~~ 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 ~~is~~ increases d the most through enhanced LH, i.e. in areas with an increase in taller vegetation.

Top panels in Fig. 7 show the relative change in low cloud cover resulting from increased shrub cover. Here the change in cloud cover is shown as the fractional cloud cover as averaged over the lower 3 km [ref.above is it the same variable?] of the atmosphere (further details about this variable in the supplementary material). The most prominent increase in low cloud cover is occurring in spring (Fig. ~~67~~ 67, upper left panel) ~~and is~~ largely covering areas with vegetation changes. The ~~pattern for the~~ summer season's response ~~is is~~ more patchy, although a tendency ~~of~~ towards increased cloud cover in areas with vegetation change (ref Fig. 3) is recognizable, ~~and statistically significant [first time mentioned — also mapped in earlier figures]~~ (see Table 2).

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, and~~ the relative change in precipitation is based on daily accumulated values. As with the cloud cover, ~~The~~ spatial distribution ~~of significant values of~~ (significant) precipitation changes is ~~also~~ somewhat patchy, particularly for the summer season. However, ~~changes are concentrated above areas with applied vegetation changes~~ (the significance is higher in areas with vegetation changes, as compared to the total area (~~the relative amount of cells with significant results differences in areas with vegetation changes is 8.3%, versus 5.7% in the total domain).~~ This is indicating that most of the significant increase in precipitation is related to the vegetation changes. The increase in accumulated precipitation is most prominent in summer, ~~amounting to 186 mm i, during which the precipitation increase summarized over in all the areas with vegetation changes is 186 mm,~~ corresponding to a 2.2% increase (p -value based on the Mann-Whitney significance test is $1.2 \cdot 10^{-5}$). For spring, the increase in precipitation is 1.407% ($p = 2.8 \cdot 10^{-9}$), and for precipitation in the form of snow and ice, it is 1.4% ($p = 3.19 \cdot 10^{-9}$).

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3.1.13.2 Sensitivity to snow cover differences

The two contrasting spring seasons are characterized by large differences in snow cover, albedo and near surface temperatures ~~between the two years~~. ~~As compared to the cold season~~ In the reference simulation ~~sease~~, 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 ~~on~~-average 3.1 K warmer 2 m temperature ~~(numbers are averages over the land area of covered areas of the total study simulation domain)~~. There are small differences in Total precipitation is similar for among the two years, although the rain-to-snow ratio is larger in the warm ~~season~~-spring due to higher temperatures. ~~The difference in mean spring snow cover between the warm and cold spring seasons is presented in Fig. 78.~~

~~It is clear from Fig. 7 that~~ The snowmelt ~~iso~~ starts earlier in the warm spring season (RefVeg_{warm}) (more than two weeks) and a faster ~~onset and speed of the melting rate of snowmelt is seen as~~ ~~seen for the warm season~~ differ between the two ~~as~~ compared to the cold spring season (RefVeg_{cold}) ~~years, with and the main~~ the largest difference in snow cover ~~is~~ in May (Fig. 7). ~~The melting starts more than two weeks earlier in the warm spring season.~~ It is worth noting that the ~~The dominating most pronounced~~ effects of increased shrub cover ~~differ between snow covered and snow free conditions and the differences in the shrubs' influence on the atmosphere are largest during the melting season, i.e. in May-June.~~

~~The difference in 2 m temperature response to increased shrub cover (AT2m = Veg0K - RefVeg) between the warm and cold spring seasons (AT2m_{warm} - AT2m_{cold}) is shown in Fig. 89.~~ 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) ~~spring season~~. As seen in the right panel of Fig. 89, the anomaly distribution is shifted towards overall higher values ~~in general~~ in the warm season. The shrubs act to enhance warming more in the warm ~~spring season more~~ than in the cold spring season. This represents a positive feedback to warm conditions and early snowmelt.

The increased shrub and tree cover ~~decreases~~ leads to a reduction in the snow depth in the ~~spring season~~ as averaged over all areas with vegetation changes, as seen in Fig. 94a; ~~top panel~~ (the spatial pattern distribution of snow cover is shown in Fig. S3, in the ~~supplementary material)~~. An exception is seen in the ~~late spring~~ (and early cold ~~season~~-summer, not shown). This is owing related to the ~~above mentioned~~ late spring and early summer increase in snow cover found in areas with low ~~alpine shrub increase~~. ~~These areas experience.~~ In these areas the mean increase is due to an increase in ~~and~~ snow fall in the cold ~~summer~~ season and subsequently, ~~and possibly the increased shading effect of the shrubs. These effects dominate over the effect of the weak albedo decrease.~~ This increase in late spring/early summer snow cover leads to a ~~a~~ shortening of the snow free season in these areas (a grid cell is considered snow free ~~here defined as~~ 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, but however, it speeds the onset of melting by several days.

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Also, increased shrub and tree cover acts to enhance the soil temperatures (Fig. 9c-), with maximum impact in the upper layers of the soil (not shown). The increased precipitation throughout both spring and summer seasons also influences the soil moisture. The soil moisture (Fig. 9d) is increased in areas with increased shrub and tree cover throughout the warm spring, and due to the shrubs' ability to decrease surface runoff during the main snowmelt. A notable increase in the mid-May soil moisture, and corresponding decrease in surface runoff, is particularly increased seen in mid-May at the time of maximum snow melt. Increased shrub and tree cover also influences the soil moisture and temperature, as shown in Fig. 10. The shrubs act to decrease surface runoff (Fig. 9e), during the peak of for both the cold and warm melting seasons. However, during the warm spring season before the main snowmelt starts, runoff is slightly increased higher due to shrubs during the warm spring season, because of their effect on the increased snow melt earlier in spring for areas with increased shrub and tree cover. The soil moisture is increased in areas with increased shrub cover throughout the warm spring, and due to the shrubs' ability to decrease surface runoff during the main snowmelt, the mid-May soil moisture is particularly increased. Also, increased shrub and tree cover acts to enhance the soil temperatures (Fig. 10, third panel), with maximum impact in the upper layers of the soil (not shown). The increased precipitation throughout both spring and summer seasons also influences the soil moisture.

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3.1.23.3 Sensitivity to summer temperatures

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

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The difference in atmospheric temperature response to increased shrub and tree cover between the two summers ($AT_{2m_{warm}} - AT_{2m_{cold}}$) is shown in Fig. 10.

The response of the atmosphere to increased shrub cover (Veg0K-RefVeg) shows more similarity across the two warm and cold summer seasons as compared to the two warm and cold spring seasons. For the summer seasons, the mean difference in near surface 2 m temperature response between the warm and cold season is smaller and more rather evenly distributed around zero (Fig. 10, right panel). The positive values over areas with low alpine shrub expansion largely indicate less cooling in the warm summer season as compared with the cold summer season, during which these areas were partially covered by snow. The tall vegetation changes contributes 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 positive larger vegetation feedback to warmer summer temperatures in the warm summer season when compared with the cold.

5 ~~As the difference in atmospheric temperature response is larger between the warm and cold spring season when compared with than between the warm and cold summer season, Thus, it seems like seems that the strength of the temperature feedback to increased shrub cover feedback is more sensitive to snow-meteorological conditions in spring than summer-temperatures. This is likely due to the fact that to the temperature feedback is being closely linked to albedo changes, which again are heavily dependent on snow cover. Therefore, the strength of the feedback is more sensitive to temperature in the melting season.~~

3-23.4 ~~SSensitivity to a 1 Kthe degree of -shift in-vegetationvegetation changes-cover: "future scenario"~~

10 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 -migration of distribution of~~ 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. 32). The increased cover of trees ~~rather than 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).

15 The mean seasonal response in 2 m temperature ~~caused by this vegetation shift to the increase in shrub and tree cover corresponding to the 1 K increase in the most substantial vegetation change case (Veg1K-RefVeg)~~ is shown in Figure 121.

20 The ~~atmospheric warmingheating~~ effect at 2 m ~~resulting from the "future" vegetation shift~~ is on average more than doubled as compared to that of the ~~more moderate~~ shrub and tree cover ~~increase-distribution according to present-day climate (in (Veg0K-RefVeg),-RefVeg)~~ in both seasons (Table 2). This is due to the ~~more drasticstronger effectmore extensive changes in-on-the~~ biophysical properties related to the ~~extensive~~ shift towards taller vegetation. ~~In Veg1K Tt~~The warming is most prominent in ~~the spring season, particularly in~~ late spring ~~whenas~~ the increased vegetation cover ~~notably~~ affects the snow melt and corresponding albedo and surface heat fluxes. The average spring ~~season-heatingwarming~~ is therefore strongest in areas with the tallest vegetation. ~~However, aStillthough highly localized t-~~The highest ~~peak peak~~-values, up to 0.71 K, are ~~however~~ found in summer (Fig. 112). ~~The potential enhancement of the warming effect in Veg1K (as compared to the warming resulting from Veg0K) is thus largest in the summer season.~~ Increased LH also leads to enhanced atmospheric moisture and more summer precipitation ~~in this experiment~~ (Table 2) and corresponding greenhouse effect of up to 5 W m⁻² (not shown).

35 The response of the ~~isVeg1K~~ vegetation change also differs between the warm and cold summer ~~and spring seasons~~. In contrast to ~~the response of the previous experiment (Veg0K)~~, the strongest warming is ~~taking placefound~~ in the cold summer in most areas. ~~However, due to the influence of early summer cooling in areas with low alpine shrubs caused by increased snow cover in the cold summer (as in the previous experiment), the average response across the entire area with vegetation changes is a slightly stronger warming in the warm summer (0.16 K versus 0.15 K in the cold summer, Table 2).~~

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 the areas with the tallest vegetation. The warming as averaged over the entire area with vegetation changes reached 1.0 K during the ~~warm~~-melting season in the warmest of the two years studied (Veg0K_{warm}-RefVeg_{warm}), 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°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. ~~that~~, interesting in ~~in~~ up to high

Lawrence and Swenson (2011) also applied a 20% increase in shrub cover north of 60°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°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.

5 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).

10 The sensitivity of shrub expansion to mean-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 ~~Assuming that future climate in this region inherits an increase in JJA temperatures and corresponding increase in shrubs and trees, the vegetation distribution applied according to a theoretical 1 K increase in JJA temperatures.~~This may serve as a simplified proxy for a future vegetation re-distribution scenario with regard to vegetation trajectories and re-distribution. 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 ~~would~~ 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 wide-range of climatic conditions represented by the two contrasting years in this study. ~~However if~~ Keeping all this is kept in mind, a careful interpretation of the results as representing some future state can still be interesting. ~~The increased vegetation cover resulting from the 1 K increase in JJA temperatures.~~ 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 mean values of Δ SPeak~~ seasonal anomalies in this experiment were also higher in the summer season as compared to the spring season.

30 Combining our findings, ~~These findings lead us to conclude.~~ 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.

40 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 of the 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 the 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 changing further alteration them 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.

As-Since we have chosen to focus on biophysical aspects of the effects of increased shrub and tree cover expansion, 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, which have enabled a more realistic representation of finer scale features of the shrub-atmosphere feedbacks as compared to the other previous modelling studies mentioned. 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 off 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’ effects on the atmosphere. As such, our results for impacts on upper atmospheric features, such as cloud cover and precipitation, are more heavily influenced by the

meteorological boundary conditions ~~than the~~ and not only near surface variables. This effect could influence our results for atmospheric response to be more modest ~~as~~ when compared to results of similar studies on circumpolar domains (e.g. Bonfils et al., 2012; Liess et al., 2011).

5 ~~No~~ VVegetation 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 variations of in vegetation in these simulations, are results of the daily interpolated greenness factor (based on monthly values), acting to scale between maximum and minimum parameter values representing each vegetation category (such as the LAI and vegetation albedo etc.). The greenness fraction describes the vegetation density distribution within each grid cell. As Since we have made no assumptions about changes in the density of vegetation, only about the type of dominant vegetation, vegetation density distribution within each grid cell besides that of the vegetation specific properties, the greenness fraction 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) (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, and in particular could influence the partitioning between latent and sensible heat flux could be affected by the choice of perturbations applied.

Comment [-3]: Phoenix, G. and Bjerke, J.W. (2016): Arctic browning: extreme events and trends reversing arctic greening. Global Change Biology 22, 2960-2962.

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25 ~~The spring albedo effect on absorbed radiation 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 and precipitation, versus the effect of albedo decrease and enhanced melting, determine the net SW and influence the near surface temperatures. Albedo changes related to more complex canopies and enhanced snowmelt dominate the spring effects in areas with increase in tall vegetation. The net effect related to increase in lower shrub cover is more dependent on the balance between the albedo decrease and added snowfall and snow cover due to more moisture in the atmosphere.~~

35 ~~Taller vegetation has a stronger impact on the summer surface fluxes and temperature due to the large increase in LAI and decrease in albedo in summer for the boreal and sub alpine deciduous trees. The surface albedo decrease is largest in summer, despite the snow masking effect in winter, 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.

Bonfils et al. (2012) applied a 20% increase in shrub cover in bare ground areas north of 60°N in order to study the influence of shrubs on climate. They found a regional annual mean temperature increase of 0.66 K for shrubs with height 0.5 m, 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. They also found an increase in summer precipitation, particularly in the case of tall shrubs.

The seasonal mean spring temperature increase in our simulation for present day shrub distribution (Veg0K) reached 0.59 K in in some areas with the tallest vegetation. The warming as averaged over the entire area with vegetation changes reached 1.0 K during the warm melting season, 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 here. However, we find large differences in the response related to the varying heights of the shrub cover, as was also found by Bonfils et al. (2012). In the large areas with low alpine shrub cover increase, the average warming was of only 0.1 K, reflecting the increased snow cover in late spring in these areas which was partly caused by increased snowfall and partly by the increased shading. Combined with the weak counteracting effect of small albedo decreases associated with the low alpine shrubs as compared to the low shrubs previously present in these areas, the net results for the SW and 2 m temperature were negative in early summer. The summer maximum increase in near surface temperature reached 0.39 K in areas with taller vegetation. The warming was mainly associated with taller vegetation, confirming the strong dependence of the atmospheric response on vegetation height also in this season.

Lawrence and Swenson (2011) also applied a 20% increase in shrub cover north of 60°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.

Swann et al. (2010) applied a 20% increase in shrub cover north of 60°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 temperature increases in our results, both for the peak melting seasons and in seasonal means, are below the seasonal estimates of some of the 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 the

mentioned modelling studies, despite qualitatively similar responses of enhanced ET and LH related to increased shrub cover.

The response of shrub expansion in our simulations was larger in the warm than in the cold year, when averaged over the entire area with vegetation shifts, both in spring and summer. However, the difference in response between warm and cold summers was more moderate. Based on these results, we might expect that in a warmer climate, the effect of shrub expansion would enhance the positive feedback of early snow melt, and contribute to prolonged growing season and particularly increase spring surface temperatures. The areas with strongest feedback to the summer season warming were related to taller vegetation (sub-alpine and boreal).

We assume that the vegetation distribution applied according to a theoretical 1 K shift in summer temperatures may serve as a simplified proxy for a future scenario with regard to vegetation trajectories and re-distribution. However, precautions should be made when interpreting these results, as the time delay related to such a vegetation shift could be substantial (Corlett and Westcott, 2013), and the fact that the actual vegetation re-distribution according to such a shift in summer temperatures would 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). If this is kept in mind, a careful interpretation of these results is still useful. The increased vegetation cover resulting from the 1 K shift in JJA temperatures was largely represented in this study 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 enhanced the warming in both seasons, but to a larger degree in summer (on average 0.16 K in Veg1K RefVeg, as compared to 0.04 in Veg0K RefVeg, Table 2). Peak mean values of seasonal anomalies in this experiment were higher in the summer season as compared to the spring season.

These findings lead us to conclude that the main summer temperature feedbacks are related to taller vegetation. As the mean summer temperature is assumed here to be the main environmental driver of shrub expansion, we find that the warming effect on summer temperature and thus feedback to further shrub and tree growth is subject to a time lag corresponding to that of establishment of taller shrubs and sub-alpine trees in tundra areas, as also found by de Wit et al. (2014).

Also, based on the differences in response between the warm and cold summer in these experiments, a positive feedback to summer warming seems to be a robust feature across inter-annual differences, as warming of the summer atmosphere occurs quite evenly in cold and warm summers. 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 rather probable, and this would be an interesting topic to investigate further. The term refers here 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).

5 Summary and conclusions

~~In this study, we~~We have applied the weather, research and forecasting model (WRF) coupled with the Noah-UA land surface model; ~~in to~~ evaluating the biophysical effects of shrub expansion and increase in shrub height on the near surface atmosphere on a state-of-the-art fine resolution. We ~~have 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 (Veg0K vs. RefVeg)~~ region (bioclimatic envelopes). To evaluate the sensitivity of the atmospheric response to ~~inter-annual climatic~~ variations, simulations were conducted for two ~~different 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 ~~corresponding to a 1 K increase in mean summer temperature~~, we conducted additional simulations for each year, applying a new second vegetation cover shifted according to new bio-climatic envelopes corresponding to a 1 K increase in mean summer temperature (Veg+K).

Our results show that shrub and tree cover increase leads to a general increase in near surface temperatures, enhanced surface fluxes of heat and moisture, increase in precipitation and cloud cover across both warm and cold years and seasons. A notable exception is areas with sub-alpine shrubs ~~early in the cold summer season~~, where increased ~~snow-atmospheric moisture cover~~ resulting from shrub expansion leads to increased snowfall and surface albedo, ~~early in the colder summer season. dominating over the decrease in albedo resulting from the shrub increase.~~ 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 ~~enhanced snow cover. The strength of the albedo effect is also influenced by the~~ 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~~ ing a positive feedback to warm spring temperatures. Taller vegetation influences summer temperatures more than spring temperatures in most areas, ~~and~~ 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 ~~in summer temperatures~~.

Summer temperatures have been estimated to be one of the strongest drivers of vegetation expansion in high latitudes. Here, we find that the strongest ~~impacts on~~ 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

~~differences-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 ~~clear~~-potential for a so-called vegetation-feedback tipping point. This is a possibility,—which we find to be an interesting subject for further research. ~~s~~

5 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.

<i>Parameterization scheme</i>	<i>Reference</i>
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	JJA	MAM	JJA	MAM	JJA
	(Warm,Cold)	(Warm,Cold)	(Warm,Cold)	(Warm,Cold)	(Warm,Cold)	(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)	1.43% (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

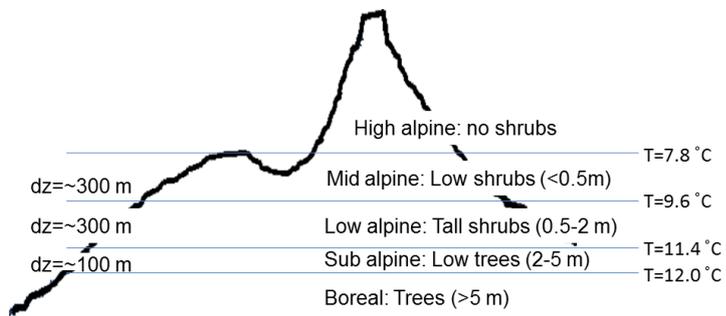
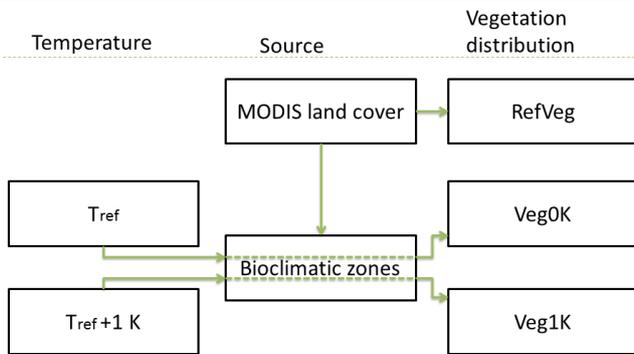
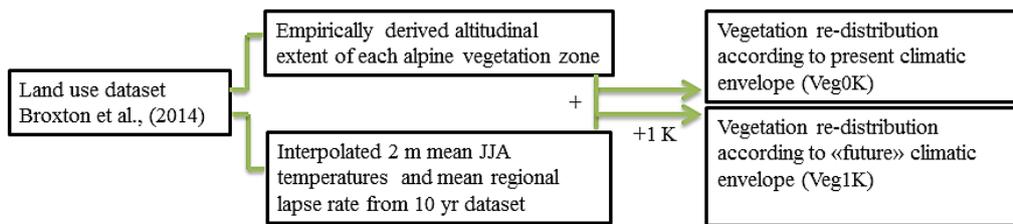


Figure 21: Illustration of alpine zones and corresponding dominating shrub vegetation. The altitudinal extent of each alpine zone is indicated by the values of elevation differences (dz), and corresponding mean JJA temperatures dividing the zones based on mean summer lapse rates in the area.

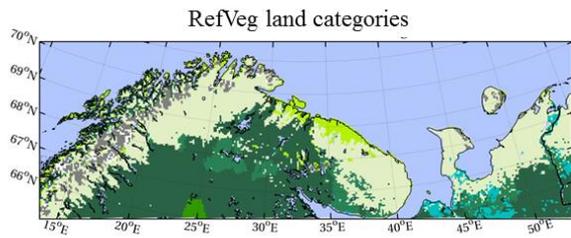
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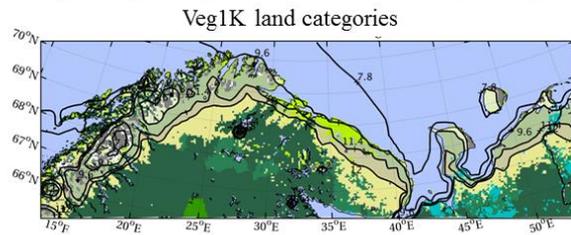
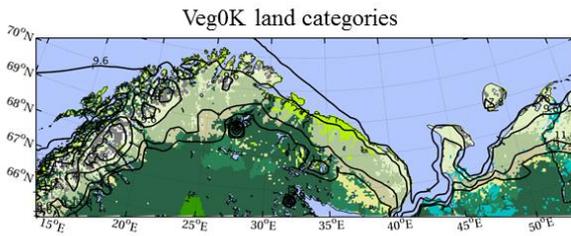
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Figure 32. Illustration of the procedure applied to derive the re-distribute the alpine vegetation distributions used in each simulation. across the study domain. T_{ref} is the mean summer (JJA) temperature distribution in the area as averaged across 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.

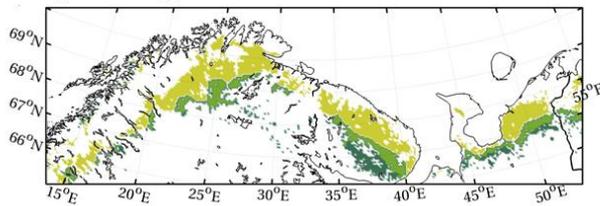
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- Lake
- Barren tundra
- Tall shrubs/trees (2-5m)
- Tall shrubs/trees (>5m)
- Water
- Barren or Sparsely Veg.
- Snow and Ice
- Permanent Wetland
- Grasslands
- Low shrubs (<0.5m)
- Tall shrubs (0.5-2m)
- Evergreen Needleleaf



Veg0K-RefVeg, areas with increased shrub and tree cover



- Low alpine shrubs (0.5-2m)
- Sub alpine shrubs/low trees (2-5m)
- Boreal deciduous (>5m)

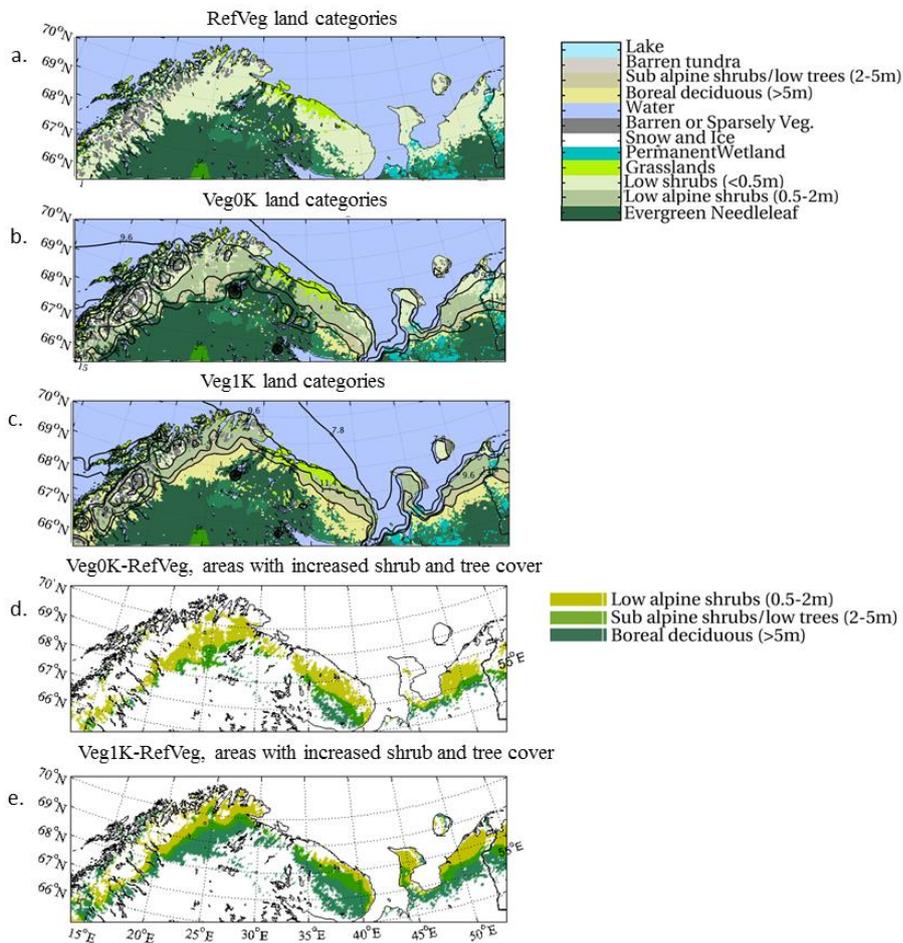


Figure 13: Dominant land use categories (colors) in the a. reference simulations (RefVeg) (~~top panel~~), and as distributed according to 2-m temperature limits the derived bioclimatic zones (indicated by contour lines) in each of the perturbed simulations. Panel b. shows Re-distributed vegetation according to present day climatic envelopes (Veg0K distribution) in the second panel, - and future scenario (Veg1K) and c. based on a 1 K temperature increase Veg1K vegetation distribution in the third panel. Only the temperature contour lines calculated to distinguish between the various alpine zones are shown. In the bottom panels ~~the bottom panel~~, only areas with increased shrub and tree cover are colored, given to show as the difference in vegetation cover between the Veg0K-perturbed and the reference simulations. Panel d. shows Veg0K-RefVeg vegetation changes. e. shows Veg1K-RefVeg vegetation changes.

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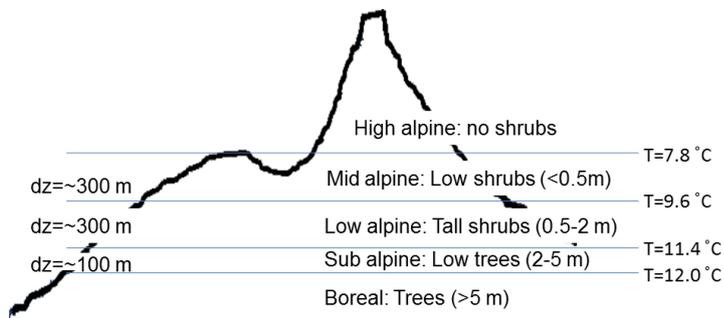


Figure 2. Illustration of alpine zones and corresponding dominating shrub vegetation. The altitudinal extent of each alpine zone is indicated by the values of elevation differences (dz), and corresponding mean JJA temperatures dividing the zones based on mean summer lapse rates in the area.

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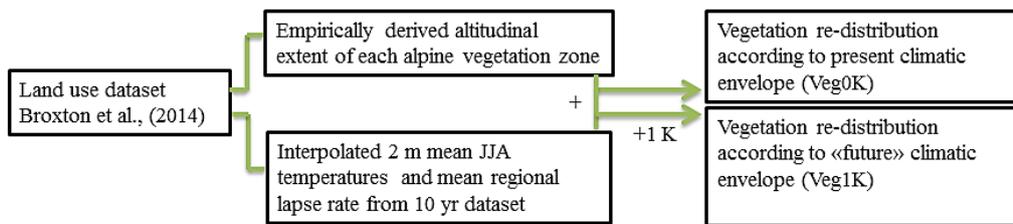
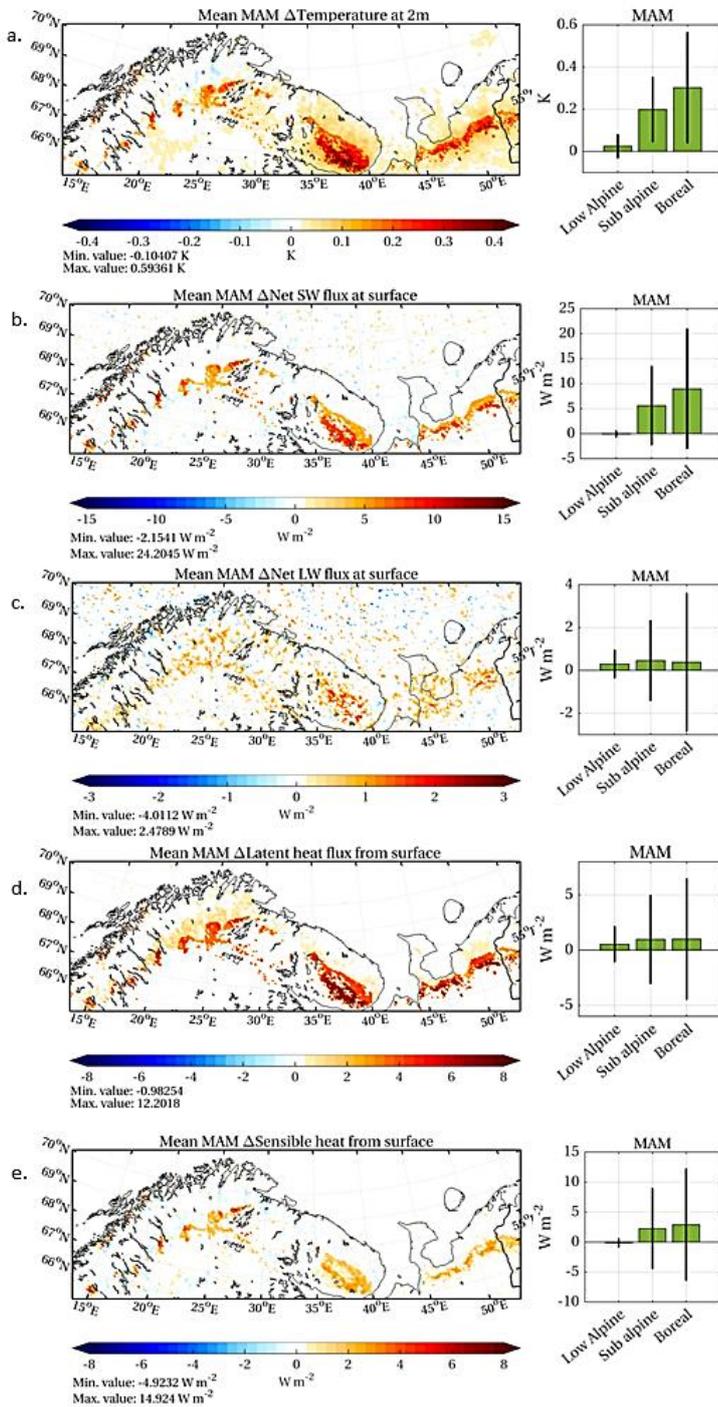
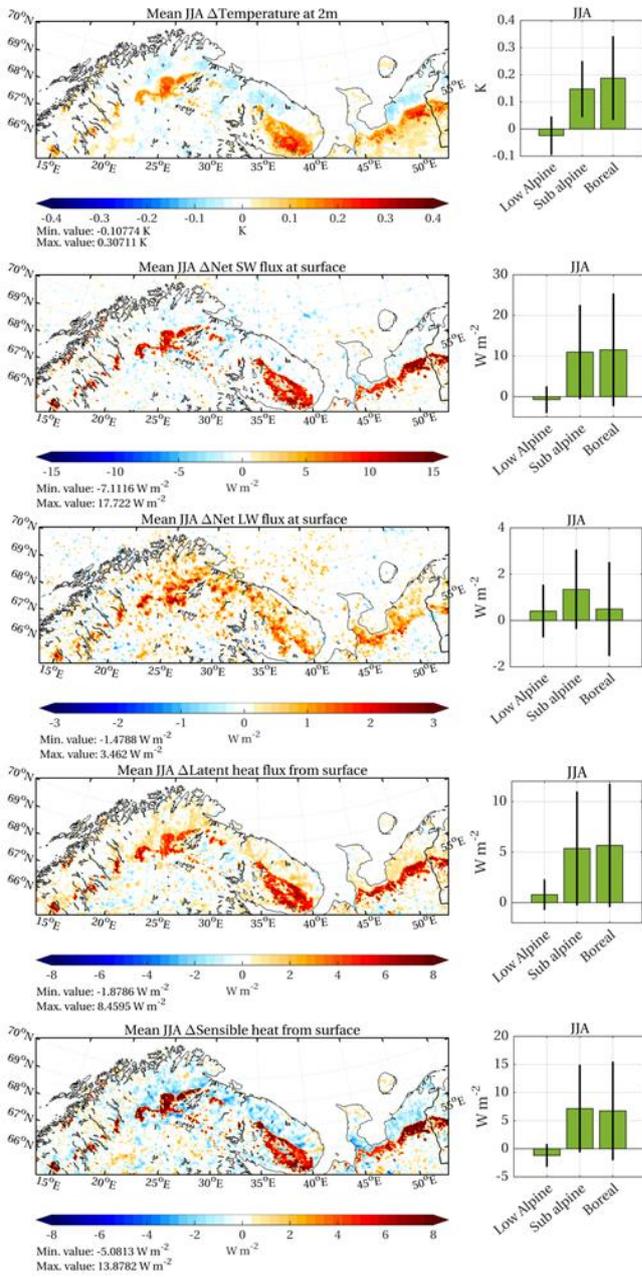


Figure 2. Illustration of procedure applied to re-distribute the alpine vegetation across the study domain.



5 **Figure 44:** Effects of increased shrub cover (Veg0K-RefVeg) on the MAM season **a.** 2 m temperature (**top panel**), **and** surface fluxes of **b.** net SW, **and** **c.** LW radiation (**both** direction downward), **and** **d.** LSH **and** **e.** SLH (**direction** upward from surface). The minimum and maximum **in mean** seasonal **mean** values are shown below each map, to present the full spatial variations in the average seasonal mean. 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.



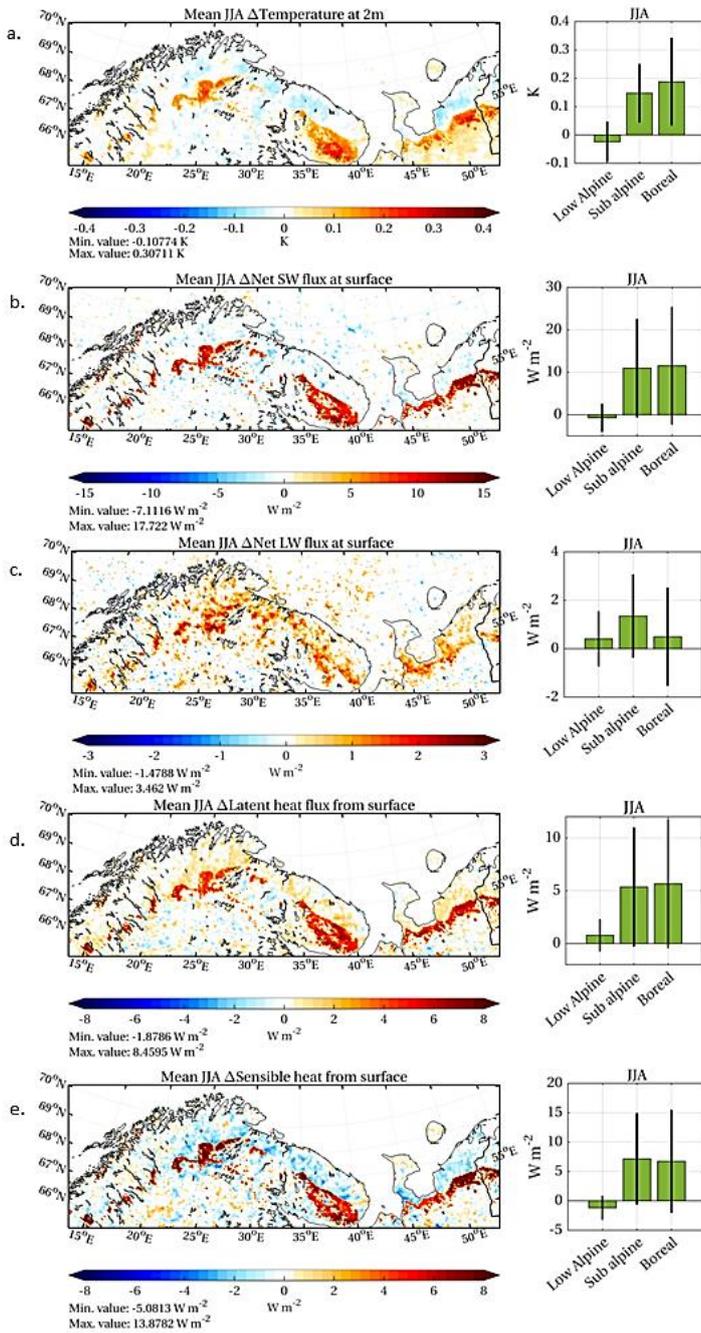


Figure 55. Effects of increased shrub cover (Veg0K-RefVeg) on the JJA season. Variables as in Fig. 4. -2 m temperature (top panel) and surface fluxes of net SW and LW radiation (direction downward) and fluxes of LH and SH (upward from surface) (Only showing significant results at the 95% confidence level, as in Fig 3). 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.

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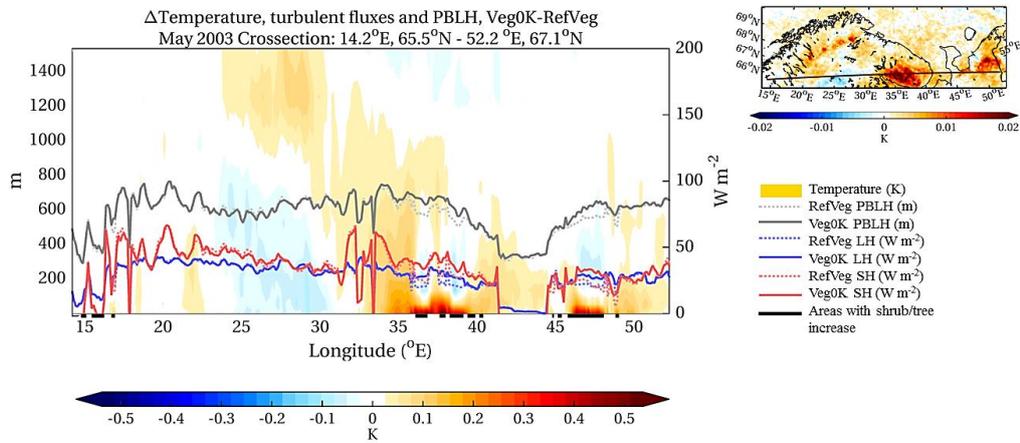


Figure 6: Cross section showing anomalies resulting from increased shrub cover (Veg0K-RefVeg) as averaged over the warm May month. The air temperature anomaly ΔT is shown in colors, and PBL height in grey lines, left axis. Blue and red lines show LH and SH, respectively (in $W m^{-2}$, right axis). Stippled lines show RefVeg values, and solid lines show Veg0K values. Black lines along the bottom line indicate areas with shrub expansion along the cross section. The placement of the cross section line is shown in the inset, along with mean monthly bottom model layer air temperature anomalies.

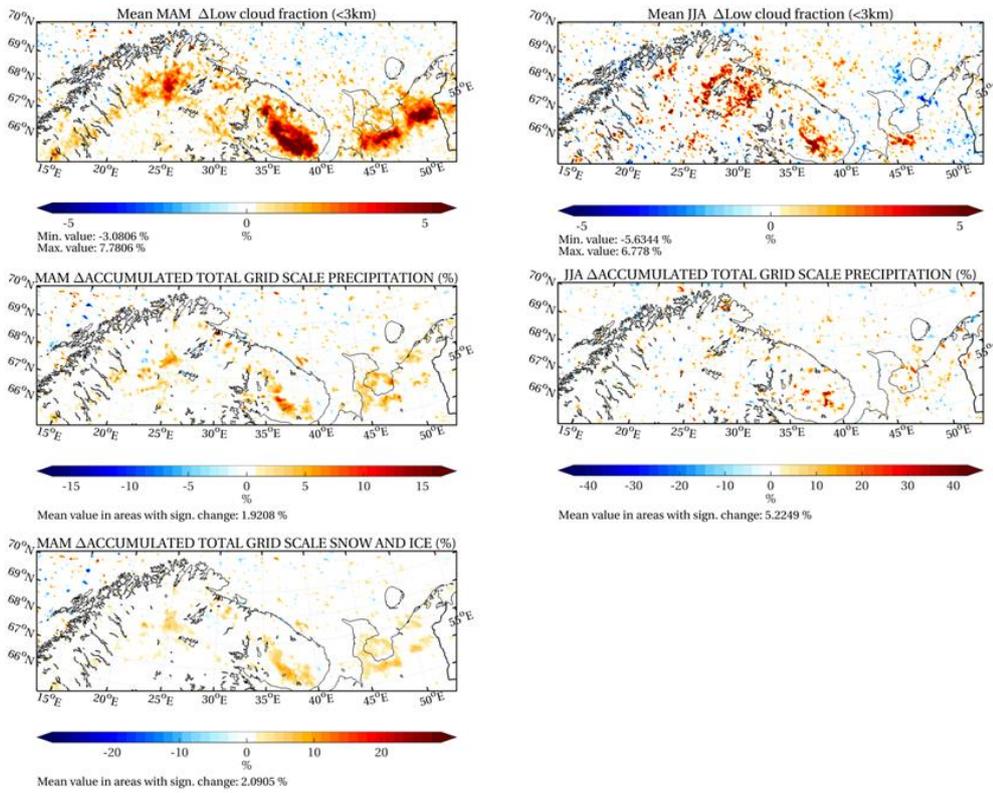
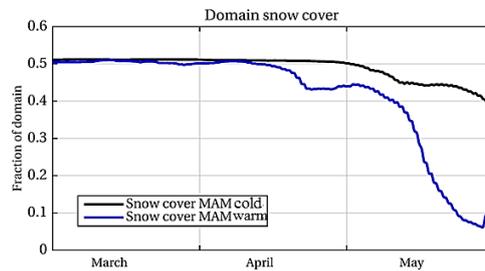
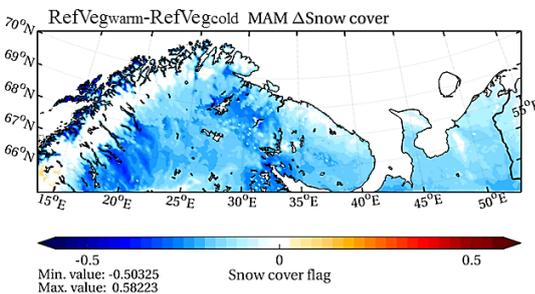


Figure 67. Effects of increased shrub cover (Veg0K-RefVeg) Mean seasonal-effects on low level (< 3 km) cloud cover fraction (top row), relative change in accumulated seasonal precipitation (middle row) and spring season snow and ice precipitation (bottom panel). (Only showing significant changes at the 95% confidence level, as in Fig. 4)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.

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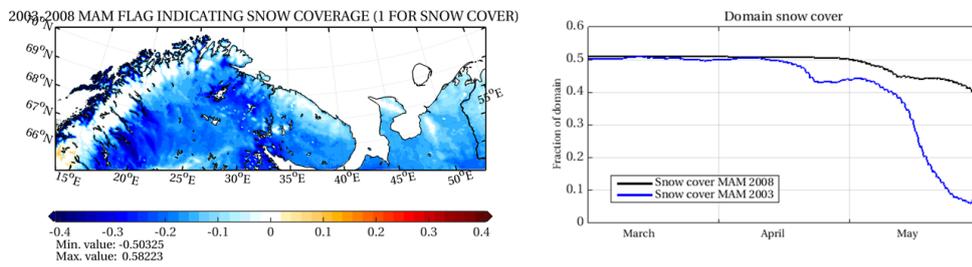


Figure 87: Difference in mean seasonal snow cover between the warm and cold spring season ($\text{RefVeg}_{\text{warm}} - \text{RefVeg}_{\text{cold}}$). Mean seasonal spatial differences are shown in the left panel, and the temporal development over the seasons in the right.

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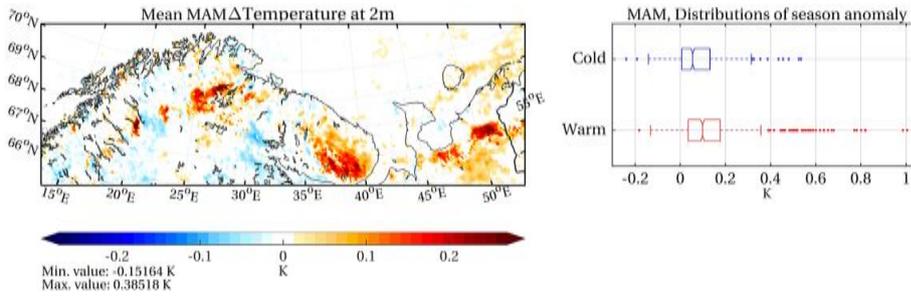


Figure 98: Difference ($\text{warm}_{\text{cold}}$) in temperature response due to increased shrub cover ($\text{Veg0K} - \text{RefVeg}$) between the warm and cold year (only showing significant results at the 95% confidence level). The distributions of shrub induced anomaly values are shown in box plots, the red box shows warm season anomalies and blue box cold season anomalies in areas with vegetation changes.

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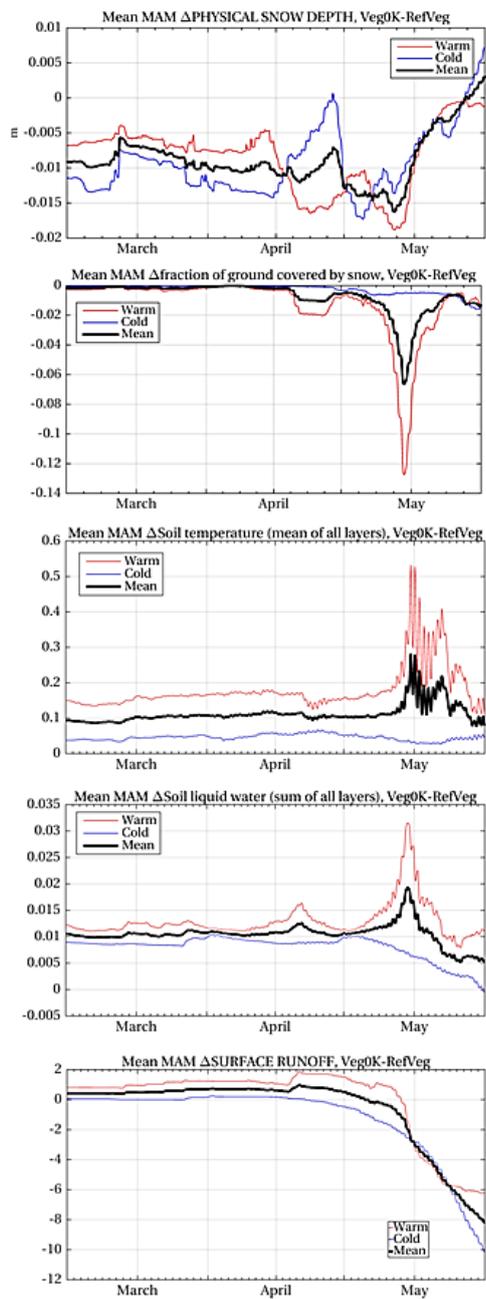
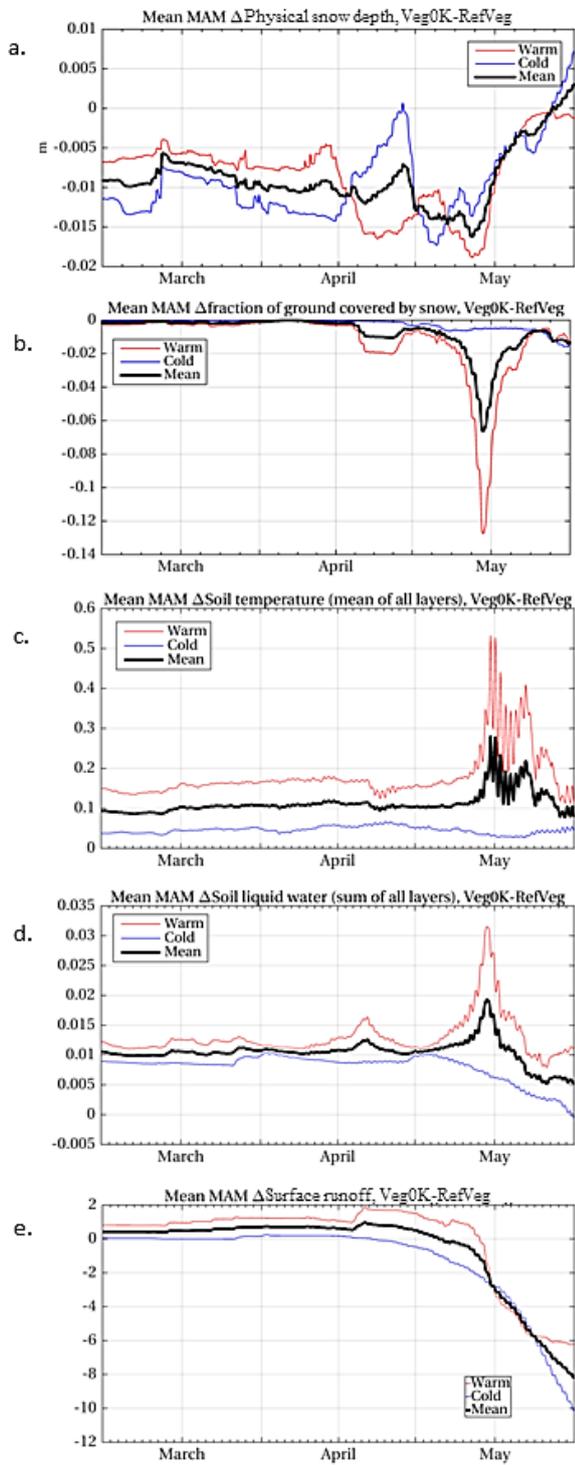
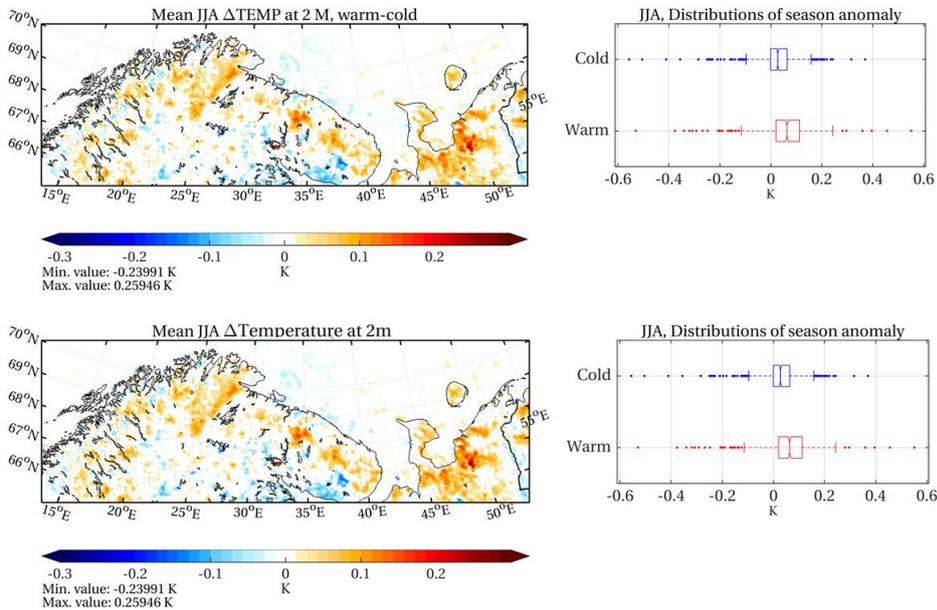
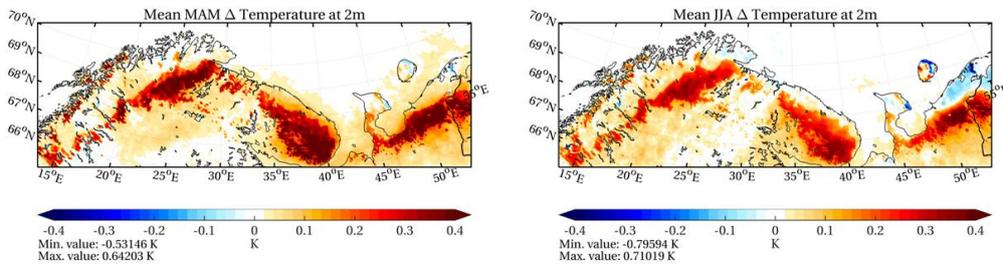


Figure 499: Effect of increased shrub cover (Veg0K-RefVeg) on spring snow depth and cover, soil temperatures and moisture content and surface runoff, as averaged over all areas with vegetation changes. Red and blue lines indicate warm and cold season response, respectively. Black lines indicate inter-seasonal means.





5 **Figure 110:** Difference ($\Delta T_{2m\text{warm}} - \Delta T_{2m\text{cold}}$) 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.



10 **Figure 111:** Effects of increased shrub cover (Veg1K-RefVeg) Effect on the 2 m temperature resulting from a shrub and tree cover increase corresponding to a 1 K warming of JJA temperatures (Veg1K-RefVeg) (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.

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Supplementary material

To support the findings described in the results chapter, some extra figures are attached, along with Table S1, containing details of key shrub category parameter values.

5 Cloud fraction which is shown in Fig. 6 is parameterized based on a modified computation as suggested by Xu and Randall (1996). It depends on the cloud ice and water content, large scale RH and saturation vapor pressure. The cloud fraction is given as a value between 0 and 1.

10 The effect on LAI changes resulting from increased shrub cover is shown in Fig. S1, as averaged over each season (top row) and as averaged over areas with vegetation changes (bottom row).

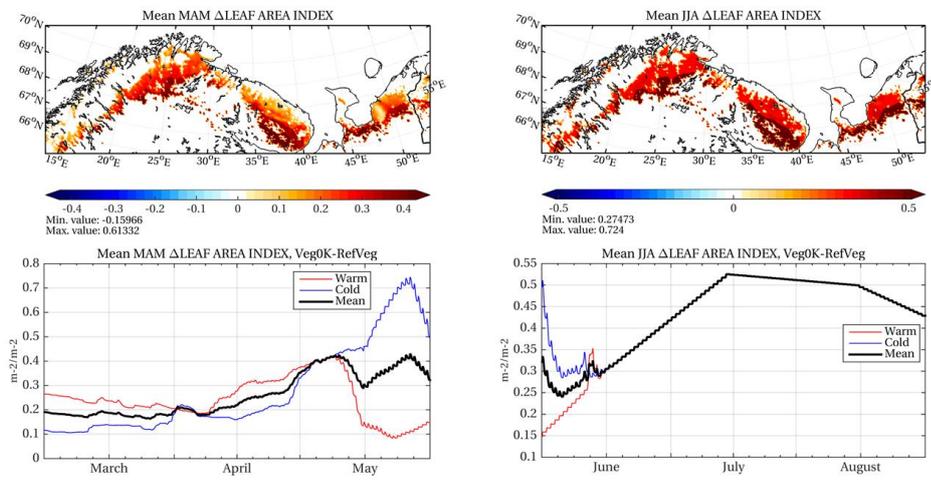


Figure S1: Effects on leaf area index (LAI) for the spring (left column) and summer season (right column) resulting from increased shrub cover (Veg0K-RefVeg). Note that scales differ among panels.

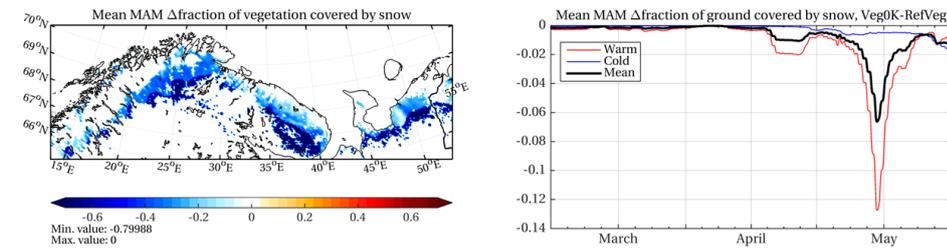


Figure S2. Mean MAM season change in fraction of vegetation canopy buried by snow (left panel) and changes in fraction of ground covered by snow, as averaged over all areas with vegetation changes (right panel) (Veg0K-RefVeg).

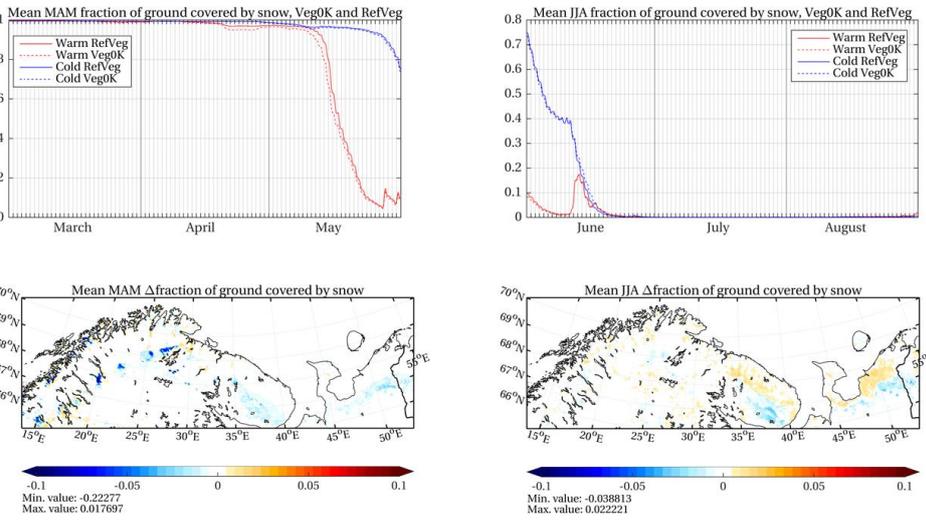


Figure S3. Mean seasonal changes in fractional snow cover resulting from increased shrub and tree cover (Veg0K-RefVeg). Spring (left column) and summer season (right column).

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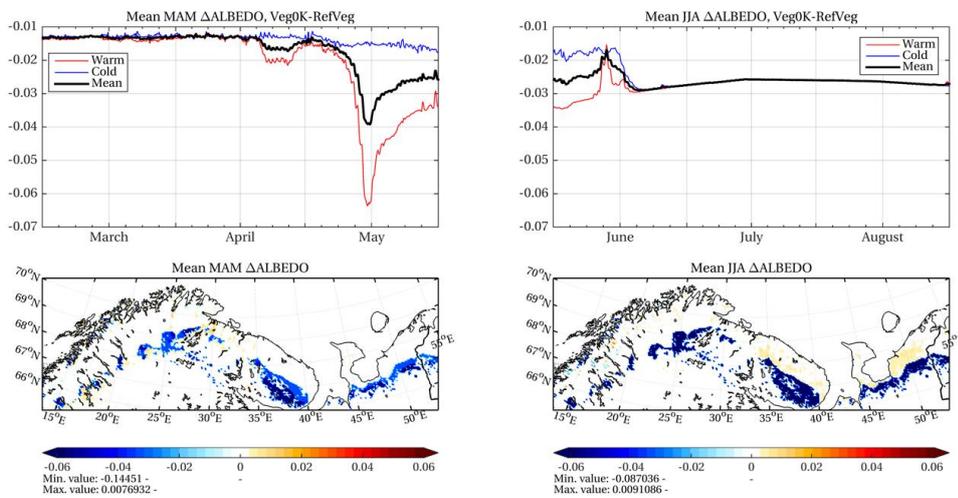


Figure S4. Mean seasonal albedo changes resulting from increased shrub and tree cover (Veg0K-RefVeg). Spring (left column) and summer season (right column).

10

In Fig. S5 changes to surface variables resulting from vegetation changes corresponding to a 1 K shift in summer temperatures are presented. Average anomalies over the spring season in the left column, and summer in the right column. Increased shrub cover leads to higher ET and LH and acts to increase cloud cover and precipitation.

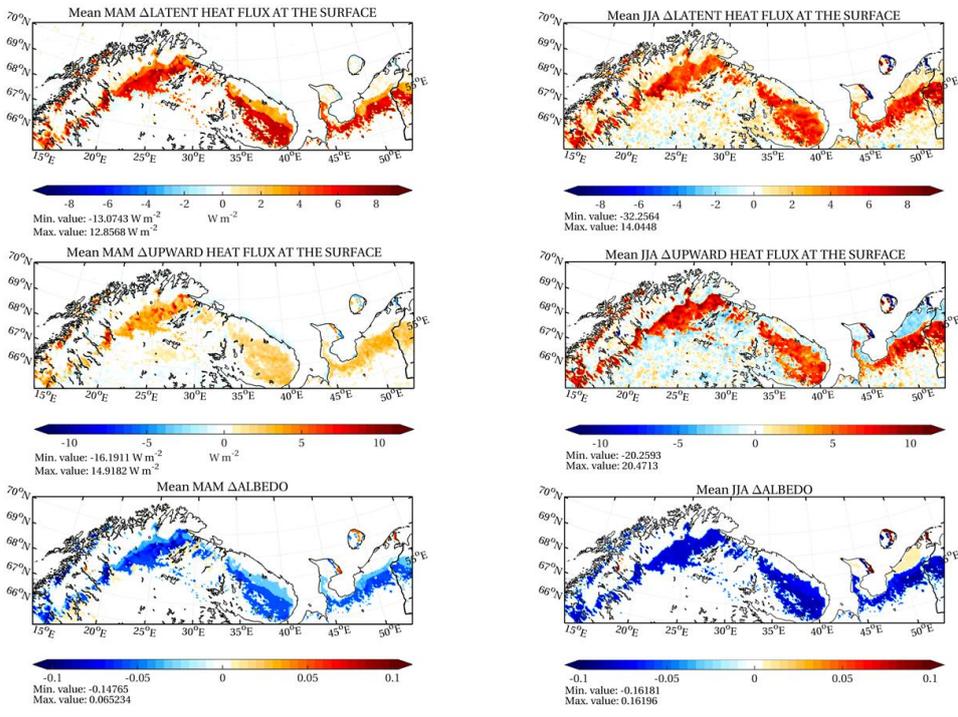


Figure S5: Changes in surface fluxes of heat and moisture (top two rows) and surface albedo (bottom row) resulting from a theoretical 1 K shift in shrub and boreal tree distribution (Veg1K-RefVeg). Spring (left column) and summer season (right column).

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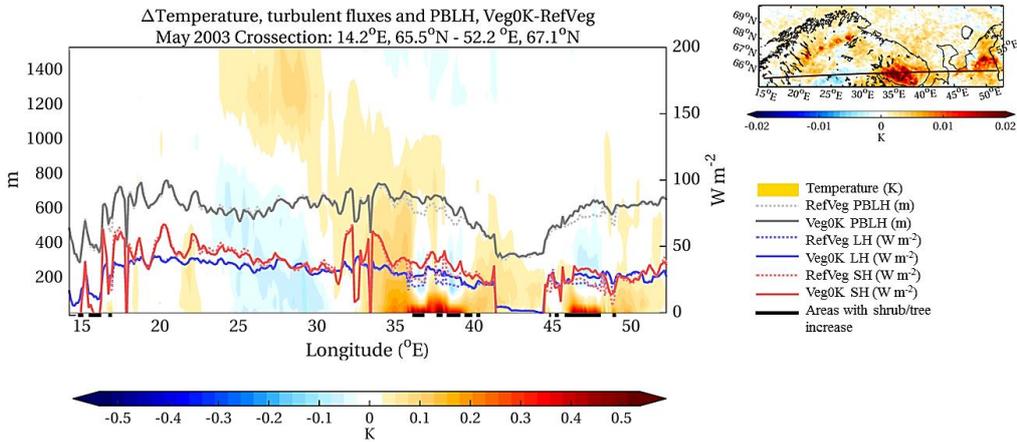


Figure S6: Cross section showing anomalies resulting from increased shrub cover (Veg0K-RefVeg) as averaged over the warm May month. The air temperature anomaly ΔT is shown in colors, and PBL height in grey lines, left axis. Blue and red lines show LH and SH, respectively (in $W m^{-2}$, right axis). Stippled lines show RefVeg values, and solid lines show Veg0K values. Black lines along the bottom line indicate areas with shrub expansion along the cross section. The placement of the cross section line is shown in the inset, along with mean monthly bottom layer air temperature anomalies.

10

It is clear from Fig. S6 that the changes in LH and SH fluxes are local to the areas with vegetation changes, as is the increase in PBL height. The values are mean monthly May values from the warm spring season, and as such they represent one of the months with the largest heating anomaly. The heating anomaly extends well beyond the PBL, however the main heating is occurring within the lower 200 meters.

5

Parameter values for biophysical properties of the key vegetation categories in this study are presented in Table S1.

10

Table S1. Key vegetation categories and corresponding parameter values.

Vegetation type (original name/usage in model system)	<u>Shdfac^c</u>	<u>Nroots^b</u>	<u>Rs^c</u>	<u>Snup^d</u>	<u>Max albedo (with snow)</u>	<u>LAI</u>	<u>Emissivity</u>	<u>Albedo</u>	<u>Z₀</u>	<u>Can. height</u>
						<u>Min</u> <u>Max</u>	<u>Min</u> <u>Max</u>	<u>Min</u> <u>Max</u>	<u>Min</u> <u>Max</u>	<u>Min</u> <u>Max</u>
<u>Sub-alpine tall shrubs/trees (2-5m)</u> (<u>Mixed tundra</u>)	<u>0.60</u>	<u>3</u>	<u>150</u>	<u>0.025</u>	<u>60</u>	<u>0.41</u> <u>3.35</u>	<u>0.920</u> <u>0.920</u>	<u>0.15</u> <u>0.20</u>	<u>0.15</u> <u>0.15</u>	<u>0.1</u> <u>5.0</u>
<u>Below tree line shrubs/trees (>5m)</u> (<u>Wooded tundra</u>)	<u>0.60</u>	<u>3</u>	<u>150</u>	<u>0.025</u>	<u>55</u>	<u>0.41</u> <u>3.35</u>	<u>0.930</u> <u>0.930</u>	<u>0.15</u> <u>0.20</u>	<u>0.30</u> <u>0.30</u>	<u>0.1</u> <u>10.0</u>
<u>Low-alpine shrubs (0.5-2m)</u> (<u>Open shrubland, adjusted</u>)	<u>0.70</u>	<u>3</u>	<u>170</u>	<u>0.035</u>	<u>65</u>	<u>0.60</u> <u>3.00</u>	<u>0.930</u> <u>0.950</u>	<u>0.22</u> <u>0.30</u>	<u>0.01</u> <u>0.06</u>	<u>0.1</u> <u>2.0</u>
<u>Mid-alpine shrubs (0.1-0.5 m)</u> (<u>mixed shrubland/grassland</u>)	<u>0.70</u>	<u>3</u>	<u>170</u>	<u>0.035</u>	<u>65</u>	<u>0.60</u> <u>2.60</u>	<u>0.930</u> <u>0.950</u>	<u>0.22</u> <u>0.3</u>	<u>0.01</u> <u>0.06</u>	<u>0.1</u> <u>0.5</u>
<u>High-alpine (tundra/barren)</u> (<u>Barren/Sparsely vegetated</u>)	<u>0.01</u>	<u>1</u>	<u>999</u>	<u>0.02</u>	<u>75</u>	<u>0.1</u> <u>0.75</u>	<u>0.900</u> <u>0.900</u>	<u>0.38</u> <u>0.38</u>	<u>0.01</u> <u>0.01</u>	<u>0.01</u> <u>0.02</u>

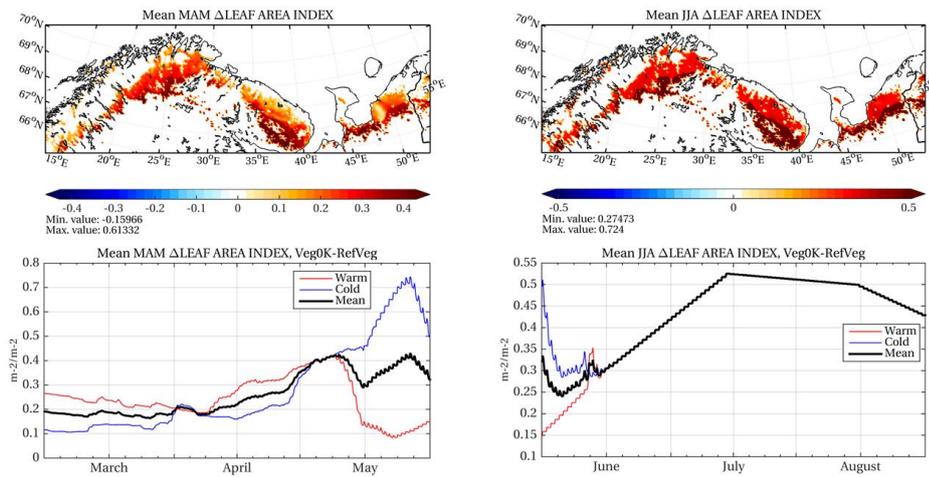
^aShading factor, ^bNumber of root layers, ^cMinimum stomatal resistance, ^dSnow water equivalent for total snow cover

5 **Supplementary material**

To support the findings described in the results chapter, some extra figures are attached, along with Table S1, containing details of key shrub category parameter values.

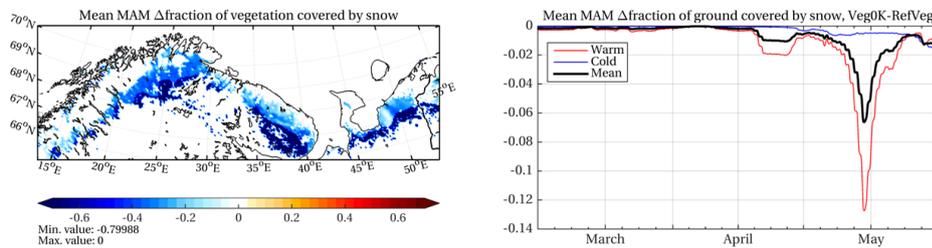
10 Cloud fraction which is shown in Fig. 6 is parameterized based on a modified computation as suggested by Xu and Randall (1996). It depends on the cloud ice and water content, large scale RH and saturation vapor pressure. The cloud fraction is given as a value between 0 and 1.

The effect on LAI changes resulting from increased shrub cover is shown in Fig. S1, as averaged over each season (top row) and as averaged over areas with vegetation changes (bottom row).



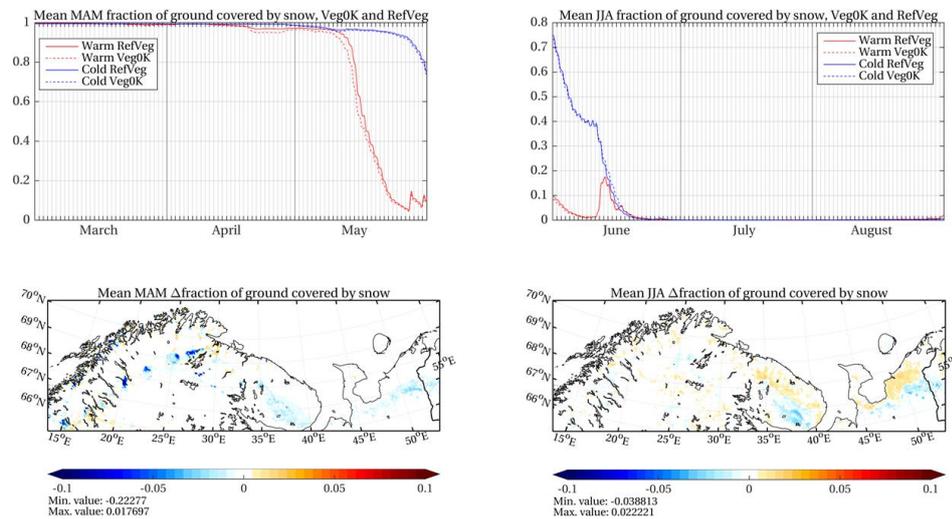
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Figure S1: Effects on leaf area index (LAI) for the spring (left column) and summer season (right column) resulting from increased shrub cover (Veg0K-RefVeg). Note that scales differ among panels.

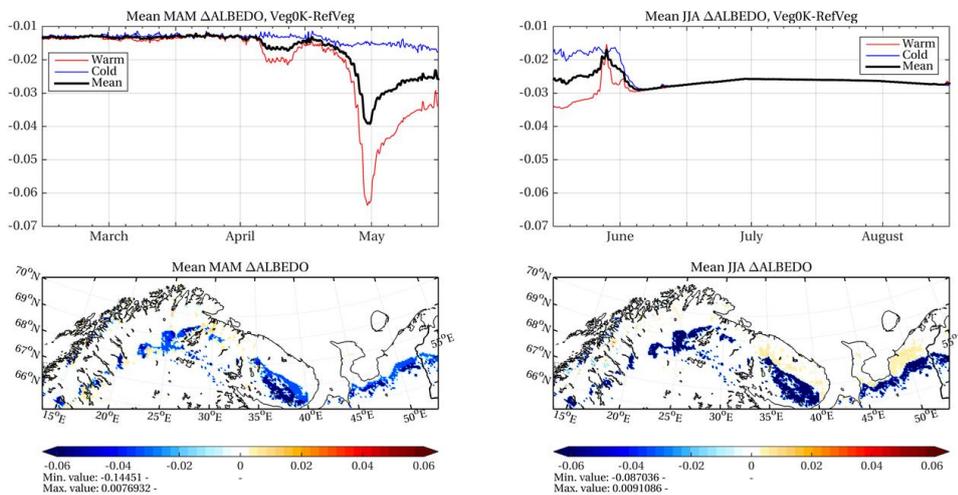


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Figure S2. Mean MAM season change in fraction of vegetation canopy buried by snow (left panel) and changes in fraction of ground covered by snow, as averaged over all areas with vegetation changes (right panel) (Veg0K-RefVeg).



5 Figure S3. Mean seasonal changes in fractional snow cover resulting from increased shrub and tree cover (Veg0K-RefVeg). Spring (left column) and summer season (right column).



10 Figure S4. Mean seasonal albedo changes resulting from increased shrub and tree cover (Veg0K-RefVeg). Spring (left column) and summer season (right column).

In Fig. S5 changes to surface variables resulting from vegetation changes corresponding to a 1 K shift in summer temperatures are presented. Average anomalies over the spring season in the left column, and summer in the right column. Increased shrub cover leads to higher ET and LH and acts to increase cloud cover and precipitation.

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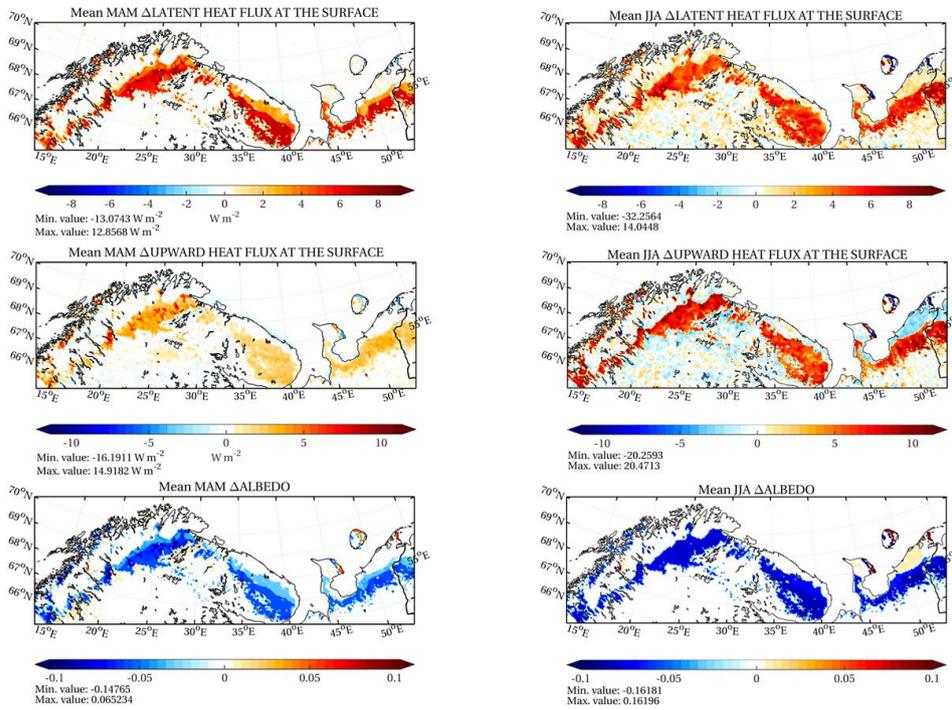


Figure S5: Changes in surface fluxes of heat and moisture (top two rows) and surface albedo (bottom row) resulting from a theoretical 1 K shift in shrub and boreal tree distribution (Veg1K-RefVeg). Spring (left column) and summer season (right column).

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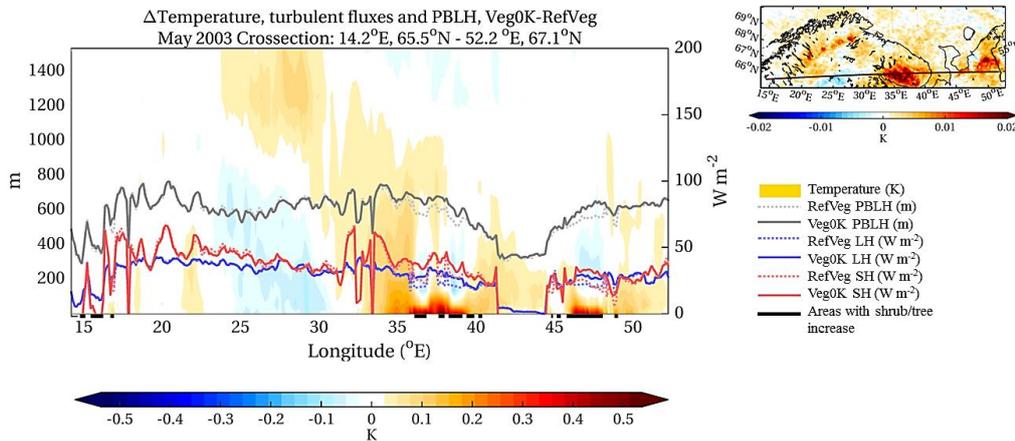


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It is clear from Fig. S6 that the changes in LH and SH fluxes are local to the areas with vegetation changes, as is the increase in PBL height. The values are mean monthly May values from the warm spring season, and as such they represent one of the months with the largest heating anomaly. The heating anomaly extends well beyond the PBL, however the main heating is occurring within the lower 200 meters.

5

Parameter values for biophysical properties of the key vegetation categories in this study are presented in Table S1.

10

Table S1. Key vegetation categories and corresponding parameter values.

Vegetation type (original name/usage in model system)	Shadfac ^a	Nroots ^b	R _s ^c	Snup ^d	Max albedo (with snow)		LAI		Emissivity		Albedo		Z ₀		Can. height	
					Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Sub-alpine tall shrubs/trees (2-5m) (Mixed tundra)	0.60	3	150	0.025	60	0.41	3.35	0.920	0.920	0.15	0.20	0.15	0.15	0.1	5.0	
Below tree line shrubs/trees (>5m) (Wooded tundra)	0.60	3	150	0.025	55	0.41	3.35	0.930	0.930	0.15	0.20	0.30	0.30	0.1	10.0	
Low-alpine shrubs (0.5-2m) (Open shrubland, adjusted)	0.70	3	170	0.035	65	0.60	3.00	0.930	0.950	0.22	0.30	0.01	0.06	0.1	2.0	
Mid-alpine shrubs (0.1-0.5 m) (mixed shrubland/grassland)	0.70	3	170	0.035	65	0.60	2.60	0.930	0.950	0.22	0.3	0.01	0.06	0.1	0.5	
High-alpine (tundra/barren) (Barren/Sparsely vegetated)	0.01	1	999	0.02	75	0.1	0.75	0.900	0.900	0.38	0.38	0.01	0.01	0.01	0.02	

^aShading factor, ^bNumber of root layers, ^cMinimum stomatal resistance, ^dSnow water equivalent for total snow cover

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