Final author response to anonymous referee #1

Bg-2014-478: "Long term effects on regional European boreal climate due to structural vegetation changes" by J. H. Rydsaa, F. Stordal, and L. M. Tallaksen

The referee comments are answered in the following way:

I. the referee comment in italics
II. author response comments
III. reference to corresponding changes in the manuscript.

General comments:

Comment 1

I. "*The authors describe two WRF experiments to demonstrate the effects of northward shifts of boreal vegetation due to anticipated climate change. The experiments include the structural changes in high latitude ecosystems, which result in changes in soil moisture properties and heat fluxes.*"

II. We greatly appreciate the referee taking time to read and comment our manuscript. We have revised the manuscript in accordance with the referee's constructive comments and suggestions.

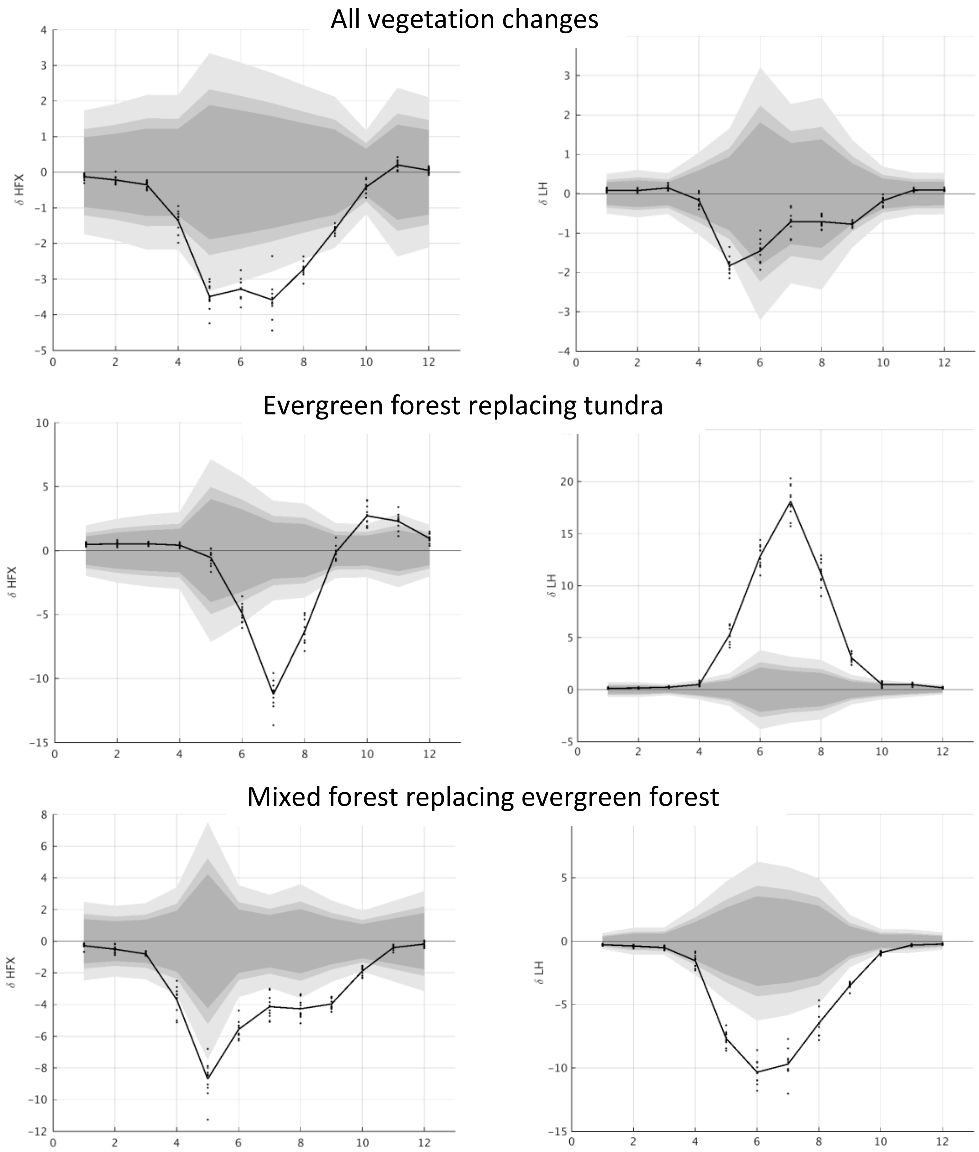
Specific comments:

Comment 1

I. "*Are 10 years sufficient for statistical analysis? Is it possible to either increase the number of years (e.g. to 2001-2012) to have at least twelve annual samples, or to analyze seasonal data with taking all months into account (to have at least 30 months per season) and perform some sort of statistical analysis to show the significance of the results (see also technical comment 11)?*"

II. The referee makes a good point, and we agree that statistical significance of the results would greatly improve the manuscript. We have added a statistical analysis to be able to comment on the significance of the results on a seasonal scale. As the separate monthly values of surface fluxes within each season are not independent of each other, due to temporal autocorrelation in the form of soil moisture etc., in our opinion using

30 months as the population of an analysis might yield biased results. Instead, we have computed monthly mean confidence intervals based on Student's t-test statistics. Monthly means are computed for each area with vegetation changes. Plotting the difference compared to the control simulation with the normalized confidence interval indicates the seasonal statistical significance of monthly means of each area. Each monthly mean outside the confidence interval (chosen here as 95%) is significantly different from the control run mean (i.e. have a 5% chance of passing the interval by chance). Below we have included a figure with results that show the seasonal significance of monthly mean sensible and latent heat flux for different areas of vegetation changes (gray shadings indicate 90, 95 and 99 % conf. intervals). It is clear that the area averaged monthly mean anomalies are only significant in the summer months (May through September), when taking into account all areas with vegetation changes together (upper, left panel). Breaking it up and looking at the areas separately, the area where the tundra pft is changed for the evergreen forest pft (middle, left panel), significant changes are seen in June, July and August, and for the area with mixed forest northward migration, the period from April through October, shows significantly different means from the control simulation (lower left panel). For the latent heat flux, similar results show significant changes during the summer months for each area with forest expansion (middle and lower right panels), and only for May when all areas are averaged together (upper, right). Black dots indicate the ten monthly values.



The manuscript is rewritten in accordance with these findings (See reference to changes in the results and discussion section in technical comments number 11). To avoid excessive figures in the manuscript, the statistical significance of monthly mean anomalies is presented in revised version of Figure 10, where significant results are indicated by circles (as explained in the new figure caption).

Comment 2

I. “*Especially sensible heat flux seems to have a strong annual cycle with observed increases especially during the growing season (Beringer et al., 2005, their Fig. 7) and warmer daytime (Beringer et al., 2001, 2005). Over Norway and Sweden, previous studies found simulated decreases in Sept.-Feb. and increases otherwise (see Snyder and Liess (2014, Climate Dyn. 42, 487–503, their Fig. 6), Jeong et al., (2014,* *Environ. Res. Lett. 9, 094007, doi:10.1088/1748-9326/9/9/094007, their Table 1), and Jeong et al. (2011, Climate Dyn. 37, 821-833, their Fig. 5). The present study finds a decrease in sensible heat flux with resulting decrease in 2m temperature. This should be discussed and maybe related to possible changes in simulated precipitation (see also technical comments 15, 18, and 21).”*

II. The opposite sign of the sensible heat response compared to these other studies is not as expected, as mentioned in the discussion. A more thorough investigation of these results have been conducted and added to the results section and is further discussed and compared to the suggested references. As suggested by the referee, an analysis of the precipitation pattern to explain heat flux partitioning has been included in the revised manuscript.

III. See technical comments 15, 18 and 21 for further details on changes in the manuscript.

Comment 3

I. “*More emphasis should be put on spatially different seasonal changes, which can be of opposite sign between winter and summer, due to different influences from solar radiation and evapotranspiration. Maybe show maps of latent and sensible heat flux changes for all four seasons or at least the winter and summer seasons (see also technical comments 2, 15, and 17).”*

II. The manuscript is rewritten to put more emphasis on seasonal changes by expanding section 3.2 about the seasonal anomalies, and including a statistical analysis on the monthly means. Also, the discussion is revised and expanded according to the seasonal focus.

III. For more specific references to manuscript alterations, see answers to technical comments number 2, 15 and 17.

Technical comments:

Comment 1

I. “*Abstract: Line (L.) 2: “Arctic” not “arctic””*

II. Corrected

Comment 2

I. “*Abstract: L. 14: Is the increase in latent rather than sensible heat fluxes occurring in all seasons? Please clarify. See also Snyder and Liess (2014) and Jeong et al. (2011,2014) about their seasonal results and compare your results to these papers in the discussion.”*

II. The significant changes to the heat fluxes occur only during the summer months (see above answer on comment 2 related to the significant changes).

III. The following has been changed in the abstract; “We find that a northward migration of evergreen needle leaf forest into tundra regions causes an increase in latent rather than sensible heat fluxes during the summer season. Shrub expansion in tundra areas has only small effects on surface fluxes. Perturbations simulating the northward migration of mixed forest across the present southern border of the boreal forest, has largely opposite effects on the summer latent heat flux, and acts to moderate the overall mean regional effects of structural vegetation changes on the near surface atmosphere. “

Added to discussion; “These findings are supported by modeled findings for heat flux changes resulting from similar vegetation changes (Snyder and Liess, 2014 and Jeong et al. 2011,2014.”)

Comment 3

I. “*Page (P.) 15509, L. 18: Delete "and"”*

II. Corrected

Comment 4

I. ” P. 15509, L. 26: Are there any references for successful simulations with dynamic vegetation models? Some studies such as Jeong et al. (2011,2014) had difficulties representing the observed changes in vegetation, but could still be cited here.”

II. We greatly appreciate the referee’s suggestions for additional references, and have added the suggested citations to the introduction.

III. *P. 15509, L. 26:* the suggested citations are added.

P. 15510, L. 5:“Bhatt et al. (2010), link increased high latitude ecosystem productivity to a decrease in near-coastal sea ice and summer tundra surface temperatures, supporting the findings of Jeong et al. (2014), who concludes that vegetation-atmosphere-sea ice interaction gives rise to additional positive feedback of the Arctic amplification based on a series of coupled vegetation-climate model simulations under $2xCO_2$ environment."

Comment 5

I. "*P. 15511, L. 13: Discuss the influence of vegetation on ground heat flux, or cite previous work such as Yang et al. (1999, JGR 104, D16, 19505–19514).*"

II. Suggested reference added.

III. P. 15511, L. 13: Reference added.

Comment 6

I. "*P. 15512, L. 18: Mention either here or in the discussion that these model setups are not able to measure downstream effects originating from outside the WRF domain, since meteorological forcing is only modified locally.*"

II. This is a good point, and specification is added to the methods section.

III. P. 15513, L. 28 : "As the meteorological conditions are only altered as response to the vegetation shifts inside the modelled domain, the simulation setup is not able to estimate downstream effects of vegetation perturbations."

Comment 7

I. *P. 15513, L. 10: Typo: "choice"*

II. -corrected

Comment 8

I. "*P. 15514, L. 1: The MODIS IGBP data used in WRF include the annual cycle. The word "static" might be misleading. This should be clarified.*"

II. The expression is changed to avoid confusion.

III. P. 15514, L. 1: "static land data" is changed to "land use data"

Comment 9

I. "*P. 15515, L. 1: "shift" should be singular here.*"

II. -corrected

Comment 10

I. “*P. 15516, L. 25: Be more specific about the difference between Ex 2 and Ex 1, and state something like "in addition to the changes made for Ex 1, the second experiment... also...". Currently, it is not clear if all Ex 1 modifications are also exactly included in Ex 2, or if only the general structure is maintained.”*

II. Corrected by adding the suggested sentence in line 27

III. P. 15516, L. 27: Added: “in addition to the changes made for Ex 1, also”

Comment 11

I. “*P. 15518, L. 16: Again, are these results statistically significant? The authors should perform some sort of statistical test to show the relevance of the detected changes.”*

II. As described above, a statistical analysis is performed on a seasonal level, indicating that the changes in mean monthly sensible- and latent heat fluxes are significantly different from control simulation during the summer season for both the areas of evergreen forest expansion into tundra vegetation, and in the areas with mixed forest expansion. The 10 year mean response is largely dominated by the summer season results, and this is clarified in the revised manuscript. The statistical analysis is performed on a seasonal scale and is therefore added in Section 3.2. The results for the monthly mean boundary layer height does not prove statistically significant, and the description of this variable is therefore omitted in the results section and corresponding Figure 5 is removed. The results for the 2 meter temperature show surprisingly small response to the vegetation perturbations, too small to yield statistically significant changes on a monthly mean scale. However, we regard this as an important feature of the results, and it is accordingly commented on in the revised manuscript.

III. P. 15518, L. 23: Added; “There are large seasonal variations in the sensible heat response, and these results are largely reflecting the summer season results (see sect. 3.2).”

P. 15519, L. 10: Added; “A statistical analysis of the surface fluxes is presented in sect. 3.2.”

P. 15520, L. 4: Added; “The weak response in the 2 m temperature is a result of the offset of lowered surface albedo by the increase in latent heat flux, yielding insignificant differences in the 2 m temperature for all seasons (Sect.3.2).”

P. 15520, L. 12: Added; “Seasonal statistical significance of corresponding variables is presented in Sect 3.2. “

Comment 12

I. “*P. 15520, L. 7: How can this cooling be explained? Please discuss the above results for sensible heat flux here.”*

II. Explanation for the observed cooling is added, along with specification of the significance of the result. Further discussion of the result is added in the discussion section.

III. *P. 15520, L. 7:* Added; “This cooling can be explained by the increase in surface albedo related to this vegetation perturbation, yielding less warming of the surface/canopy and corresponding weaker heat transfer by turbulent heat fluxes to the atmosphere.”

P. 15520, L. 12: “Seasonal statistical significance of corresponding variables is presented in Sect 3.2. “

Comment 13

I. “*P. 15520, L. 18: Fig. 8 only shows wind differences. We don’t know if there are decreased northward winds or increased southward winds. Please either show the wind field in the control experiment or rephrase to something like "reduced northward component". In general, wind fields can be represented by vectors with a reference vector in the legend to save space. However, for the present analysis it might be sufficient to show the change in absolute wind speed (sqrt(u^2+v^2)) in a single figure and relate the results to the heat fluxes.”*

II. This is a good point, and the figure is changed as suggested. The absolute wind speed is presented, and relevance to the presented heat fluxes is explained in the revised manuscript.

III. Figure 8 is replaced.

P. 15520, L. 16 :“The changing wind speed is closely related to the perturbations to the surface roughness length, and influences the turbulent heat fluxes. The reduced wind speed in the northern part of the domain contributes to decreases in the heat fluxes, and an opposite effect can be expected along the area of mixed forest perturbation.”

Comment 14

I. “*P. 15521, L. 2: Can the authors mention if there is a change in the annual cycle of soil moisture due to the change from evergreen to deciduous forests?”*

II. The soil moisture somewhat decreases in March and April and increases in July through October in response to the change from evergreen to deciduous forest. However, the monthly mean differences are only statistically significant in the area of evergreen forest expansion into tundra regions for spring and summer for the upper layer, and all year round for the bottom layer.

III. *P. 15521, L. 2:* Added; “The other vegetation changes do not significantly affect the soil moisture content, however the change of evergreen trees into mixed deciduous forest influences the annual cycle of soil moisture content by decreasing it in spring and increasing it in late summer and fall“
Figure 10 is altered and the seasonal impact on soil moisture is added, along with indications of statistical significance.

Comment 15

I. *P. 15521, L. 22: On p. 15511 l. 8-10, the authors write "Eugster et al. (2000) found that in general evergreen conifer forests have a canopy conductance half of that of deciduous forests, resulting in a higher sensible heat flux" and also Snyder and Liess (2014) and Jeong et al. (2011,2014) found an increase of sensible heat flux after evergreen forest expansion due to reduced albedo during summer. How can sensible heat flux be reduced here? Or, how is sensible heat flux defined in this study? Maybe an analysis of precipitation can shed some light on this discrepancy?*

II. Our findings are in line with Eugster et al., (2000), with reduced sensible heat flux going from evergreen forest to deciduous (mixed) forest along the southern border of our domain. However, as the referee points out, they do not match the findings of Snyder and Liess (2014) and Jeong et al. (2011,2014) with regard to changing vegetation category from tundra to evergreen forest. The referee suggests an analysis of the summer precipitation, which has been conducted, and added to the discussion of these results in the discussion section.

III. P. 15527, L.17: “The results show an increase in summer precipitation in areas with northward migrating evergreen forest, compared to the control simulation. An analysis of the mean JJA rainfall in this area alone shows an increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would increase the partitioning of increased absorbed radiation (due to lowered albedo) into latent rather than sensible heat flux.

Comment 16

I. “*P. 15522, L. 1: How can 2 m temperature increase with "a reduction in heat transfer to the atmosphere"? Please clarify if sensible or latent heat flux is meant, or both.*

II. Only sensible heat is meant, and manuscript is adjusted accordingly.

III. Corrected to “sensible heat flux”.

Comment 17

I. *P. 15522, L. 24: Spring and summer are considered the seasons with strongest PBL eight increase in Snyder and Liess (2014) due to strongest sensible heat flux increases. why is summer opposite of spring in Ex 1 in this study? Again, the authors should check if the model produces excessive summer rainfall in Ex 1, which might also explain the increase in latent heat flux and 2m moisture.”*

II. After conducting a statistical analysis of these results, the PBL height differences are not statistically significant, and will be omitted in the results section, and only mentioned in relation to the sensible heat flux in the discussion section. As mentioned in comment number 15, further discussion of the heat fluxes with relation to summer precipitation is added to the discussion section, as suggested by the referee.

III. P. 15522, L. 18-28: Analysis of the PBL height is removed from the results section.

Comment 18

I. *P. 15523, L. 6: This cooling is opposite of previous findings by Liess et al. (2012), Snyder and Liess (2014), and Jeong et al. (2011, 2014) possible reasons should be discussed (sensible heat etc.)*

II. The description of the seasonal variations in the 2 m temperature is revised, and explained in relation to the sensible heat fluxes and the statistical analysis.

III. P. 15522, L. 1-12: Revised; “The effects of vegetation changes on the 2 m temperature are complex and vary across the areas of vegetation shifts and seasons (Fig. 10, lower right panel). However, despite in part large effects on surface heat fluxes, the overall 2 m temperature response is low and the monthly mean not statistically significant. In areas with shrub expansion there is a small, yet persistent year-round positive effects on the temperature compared to the control run, with the largest effects occurring in fall and winter months. In areas with evergreen forest expansion we see a wintertime heating, whereas the summer time effect is opposite, causing a cooling of the 2 m temperature in June through August, reflecting the decrease in sensible heat flux in the same period. The effect of the mixed forest migration is a modest year-round cooling of the 2 m temperature, and the effect is largest in the spring and autumn months, and lowest in mid-summer. The overall effect is a net increase in 2 m temperatures in winter, and decreasing 2 m temperatures in summer (solid line). This is accounting for all vegetation shifts. "

Comment 19

I. *P. 15524, L. 8: What does "energy limited rather than water limited" mean? Evaporation is related to temperature and kinetic energy from the low-level wind field.*

II. The term energy limited refers to areas in which the actual evaporation is limited by the radiative energy available, rather than the water available in the soil and canopies, which is the case in water limited regimes. Explanation is added to the revised manuscript for clarity.

III. P. 15524, L. 8: Changed into "This indicates that the soil moisture content does not limit the rate of latent heat, suggesting that the latent heat flux is limited by the available radiative energy, rather than available water (Seneviratne et al., 2010)."

Comment 20

I. *P. 15524, L. 13: Can the authors comment on the rooting depth for forest vs. shrubs here? If forests have higher rooting depth, they are less affected by lower soil moisture in the upper layers.*

II. This is a good point, as the rooting depth of the evergreen forest is four root layers, instead of three, as is the case with the shrub/tundra.

III. P. 15524, L. 13: Added; "Also, the evergreen forest can reach four root layers rather than three, which is the case for the tundra, making more soil water available to the evergreen forest."

Comment 21

I. *P. 15527, L. 2: These results by Beringer et al. (2005) are consistent with the WRF experiments by Liess et al. (2012), but Fig. 4 in the present study shows decreases. Again, the present results might show different sensible heat flux based on possible precipitation increase. Please check this and discuss a possibly different WRF setup used here.*

II. As the referee correctly suggests, the vegetation shift does lead to an increase in the summer precipitation, which acts to increase the evaporation and thereby the latent heat flux rather than the sensible heat flux in the area. With regard to the model setup, rain is produced in both the microphysics scheme and in the cumulus scheme. There are several options for such schemes within the WRF framework, and results could well be influenced by the choices made for these, along with the choices related to the applied vegetation changes. Further discussion on this subject is added to the discussion.

III. P. 15527, L. 17: Added ; "Also, the applied vegetation perturbations lead to increases in summer precipitation in the region, acting to increase the latent rather than the sensible heat flux. Our results show an increase in summer precipitation in areas with northward migrating evergreen forest, compared to the control simulation. An analysis of the mean JJA rainfall in this area alone shows an increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would increase the partitioning of increased absorbed radiation (due to lowered albedo) into latent rather than sensible heat flux. Also, the specifics of vegetation perturbations made might influence these results. Here, we have chosen to only perturb the vegetation type in each area. The greenness fraction is not altered, which might influence the results with regard to the evapotranspiration and thereby available energy for sensible heat, as demonstrated by (Hong et al., 2009). Further investigation of the sensitivity of these parameters is beyond the scope of this study, but certainly important subjects for further work."

Comment 22

I. *P. 15529, L. 20: See comment 19.*

II. See answear and corresponding manuscript changes in comment 19. The manuscript at this point is left as is, as the expression is explained earlier along with added citation.

References

Bhatt, U. S., Walker, D. A., Raynolds, M. K., Comiso, J. C., Epstein, H. E., Jia, G., Gens, R., Pinzon, J. E., Tucker, C. J., Tweedie, C. E., and Webber, P. J.: Circumpolar Arctic Tundra Vegetation Change Is Linked to Sea Ice Decline, Earth Interact, 14, 8, 2010.

Hong, S. B., Lakshmi, V., Small, E. E., Chen, F., Tewari, M., and Manning, K. W.: Effects of vegetation and soil moisture on the simulated land surface processes from the coupled WRF/Noah model, Journal of Geophysical Research-Atmospheres, 114, Artn D18118

Doi 10.1029/2008jd011249, 2009.

Jeong, J. H., Kug, J. S., Linderholm, H. W., Chen, D. L., Kim, B. M., and Jun, S. Y.: Intensified Arctic warming under greenhouse warming by vegetation-atmosphere-sea ice interaction, Environ Res Lett, 9, Artn 094007

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Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Sci Rev, 99, 125-161, DOI 10.1016/j.earscirev.2010.02.004, 2010.