Response to the Interactive comments of Referee #1 and #2 on **"Satellite observations of changes in snow-covered land surface albedo during spring in the Northern Hemisphere"** by K.Atlaskina et al.

We are grateful to both referees for their time to provide critical comments to our manuscript. Their reviews and thoughtful comments led to the valuable changes and helped us greatly to improve quality. The comments of Referee #2 are similar to those of Referee #1, point 1, and are therefore not addressed separately.

Authors' response to the comments of Referee #1.

We reply to these comments below, point by point. Note that the referees' comments are shown in **bold**, our response in regular font and changes in the manuscript are reported in *italics*, rejected parts of the text are marked with ~~strikethrough~~. Numeration is identical to the one in Referee#1 interactive comment.

Major comments

1. **The interpretation of the results is complicated somewhat by the use of monthly data. In principle, a better temporal resolution could be achieved by averaging daily atmospheric reanalysis data (e.g. ERA-Interim) to the 8-day resolution of the MODIS data, although of course, reanalyses are partly model-dependent. Since such an endeavour would involve redoing most of this study, and probably quite a large amount of work, this suggestion is optional. At any rate, some more discussion of this issue should be included in the manuscript. One specific example concerns the relation between albedo and temperature for snow-covered regions. In the present study, the albedo is found to decrease with temperature at temperatures above -15°C while Aoki et al. (2003) shows that the snow albedo is very stable at temperatures below -10°C (as noted on p. 2748). This difference might well arise from the use of monthly-mean temperature data. Even if the monthly mean is -15°C, substantially higher temperatures favoring faster snow metamorphosis could well occur within the month, and perhaps even the melting point is reached occasionally. In the same vein, even if the monthly-mean temperature is well below 0°C, occasional liquid-phase precipitation could occur.**

Thank you for pointing out this concern. We understand that averaging to the monthly levels has that limitations. Nonetheless, we believe that our results are interesting and useful for the scientific community. Since our study covers a large territory and spatial resolution which are comparable with that of CMIP5 models, which also mainly provide their results as monthly means (Taylor, 2011). In this context, the shift evidenced by our analysis of the relationship between albedo and temperature might serve as an indicator of a climatically important threshold. Anonymous Referee #2 also discusses this data resolution limitation, therefore, we conducted additional analysis and propose to include these results as a supplement. Modifications to the manuscript are reported below as well as the addition to the Supplement.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bulletin of the American Meteorological Society, 93, 485-498, 2011.

To the Supplement:

To study the effect of the temporal data resolution on the effects described in the manuscript, we analyzed NCEP North American Regional Reanalysis NARR data (Mesinger et al, 2006). It is the high resolution combined model and assimilation dataset that provides 8-times daily, daily and monthly means of various meteorological parameters at the surface and at 29 pressure levels. It covers North America and has a spatial resolution of about 0.3 degrees (32 km). NARR is known to have a better accuracy in comparison with global reanalysis datasets due to the use of better/more observations, better assimilation techniques and model performance in combination with finer spatial resolution.

We analyzed 13 years of daily surface air temperature data. The dataset was reprojected and resampled to the 25km EASE grid to allow for direct comparison. We calculated mean values for each of the 16-days MODIS albedo product collection periods. Three regions were analyzed — Arctic Archipelago, North Canada and Labrador Peninsula. Masks equivalent to those of April (Fig 1. of the manuscript) in the main analysis were applied. Mean region values were calculated if at least 500 pixels with 100% SCF (312 500 km2) had valid data, which resulted in 168 data points for the Arctic Archipelago and North Canada, and 150 for Labrador.

Scatterplots of regionally-averaged values of albedo vs. air temperature are shown in Fig S3. Because the threshold of -15°C found in our work did not coincide with those described in the literature (e.g. Aoki et al, 2003), it is of interest to study whether substantially warmer temperatures occur within MODIS data collection periods. We counted the number of days in each of the 16-days intervals when the temperature exceeded the mean temperature for that period by half the value. For example, for a mean temperature of -10°C, days warmer than -5°C were counted. This number is shown with color in Fig S3. Such simple metric provides insight in the positive temperature fluctuations with emphasis on the temperatures range from -10 to -15°C. Similar to the main analysis, this graph reveals a relationship between albedo and temperature. However, for the warmer regions of Labrador and North Canada, the temperature threshold above which negative albedo-temperature correlation is observed, can be drawn at about -10°C. For the Arctic Archipelago, which is the coldest of the three regions studied, the threshold coincides with the one we found previously. The number of warmer than average days in the temperature range from -10 to -15°C is smaller in the Arctic Archipelago, yet surface albedo decreases at the lower temperatures than in warmer regions. Based on these findings we can conclude that regional differences exist, and in the colder regions snow covered surface albedo decreases at the lower temperatures.

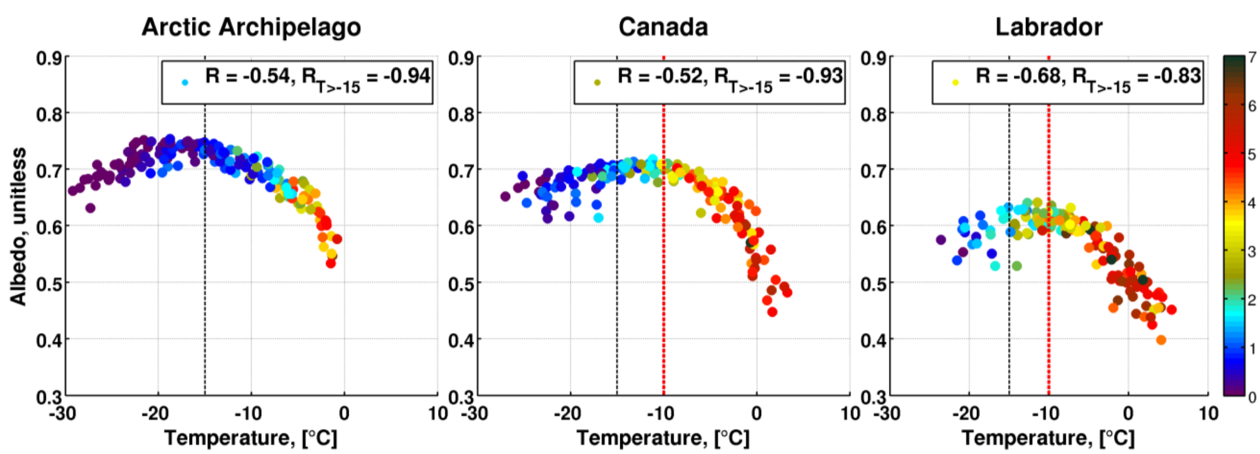


Fig S3. Snow-covered land area albedo vs. NARR mean regional air temperature for the selected regions. The correlations for all data points and for data points corresponding to the mean temperatures above -15°C are displayed in the legend. The black dashed line shows -15°C, and the red *line -10°C. The colorbar shows the number of days for a given 16-days MODIS data accumulation period with temperatures exceeding the mean value by half in absolute values.*

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., Jović, D., Woollen, J., Rogers, E., Berbery, E. H., Ek, M. B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D., and Shi, W.: North American Regional Reanalysis, Bulletin of the American Meteorological Society, 87, 343-360, 2006.

To the manuscript:

<u>Abstract:</u>
The second largest driver for snow-covered land surface albedo changes is the air temperature when it exceeds *a value between -15°C and -10°C, depending on the region.*
<u>Section 5:</u>
Air temperature affects surface albedo most in conditions of non-changing SCF during spring. The results presented in Sect. 4 suggest that there is a threshold of about -15°C, above which the temperature does have a significant effect on the surface albedo, while at lower temperatures there seems to be no effect. This finding is supported by the relations found between regionally averaged albedo and air temperatures and also by the Spearman correlation maps. *Averaging to the monthly means, however, complicates interpretation of the results. A long averaging period may level possible temperature fluctuations and hence the effect of potentially occurring warmer periods during the month over which the data are averaged, which favor snow metamorphosis, cannot be observed. To address this limitation, an independent dataset of finer temporal resolution was analyzed. Data, methods and results are described in the Supplement. We found that temperature threshold value depends on the region and can depart from -15°C. Notably, the coldest region of the Arctic Archipelago is characterized by the lowest threshold value of -15°C consistent with the one found in the current analysis.*
<u>Conclusions:</u>
Our results suggest that air temperature is one of the possible reasons for the albedo change when it exceeds *a value between -15°C and -10°C, depending on the region*, above which the albedo and the temperature are negatively correlated.

The 13-year satellite record is still somewhat short from the climatological point of view. The geographical patterns and especially trends are bound to have "random" features related to short-term climate variability. Therefore, perhaps too much emphasis is put on describing the geographical patterns. E.g., the discussion on p. 2757, line 17 – p. 2758, line 17 could be shortened. Instead, I would suggest adding an analysis of how the correlation (or alternatively regression coefficient) between albedo and various quantities depends on monthly-mean temperature. On physical grounds, I would expect a more negative albedo-temperature relationship at higher temperatures, as snow metamorphism accelerates with increasing temperature, especially if the temperature occasionally reaches the melting point. Similarly, the relationship between albedo and precipitation might change from positive at lower temperatures to negative in warmer conditions (snowfall generally increases the albedo by adding a layer of new, highly reflective snow, while rain very likely decreases the albedo). It would be interesting to see if these relationships can be seen from the monthly data. I suggest plotting the correlations (albedo–temperature, albedo–precipitation, albedo–wet days, perhaps also albedo–EVI) against monthly-mean

temperature for each grid point (i.e., a scatter plot with temperature on the x-axis, correlation on the y-axis). This would enhance the analysis reported in Section 4.3.

Indeed the datasets we used in our study are short for climatological significance. Nonetheless, this short data is a good alternative to other sources of environmental information, such as ground-based measurements which are not available over most of the study area, or reanalysis that, as Referee #1 pointed out, are partly model-dependent and have coarser spatial resolution. It must be kept in mind that most of our study area is sparsely populated and weather stations are sparse. Therefore, we believe that it is worth to utilize existing satellite data to observe possible changes and try to find an explanation for them. We suggest to mention in the manuscript both concern and motivation to use this data:

We use surface albedo data which are routinely provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) *since the year 2000*. *This dataset is not yet sufficiently long to be appropriately utilized to provide climatoligically significant results. Nonetheless, i*t is a consistent validated product readily available for different research purposes (Schaaf et al, 2011)*, and we aim to describe observed changes as they are seen and give an explanation where possible.*

Concerning the detailed description of geographical patterns in the observed temporal variations, we would like to keep it unchanged. Our approach was to report in a straightforward manner patterns we observed and map them well geographically.
Suggested correlation plots were produced and are shown below in Fig. R1. Plotting these parameters for each grid point did not add new information to the analysis. As expected, the correlation coefficient between albedo and temperature becomes predominantly negative as the spring proceeds. Values for other parameters are too scattered to identify any dependency or shift in the correlation strength in different temperature ranges.

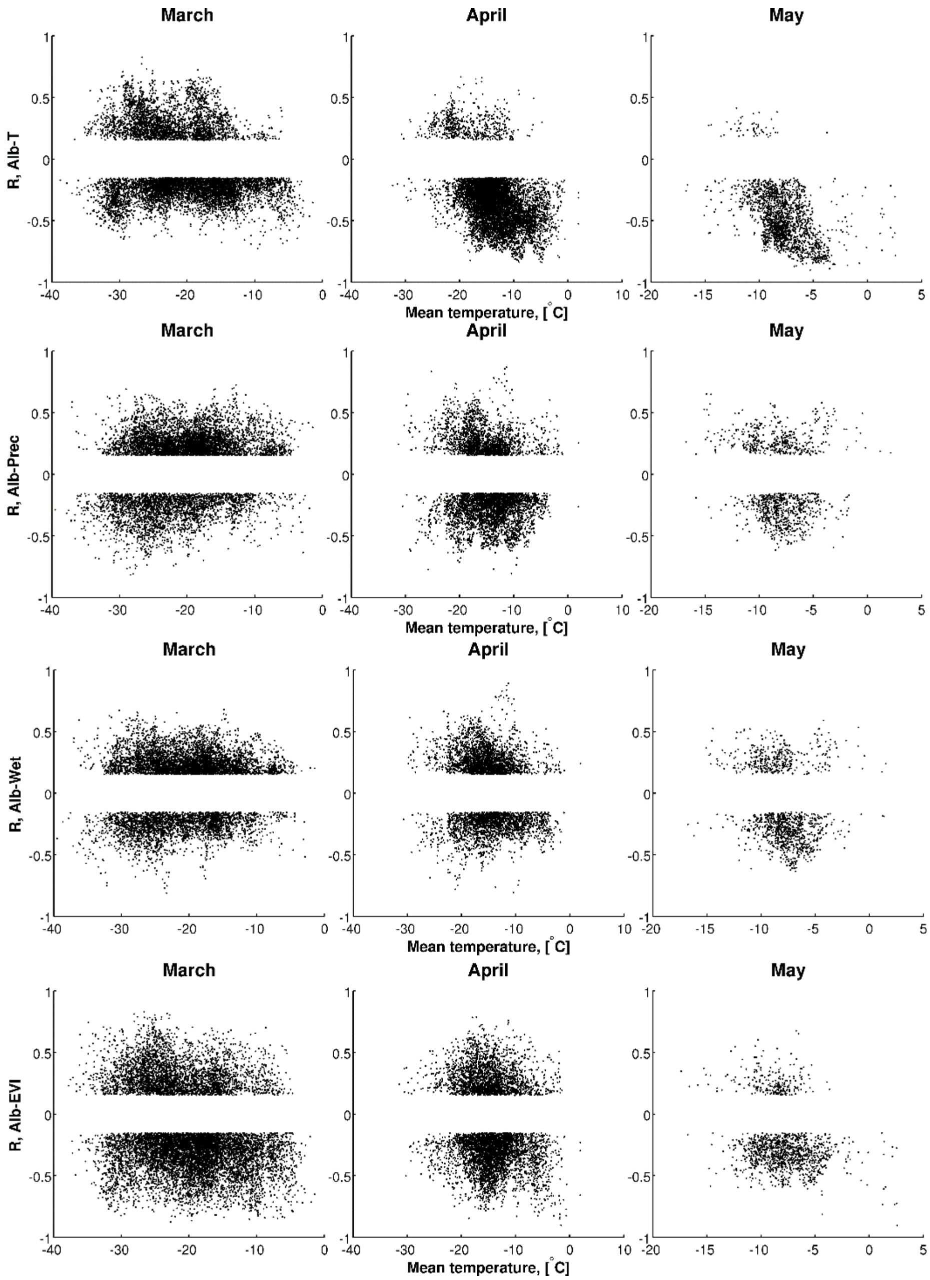


Fig. R1. Correlation coefficient between surface albedo and surface air temperature, precipitation amount, wet days and EVI as a function of mean air temperature for the years 2000-2012. Each data point represents a single grid point. Only correlation coefficients with corresponding p-values larger than 0.05 are shown.

Minor comments

> **p. 2746, lines 22–23: It is very appropriate to start the paper by defining surface albedo, but "reflected back into space" is not correct. Surface albedo is simply the fraction of solar energy reaching the Earth's surface that is reflected upward. Part of the upward reflected radiation is absorbed in the atmosphere and does not reach space. Please also mention already here that you consider the broadband albedo.**

The text was changed as follows:

Broadband surface albedo, defined as the fraction of the solar energy (shortwave radiation in spectral range from 0.3 to 5 μm) reaching the Earth surface and reflected upward, plays an important role in the Earth energy balance (IPCC AR5, 2013).

1. **p. 2747, line 17: Which season and region does the 1 °C warming refer to?**

We extended and revised reference as follows:
Brown and Robinson (2011) estimated that for each 1°C of warming *in the NH (40-60° N) the loss of snow is 1.44 million* km^2 *in March and 2.00 million* km^2 *in April.*

2. **p. 2748, lines 2–8: The explanation of the effect of snow grain size is confusing. In particular, "larger grains not only scatter more radiation . . . " is misleading. For a given mass of snow, the optical depth is larger (also for scattering) if the snowpack consists of small rather than large grains. The primary reason for the decrease of snow albedo with increasing grain size is that the single-scattering albedo decreases with increasing grain size (i.e., absorption increases when the path length of radiation within the snow grains increases). The size also influences the asymmetry parameter, but this is complicated if grain shapes also change with size (relationships typical of spheres may not hold).**

We revised the explanation and restricted it to a simpler and clearer form. Two references are also added.
At higher temperatures snow grains are larger as the air temperature is higher *(e.g. Marbouty, 1980; Flanner and Zender, 2006) which results in a decrease of the single scattering albedo (SSA). In the larger snow grains the chances of a photon to be absorbed are greater due to the increased optical path within an ice crystal. (Warren, 1982). A decrease in the SSA is the primary reason for the decrease of snow albedo for wavelengths shorter than 2.5 μm (Wiscombe and Warren, 1980; Nakamura et al, 2001). Grain size is the main physical factor responsible for snow albedo variations (Domine et al, 2006). The snow grain growth process contributes to the positive snow-albedo feedback loop, increasing the absorption of radiation by the snow in the surface layer.* It results in the increase of snow melt and thus in a decrease of the surface albedo which consequently results in stronger absorption of solar radiation.

Marbouty, D.: An experimental study of temperature-gradient metamorphism, J. Glaciol., 26, 303–312, 1980.
Warren, S. G.: Optical properties of snow, Rev. Geophys. Space Phys., 20, 67-89, 1982.

3. **p. 2750, line 8: State explicitly that you mean "ground-based albedo observations".**

The text was changed as suggested:
Ground-based observations of albedo properties at high latitudes are very sparse.

4. **p. 2751, line 13: It would be helpful to list the wavelengths of the MODIS bands 1–7 explicitly.**

Centers of bands are added to the text:
Cloud-free, snow-flagged and atmospherically corrected surface reflectances at seven MODIS bands (1-7, centered at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm consecutively).

5. **p. 2754, line 22: "temporal resolution" should be "spatial resolution".**

The mistake was corrected:

The Climatic Research Unit (CRU) TS3.21 data set (Jones and Harris, 2013) provides homogenized monthly climate data interpolated from over 4000 weather stations spread around the world gridded to a spatial resolution of 0.5° (Mitchell and Jones, 2005).

6. **p. 2754, line 26: to avoid the impression that you use daily temperature data, replace "daily mean temperature" with "monthly mean of the daily-mean temperature", or simply, "monthly mean temperature".**

Thank you for this comment. We changed text to avoid wrong impression as follows:

In this study we used monthly means of daily mean temperatures, precipitation and wet day frequency.

7. **p. 2755–2756: I found the description of spatial sampling (which data pixels are included and which not) confusing. In particular, you should be clear about the following:**

p. 2755, line 11: "All data pixels with corresponding SCF less than 1% were discarded from the analysis". Does this refer to SCF for the 25x25 km EASE grid cells? Was the spatial screening done separately for each month and year, or was the same screening used for a given month in all years?

- **p. 2755, line 22: Which pixels did you include: only those for which SCF=100% in a given month for all years 2000–2012, or those in which SCF=100% for at least one year in 2000–2012?**
- **p. 2756, lines 1–3: In conducting the albedo analysis for snow-covered regions, it is clear that the mask is different for March, April and May. However, was the mask for a given month the same for all years considered, or was there further screening based on whether the ground was snow-covered?**

Perhaps the answers to all of these questions are available in the text, but it should be made easier for the reader.

Thank you for this very valuable comment. We agree that the data masking process should be clear to the reader. We have added clarifications to this part of the manuscript in response to your questions:

All data pixels for any given month and year with corresponding SCF less than 1% in each of the 25x25 km grid cells were discarded from the analysis. This masking out was done separately for each month and year.

To study connections between the albedo and air temperature, precipitation or vegetation under full snow cover conditions, we eliminated all pixels where snow cover was not complete (SCF < 100%) at any time during the study period. *In other words, if for any given month a pixel was assigned SCF < 100% at either of the years during the study period, it was discarded from this part of the analysis for the given month. For instance, if in April of the year 2001 the mean SCF of a pixel was < 100%, this pixel was masked out for all studied years in April.*

Applying identical masks would drastically narrow the study area, or, alternatively, May would need to be left out of the analysis. *Therefore, different masks for March, April and May were used to maximize the study area and data availability. Considering that all pixels with incomplete snow cover were masked out, the mask for any given month was the same for all years considered.*

8. **p. 2757, lines 14–16: When you say that the snow cover changes have influenced a certain fraction of the area, how is this defined? A trend different from zero? Or a trend statistically different from zero? If so, how is the statistical significance determined?**

Here we particularly meant percent of land area (NH_{50}) where SCF changed since the year 2000, meaning trend different from zero. This simple test gives a good estimate of the fraction of the territory inside the study domain where snow cover fraction is subject to changes. This has been clarified in the text:

In March, the snow cover changes *(trend different from zero)* have influenced 58 % of all snow-covered area, while in April these changes have affected 74 % and in May 91 %.

9. **p. 2758, line 20 (and elsewhere): the period studied is from year 2000 to 2012, 12 years from the beginning to the end. Should the trends be ±0.3 12 years^{-1}?**

Thanks for noticing it. We replaced 13 years by 12 years everywhere.

10. **p. 2758, line 23: How is "moderate and strong correlation" defined? It would be helpful to give a typical value for the correlation coefficient corresponding to p = 0.05.**

Since the terms “moderate correlation” and “strong correlation” are not canonically defined, we define “moderate correlation” for R values between 0.5 and 0.7, and “strong correlation” for R > 0.7. To clarify it also for the readers, we will add these numbers to the text as follows:

The correlation was found to be significant (not shown) with p-values < 0.05 for all pixels with moderate (R = 0.5-0.7) and strong correlation (R > 0.7).

11. **p. 2759, lines 3–5. Whether or not this holds true depends on month. E.g. in Eastern Siberia, the albedo change in May is clearly associated with reduced snow cover. Please specify which months you are referring to.**

We inserted specific months we referred to.

However, in March and April in regions such as Eastern Siberia, Fennoscandia, the northern part of North America or the Labrador Peninsula, and in May for the Taymir peninsula and the Canadian Archipelago, no significant SCF changes (less than 1 % 12 years^{-1}) are observed, but the albedo did change.

12. **p. 2759, lines 11–15: Here, it would be helpful to remind the reader that this analysis is confined to the region with 100% SCF (or is it?).**

In the original text we remind that we study effects of these parameters over snow-covered surfaces in this sentence: “Below we discuss the effects of different parameters on the snow-covered land surface albedo in separate sub-sections.” However, we agree that 100% SCF is not strictly mentioned. We modified it as follows:

Below we discuss the effects of different parameters on the 100% snow-covered land surface albedo in separate sub-sections.

13. **p. 2759, lines 17–18: Mention explicitly that you consider monthly-mean temperature. It is important for the interpretation of the -15°C threshold.**

Thank you for this suggestion. The text has been changed as follows:

Regional averages show that albedo is negatively correlated with regionally averaged monthly mean air temperature when this parameter exceeds a threshold value of about -15°C (Fig. 5, top line).

14. **p. 2764: In discussing the role of snow metamorphosis on albedo, the possibility of melting (and refreezing) should also be considered. The temperature can occasionally rise to 0 °C even if the monthly-mean temperature is much colder — this is something that may be obscured by the use of only monthly data in this study.**

Very valuable point. Melting and refreezing as one of the processes, related to the snow metamorphosis, is definitely important and should be mentioned. Considering major comment 1 and analysis that was done to discuss data resolution limitation, we added the following text (shown in italics) to the discussion:

The present study is targeted to investigating changes in the snow-covered surface albedo on large spatial and temporal scales. The relatively large grid size of data and coarse averaging to monthly means could blend in complicated connections between albedo, temperature and precipitation. *For instance, an occasional rise of the temperatures favoring snowpack thawing and subsequent refreezing lead to the formation of the large amorphous ice crystals or melt-freeze crust on the snowpack surface (Colbeck, 1982) that is characterized by a decreased albedo (Albert and Perron, 2000). Decreasing albedo during snowmelt periods (Meinander et al, 2013) might have been obscured by averaging over long periods. The analysis presented in the Supplement studies the albedo-temperature relation using data with a finer temporal resolution. The results show that warmer than average days did not occur often. Moreover, even with a low number of warmer days, temperature threshold of -15°C can be observed in some regions. Considering the above discussion, we cannot be conclusive which of the processes can give the best explanation of our findings.*

References:

Albert, M. R. and Perron, F. E.: Ice layer and surface crust permeability in a seasonal snow pack, Hydrological Processes, 14, 3207-3214, 2000.

Colbeck, S. C.: An overview of seasonal snow metamorphism, Reviews of Geophysics, 20, 45-61, 1982.

15. **p. 2765, line 2: "albedo might decrease and surface air experience cooling"? I find two problems with this sentence. First, if the metamorphosis rate decreases, the snow grains remain smaller, which should increase the albedo. Second, you are discussing feedback effects resulting from warming. A negative feedback as suggested here does not turn warming into cooling; it just reduces the warming. Therefore, a better formulation would be (e.g.) "Albedo might increase, reducing the increase of surface temperature." Whether this mechanism is important in practice is of course another matter (e.g., in comparison to changes in snowfall amount/frequency, let alone changes in snow cover).**

Thank you for pointing this problem out. Firstly, we incorrectly wrote "albedo might decrease" instead of simply saying that "albedo decrease might happen slower". Lower metamorphosis rate leads to the slower SSA drop and independently does not cause albedo increase. Considering the second concern, this effect is discussed as possible consequence of increased precipitation without substantial warming. Therefore relatively to the norm, one can think of it as "cooling".

We changed the discussion as follows:

If precipitation increases in isothermal conditions, the metamorphosis rate can decrease when a certain temperature gradient in the snowpack threshold is passed. *Through this mechanism the decrease of the snow albedo is slower.*

16. **p. 2765, line 5: You could add a reference regarding sublimation, e.g. Ulrich Strasser, Michael Warscher, and Glen E. Liston, 2011: Modeling snow–canopy processes**

on an idealized mountain. J. Hydrometeor, 12, 663–677. doi: http://dx.doi.org/10.1175/2011JHM1344.1

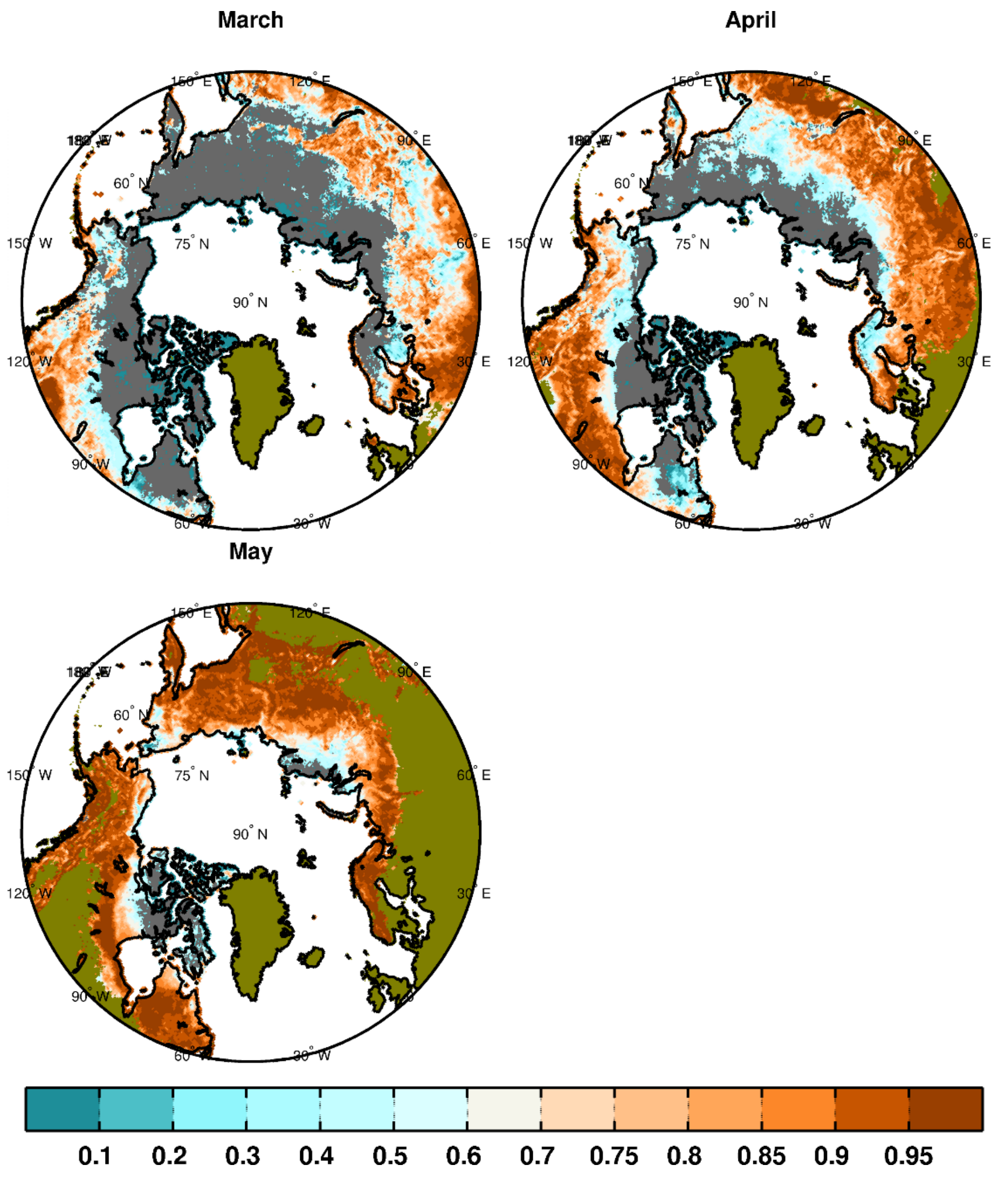
Thank you for suggesting this reference. We assume p. 2766, line 5 is meant. The reference will be inserted there.

At the same time, snow captured by a canopy can sublimate and thus this portion of snow does not reach the forest surface, resulting in a shallower snowpack *(Strasser et al, 2011).*

Strasser, U., Warscher, M., and Liston, G. E.: Modeling Snow–Canopy Processes on an Idealized Mountain, Journal of Hydrometeorology, 12, 663-677, 2011.

17. **Fig. 3: It is very difficult to draw any quantitative information from this figure, beyond the fact the albedo and SCF area positively correlated. Consider using another (discrete?) colour scale.**

We have changed the color scale by making discrete colormaps and introducing more discrimination levels for the higher R.



18. **Fig. 6: In practice, it is hard for the reader to link the p values shown in one map to the correlation shown in another. It would be better to display the correlation map only, but so that statistically insignificant values are screened out. Possibly, a more liberal significance threshold than p= 0.05 could be used, e.g. p= 0.1.**

We have replotted Fig. 6 as suggested. However, we found that there is no big difference in the amount of pixels for thresholds of p=0.05 and p=0.1. We have changed the figure caption and part of the text.

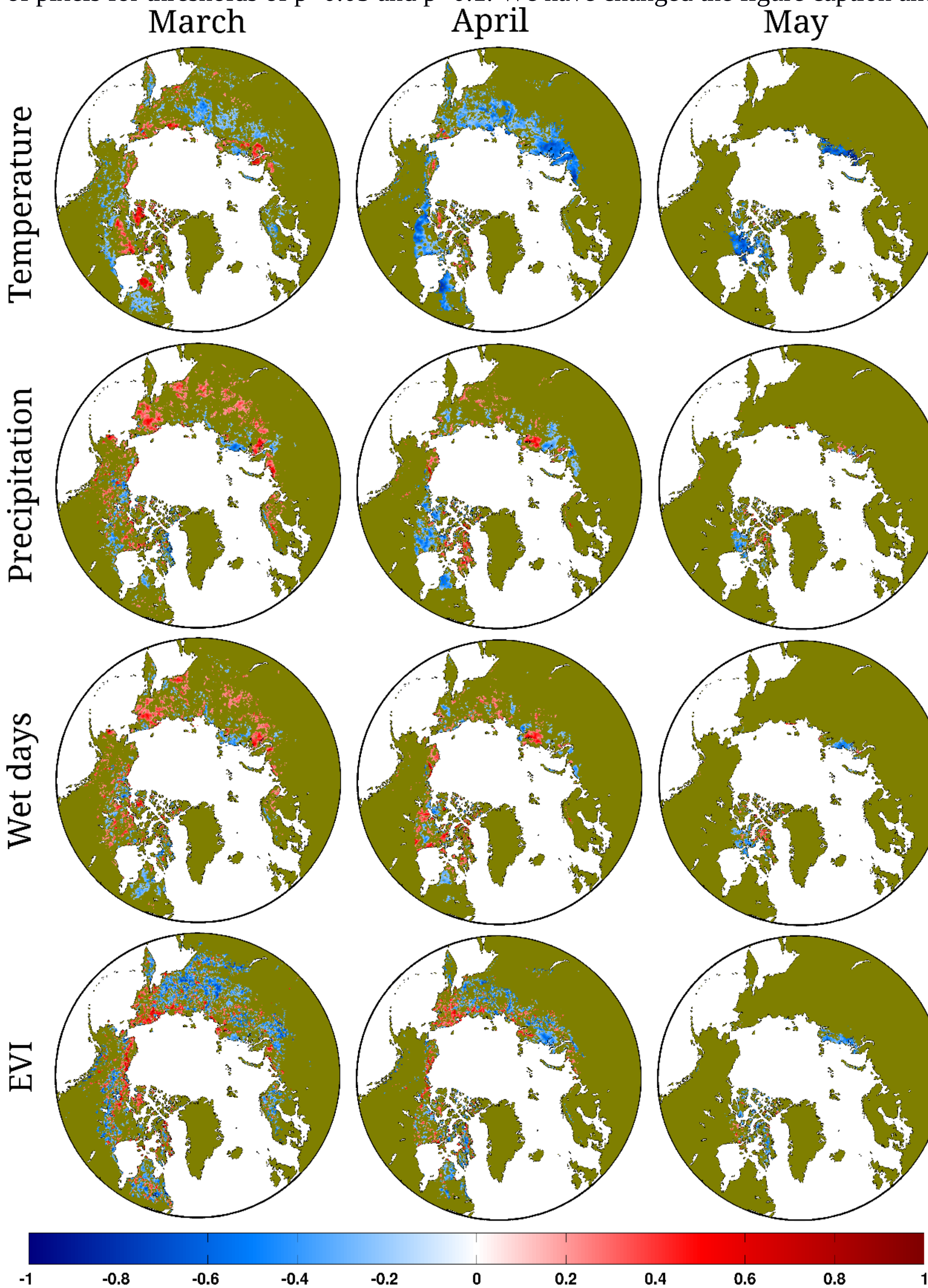


Figure 6. Spearman correlation coefficient maps for temperature (top row), precipitation (2nd row), number of days with precipitation (3rd row) and EVI (bottom row) for March (left column), April (middle column) and May (right column). Only pixels with corresponding p-values greater than 0.1 are shown.

To the text:

Fig. 6 shows the spatial distributions of the Spearman correlation coefficients of albedo with the four climate parameters considered in this study: temperature, precipitation, number of wet days and EVI (top to bottom in Figure 6). Pixels with corresponding p-values greater than 0.1 were screened out from the maps.

4.3.1 Temperature
In Eurasia the only region with monthly mean temperature above -15°C is Scandinavia*, where some areas exhibit the same relation*. There is also a vast area of the Lena and Yana rivers basins and the Vilyuy Plateau where the temperature-albedo correlation is negative and significant.

4.3.2 Precipitation
In March the correlation maps of albedo and precipitation amount ~~and corresponding p-values~~ show very high variability, which is especially prominent in North America.

In April the correlations between albedo and precipitation are negative ~~and significant~~ in study areas in North America - Nunavut and Labrador. In Eurasia the correlation coefficients ~~and corresponding p-values~~ show that there is a weaker connection between albedo and precipitation than in March.

Technical and language corrections

All the corrections were noted and fixed. Thank you for paying attention to these small details that help to improve quality, clarity and readability of the text.

Authors' response to the comments of Referee#2.

Thank you for the interest to our work and your feedback. Given comments were in line with those given by Referee#1 and were addressed by us in the response to the Major comment 1 of Referee#1.