Replies to reviewer's comments

We thank the reviewer for the valuable comments and suggestions. We have revised the paper substantially and carefully made corrections according to reviewer's comments.
Our detailed point-by-point response to the reviewer's comments is given below.

1. The text fails to adequately refer to and use existing knowledge on characteristics of simulated climate change in general and dynamics of SWE change in particular. There are (at least) three key findings that are basically known from earlier research and therefore would not require much discussion in this paper:

A. The dependence of global mean warming on the RCP emission pathway is small for the next few decades but increases rapidly towards the end of this century (IPCC WG12013, Chapter 12).

Answer: Thank you for your suggestion. This is true, which can be certified by the figures 4 and 6 in the manuscript.

B. Other aspects of anthropogenic climate change scale more or less directly with the global mean warming (Frieler et al. 2012, Journal of Climate; IPCC WG1 2013, Chapter 12). Therefore, it is logical to assume that the dependence of SWE changes on the RCP scenarios follows the pattern indicated in 1.

Answer: Thank you for your suggestion. This is logical, however, in this paper, we only want to analyze the response characteristic of SWE to climate change during different periods and emission scenarios.

C. SWE is governed by three factors: (i) total precipitation, (ii) the fraction of precipitation that falls as snow, and (iii) melting of snow in mild periods. Given that climate models project both an increase in winter precipitation in mid-to-high-latitude Northern Hemisphere (as documented in IPCC WG1 2013, Chapter 12) and an increase in temperature, it is obvious that (i) tends to increase SWE whereas (ii) and

(iii) tend to reduce it. In Räisänen (2008, Climate Dynamics), a diagnostic method was presented that helps to quantify the contributions of these factors and thus the precipitation and temperature change effects. Such a diagnostic decomposition would confirm the importance of temperature changes much more directly than the correlation analysis presented in the current manuscript.

Answer: Thank you for your suggestion. The diagnostic method recommended above is now used in the revised manuscript to identify the contribution of total precipitation, the fraction of solid precipitation, and the fraction of accumulated snowfall (page 16, L2-15,).

2. The results are almost exclusively presented as absolute SWE changes. This makes comparison between different areas and seasons difficult to interpret, because the change is necessarily constrained by the baseline SWE. If, for example, area A has baseline SWE of 50 mm and loses all of it, whereas area B has baseline SWE of 200 mm and loses half of it, is it meaningful to say that the change is smaller in A than B? To help the interpretation, relative (per cent) changes should be shown along with (or instead of) absolute changes. Furthermore, if the authors maintain that absolute changes are more important than relative changes, they should motivate this focus. While local absolute changes in SWE might indeed be important from a hydrological point of view, what (if anything) do the Northern Hemisphere mean changes tell?

Answer: Thank you for your suggestion. In fact, Figure 3 (with revised units) shows the relative change in SWE. Furthermore, the zonal and monthly changes in SWE are described in terms of the relative change in the revised manuscript (Figures 4 and 5).

3. The finding that the rate of decrease in the Northern Hemisphere mean SWE tends to slow down with increasing warming may actually not be correct (detailed comment 37 below). Even if it is correct, it would require physical interpretation and a regionally more detailed analysis. Obviously, as climate warms, some areas will lose their snow cover and will show no further decreases in SWE after that. On the other hand, some cold areas that first exhibit an increase in SWE with warming might begin

to experience decreases in SWE after a threshold temperature is passed. Thus, the behaviour in this respect is very unlikely to be uniform over all of the Northern Hemisphere.

Answer: Thank you for your suggestion. We have deleted this section in the revised manuscript.

4. Parts of the analysis seem physically meaningless. In particular, what is the point in analysing the spatial maximum of the annual mean SWE in Figure 4? These results basically reflect model behaviour in a few single grid boxes and have no wider relevance.

Answer: Thank you for your suggestion. In fact, the maximum annual SWE (abnormal value has been deleted) shows change in SWE in winter. However, as zonal changes in the maximum annual SWE are the same as changes in the zonal mean SWE, we have deleted this section in the revised manuscript.

5. The documentation of the methods is insufficient. For example, what do the correlation and regression coefficients between SWE and temperature represent in Tables 2 and 3? Were they calculated from interannual variations of Northern Hemisphere land mean temperature and SWE, or from local interannual variations of temperature and SWE with appropriate averaging afterwards, or from something else? I assume that the first alternative was used but this is not documented in the text

Answer: Thank you for your suggestion. The correlation and regression coefficients are calculated from the interannual variation of SWE and temperature over NH land where snow exists. We have added the equations used to calculate the correlation and regression coefficients to the revised manuscript (page 7, L3-9).

6. The technical presentation of the results is not well-thought. The single most out standing example are Tables 2-3, which include a huge set of highly variable numeric values. The implications of these numbers, if any, will be very hard to judge for a reader of the article – a classical "don't see the forest from the trees" problem.

Answer: Thank you for your suggestion. We want to show the relationship between SWE and temperature during different periods and for three RCPs to identify changes over time and with different emission scenarios. In this respect, Tables 2 and 3 are useful, but the manuscript has been modified (page 14, L11-27) to clarify the results.

7. There are substantial problems in the English language of the manuscript. Suggesting any detailed improvements to these goes beyond my resources. It seems that the only solution in this respect is to let a professional language editor to correct the text, or to find a skilful colleague who is able and voluntary to do this.
Answer: Thank you for your suggestion. The manuscript has been edited by Stallard Scientific Editing.

8. It seems that the manuscript was submitted very hastily without even properly checking the list of references, which is not consistent with the references cited in the text.
Answer: Thank you for your suggestion. We have checked in the revised manuscript.

Specific Comments:

1. P2136, L13 "the reduction is SWE there is related to rising temperature". You don't need to calculate correlation coefficients to make this conclusion which is obvious from physical reasoning alone.
Answer: Thank you for your suggestion. Previous studies suggest that both temperature and precipitation show an increasing trend at mid–high latitudes. Partial correlation is an effective way to identify the major control on SWE and to separate the contributions of temperature and precipitation. The present results show that temperature plays a major role in controlling SWE at high latitudes.

2. P2136, L14-15. "temperature may reach a threshold value". Regionally, "threshold values" of temperature will be reached when the climate becomes

essentially snow free. However, this will not happen everywhere in the Northern Hemisphere at the same time!

Answer: Thank you for your suggestion. We understand that the temperature threshold may not be reached simultaneously over different regions in the Northern Hemisphere. Here, we want to indicate that a threshold value exists in the relationship between SWE and temperature, across which the characteristic response of SWE to temperature may change.

3. P2136, L26 – P2137, L9. Please focus on the most up-to-date information that is available in AR5. The earlier IPCC assessments do not add anything important to that.

Answer: Thank you for your suggestion. We have revised this section in the revised manuscript (page 3, L5-16).

4. P2137, L15-16. Just like SWE, snow depth is affected by both temperature and precipitation.

Answer: Thank you for your suggestion. Snow depth is affected by temperature and precipitation. However, snow depth places an emphasis on the accumulation of snow, we have corrected in the revised manuscript (page 3, L25-26).

5. P2137, L25-27. How is the first part of the sentence "Following comparison with observational data" related to the second part "global climate models consistently project"? The model projections are not dependent of observations.

Answer: Thank you for your suggestion. The model projections are not dependent on observations. we have deleted this section in the revised manuscript.

6. P2138, L4-6. Can you give the original reference of this regional climate simulation? It is very unlikely to be the IPCC AR4 chapter by Christensen et al. (2007).

Answer: Thank you for your suggestion. We have rewritten this section, and we consider that this reference is not needed.

7. P2138, L25-27. Whether this is true or not depends on the baseline climate.

Answer: Thank you for your suggestion. We have reanalyzed the relative change in SWE in the revised manuscript, revealing that it depends on the baseline climate (figure 3,4 ,5).

8. P2138, L28-29. Rather "since climate change is dependent: : :" because this is true for all aspects of climate change.

Answer: Thank you for your suggestion. We have deleted this section in the revised manuscript.

9. P2139, L1-5. This sentence gives a strange impression. Is it not physically obvious that both temperature and precipitation play a role?

Answer: Thank you for your suggestion. Both temperature and precipitation have an impact on SWE, but the major control on SWE varies over different temporal and spatial scales.

10. P2140, L15. Be specific: spatial correlations?

Answer: Thank you for your suggestion. The correlation refers to the spatial correlation. We have revised the manuscript accordingly (page 8, L2).

11. P2140, L16-17. It does not make much sense to report that the correlation between the model simulations and observations is statistically significant (because this is highly unsurprising). In this case, the magnitude of the correlations is more interesting than their significance.

Answer: Thank you for your suggestion. We have corrected this point in the revised manuscript (page 8, L3-5).

12. P2140, L18-20. Time series of what? The Northern Hemisphere mean SWE or local SWE?

Answer: Thank you for your suggestion. This time series is the average SWE over the Northern Hemisphere during 1980–2005.

13. P2141, L18-19. (This pattern suggests: : :). Delete. There is no point in repeating well-known facts that hold for all aspects of anthropogenic climate change.

Answer: Thank you for your suggestion. This sentence has been deleted in the revised manuscript.

14. P2141, L19-20. (Meanwhile: : :). Also delete this, for the same reason.

Answer: Thank you for your suggestion. This sentence has been deleted in the revised manuscript.

15. P2142, L1-2. Is this also true when the changes are expressed in relative (i.e. percent) units?

Answer: Thank you for your suggestion. We have calculated the relative change in SWE. Due to the higher baseline SWE in winter, the reduction in spring is greater than that in winter. We have revised the manuscript accordingly (page 9, L14-17).

16. P2142, L12-15 (Viewed in greater detail :). Delete. This is well known from a large number of earlier studies.

Answer: Thank you for your suggestion. This sentence has been deleted in the revised manuscript.

17. P2142, L19-20. (And the magnitude of the decrease: : :). This is the case just because there is more snow in higher than in lower latitudes. The relative decrease in SWE (which would be more informative for many practical purposes) is larger at lower than in higher latitudes.

Answer: Thank you for your suggestion. We have calculated the relative change in SWE, revealing that the magnitude of the SWE decrease shows a gradual decline from south to north (page 10, L1-4).

18. P2142, L23-24. (The relative changes in SWE are similar: : :). While the absolute (not relative!) changes are smaller at lower latitudes, the scenario-dependence of the changes shows exactly the same pattern south and north of 60 N in Fig. 4e

Answer: Thank you for your suggestion. We have recalculated the relative change in SWE. The greatest change in SWE occurs at lower latitudes, and the magnitude of change decreases with increasing latitude for all three RCPs.

19. P2142, L26-27. (Moreover : : :). Delete. Nothing new.

Answer: Thank you for your suggestion. This sentence has been deleted in the revised manuscript.

20. P2142, L27-29. There is a large body of research on the causes of the polar amplification of greenhouse-gas induced warming (see e.g. box 5.1 in IPCC AR5). Reduced snow cover is just part of the story.

Answer: Thank you for your suggestion. We have deleted this section in the revised manuscript.

21. P2143, L1-L28. As pointed out in the general comments, the analysis of ZMSWE is meaningless. Delete

Answer: Thank you for your suggestion. The analysis of ZMSWE has been deleted in the revised manuscript.

22. P2143, L16-18. Brutel-Vuilmet et al. (2013, not 2008!) study the change in the average annual maximum SWE, not the change in maximum of annual mean SWE. These are different things!

Answer: Thank you for your suggestion. The analysis of the average annual maximum SWE has been deleted in the revised manuscript.

23. P2143, L28 – P2144, L1. This text is repetitive. Delete

Answer: Thank you for your suggestion. We have deleted this sentence in the revised manuscript.

24. P2144, L3-4. How were the slopes and correlations in Table 2 calculated? Are they based on interannual or spatial variability of temperature and snowfall?

Answer: Thank you for your suggestion. The equations used to calculate the regression slope and correlation coefficients are given in the revised manuscript (page 7, L3-9). The slope and correlation are based on the interannual variability of temperature and SWE.

25. P2144, L3-8. I would be very careful to draw any conclusions from Table 2. First, it is not self-evident that the long-term climate change relationship between temperature and SWE is quantitatively the same than the interannual relationship. Second, the large and irregular variability of the numbers in Table 2 suggests that they are substantially affected by internal variability, even when they are statistically significantly different from zero.

Answer: Thank you for your suggestion. Here, we only want to show changes in the response of SWE to temperature during different periods in the 21st century. Although the results were calculated using interannual SWE and temperature, the regress slope gradually decreases from the EP to the LP for RCP8.5, and gradually increases from south to north, which illustrates the response of SWE to temperature during different periods and for latitude bands.

26. P2144, L20-21. Why not include the observations in Fig. 5?

Answer: Thank you for your suggestion. Figure 5 shows the changes in SWE over the Northern Hemisphere where snow exists. However, observations from GlobSnow only represent SWE at high latitudes. Therefore, observations are not included in Figure 5.

27. P2144, L27. How can seasonal SWE changes be contrary to monthly changes? Or

do you mean that the decrease in SWE is smallest in summer when the baseline SWE is also smallest?

Answer: Thank you for your suggestion. SWE has the largest values in winter and the smallest in summer, and the absolute changes therefore indicate that the decrease in SWE is largest in winter and smallest in summer. Given that the baseline SWE, we now describe the results in terms of the relative change in SWE (page 12, L20-27).

28. P2145, L1-6. Shorten this text. It is well known from earlier research that larger forcing leads both to larger multi-model mean changes and larger inter-model differences in the response to the forcing.

Answer: Thank you for your suggestion. We have rewritten this section in the revised manuscript (page 12, L23-27).

29. P2145, L7-9. This pattern would be reversed if you considered relative rather than absolute SWE changes.

Answer: Thank you for your suggestion. We have calculated the relative change in SWE in the revised manuscript, which shows an opposite pattern to the absolute change (page 12, L21-23).

30. P2145, L10-26. It is not very meaningful to relate SWE change to changes in the Northern Hemisphere land mean temperature and precipitation, as much of the hemisphere is snow-free particularly in summer. It would be better to calculate the temperature and precipitation changes over the area where snow does occur during the baseline period. Even better would be to explicitly diagnose the effects of precipitation and temperature changes as in Räisänen (2008).

Answer: Thank you for your suggestion. In this manuscript, both temperature and precipitation are calculated over regions where snow exists. For diagnosing the effect of temperature and precipitation on SWE in the revised manuscript, we used the technique proposed by Räisänen (2008).

31. P2145, L25-26. In mid-to-high latitudes (which are obviously most important for the SWE change) the largest precipitation increases tend to occur in winter (e.g. IPCC AR5, Fig. 12.22).

Answer: Thank you for your suggestion. In the revised manuscript, we have analyzed the relative change in precipitation, revealing that the largest increase occurs in winter (page 13, L11-19).

32. P2146, L13-14. (The sensitivity of SWE : : :). This conclusion would most likely be reversed if you considered relative rather than absolute SWE changes.

Answer: Thank you for your suggestion. Here we want to analyze the response of SWE to temperature, and we therefore only calculate the slope of SWE to temperature during a given period. This is unrelated to the relative change or absolute change.

33. P2146, L25. (This pattern shows: : :). Delete the sentence.

Answer: Thank you for your suggestion. This sentence has been deleted in the revised manuscript.

34. P2146, L21 – P2147, L21. Maps for the annual mean SWE change were already shown in Fig. 3. The only piece of substantially new information in Fig. 7 is the seasonal distribution. Thus, there is no need for a lengthy discussion of the annual mean trends.

Answer: Thank you for your suggestion. We have deleted this section in the revised manuscript.

35. P2148, L1-2. This suggests a shift in the seasonality of the SWE, with the maximum occurring earlier in a warmer climate. This is physically expected, because the maximum of SWE in spring occurs close to the time when the mean temperature rises above zero, and the zero-crossing time becomes earlier when the climate warms.

Answer: Thank you for your suggestion. As the climate warms, snow begins to melt earlier, which leads to a significant reduction in SWE during spring.

36. P2148, L11-15. This behaviour follows the rate of global temperature change reported in IPCC AR5 (Chapter 12).

Answer: Thank you for your suggestion. We now refer to this relationship by citing Zhu et al. (2013) (page 14, L17).

37. P2148, L18-20. Instead of calculating the regression coefficients within the 20-year periods, one could infer the temperature-dependence of SWE simply by comparing the different periods and RCP scenarios with each other. This would allow more reliable conclusions, because a larger range of temperatures is covered and long-term climate change is not confounded with internal variability. Looking at Figure 9 (particularly 9c) from this perspective, it seems that SWE decreases more or less linearly with temperature for T > 5.5C. On the other hand, there is an abrupt jump at 5.5C (i.e.,. between the historical simulations and the RCP simulations) which suggests a problem in the model data or processing of these data. Moreover, for each of RCP2.6, 4.5 and 8.5, the regression coefficients calculated from the interannual variability are larger in MP and LP than EP. In all, this suggests that the purported decrease in the rate of SWE decrease with increasing temperature is questionable.

Answer: Figure 9 has been deleted in the revised manuscript and we have reanalyzed the effect of total precipitation, the fraction of solid precipitation, and the fraction of accumulated snowfall on SWE in the revised manuscript (page 16, L2-15).

38. P2148, L23-25. Yes, but (i) the slopes for each of the three RCP scenarios are smaller in EP than MP and LP, and (ii) the apparent discontinuity in the mean value between the RP and the later periods raises the question whether the regression coefficients are actually comparable.

Answer: Thank you for your suggestion. This has been deleted in the revised manuscript.

39. P2149, L6-7. This claim contradicts the regression coefficients in Fig. 9 (-1.49 for

EP, -1.68 for MP, -1.81 for LP).

Answer: Thank you for your suggestion. This has been deleted in the revised manuscript.

40. P2149, L20-22. This precisely follows the scenario and time dependence of temperature changes.

Answer: Thank you for your suggestion. We have rewritten this section in the revised manuscript (page 16, L22-25).

41. P2149, L24-26. A physically more convincing argument: as winter precipitation in snow-covered areas is simulated to increase, the increase in temperature is the only factor that can lead to a decrease in SWE.

Answer: Thank you for your suggestion. It is true that increased precipitation in winter causes SWE to increase, and increased temperature can lead to a decrease in SWE. Under the effects of both temperature and precipitation, SWE tends to decrease, and this indicates that increased winter precipitation cannot compensate for the increase in snowmelt due to rising temperatures. Therefore, temperature is the major driving factor underlying changes in SWE.

42. P2150, L1. In mid-to-high-latitude areas, the largest increase in precipitation (at least in per cent terms) is projected for winter.

Answer: Thank you for your suggestion. We have rewritten this section using relative changes to show that the greatest increase in precipitation actually occurs in winter (page 17, L8-9).

43. P2150, L3-5. Use of relative rather than absolute SWE changes would reverse this latitude dependence.

Answer: Thank you for your suggestion. We have replaced the absolute change with relative change, and revised the manuscript accordingly (page 17, L11-14).

44. P2150, L7-9. As noted above: Figure 9 does not seem to support this conclusion for the Northern Hemisphere as whole. In any case, such threshold behaviour would be more meaningfully studied in a regional than a Northern Hemisphere mean sense.

Answer: Thank you for your suggestion. Figure 9 has been deleted in the revised manuscript.

45. Tables 2 and 3.The number of numeric values in these tables is excessive. Condensation is needed. Either only show the results for RP and LP, or RP and only RCP8.5 in the three periods. Nothing more is needed, because the temperature-dependence of the correlations and regression coefficients (if there is any) should be captured by these cases. In addition to this, consider displaying the numbers in figures, instead of tables.

Answer: Thank you for your suggestion. We want to show the relationships between SWE and temperature during different periods and RCPs. Thus, Tables 2 and 3 provide valuable information in support of this analysis.

46. Figure 3. Please also show the changes in per cent units at least for the last period. Alternatively, show per cent changes for all three periods and absolute changes only for 2080-2099.

Answer: Thank you for your suggestion. In fact, Figure 3 shows the relative changes in SWE for three scenarios during three periods. We have revised the manuscript accordingly.

47. Figure 4. Delete the first column, because of the reason discussed in General comment 4.

Answer: Thank you for your suggestion. We have deleted this in the revised manuscript.

48. Figure 5. Why are the numeric values much smaller than those shown in Fig 2? Were the averages calculated over a different area?

Answer: The area and time periods differ between Figures 2 and 5. Figure 5 shows the average SWE over the NH where snow exists during 1986–2005, whereas Figure 2 shows the average SWE over non-mountainous regions of the NH during 1980–2005.

49. Figure 6. Please define the area over which the changes were averaged

Answer: Thank you for your suggestion. The average is calculated over regions where snow exists.

50. Figure 7. Show the trends in per cent units instead of / in addition to the absolute.

Answer: Thank you for your suggestion. Figure 7 in the original manuscript has been deleted in the revised manuscript.

TECHNICAL COMMENTS

1. The following studies are cited in the text but are not included in the list of references: Brown and Mote (2009), Christensen et al. (2007), Lemke et al. (2007), Maloney et al. (2012).

Answer: Thank you for your suggestion. We have added these references to the reference list in the revised manuscript.

2. P2138, L27. Apparently, Räisänen (2011) should be either Räisänen (2008) or Räisänen and Eklund (2011).

Answer: Thank you for your suggestion. We have revised this in the manuscript (page 5, L5).

1. P2140, L24. "stimulation" should be "simulation"

Answer: Thank you for your suggestion. We have revised this in the manuscript (page 8, L12).

2. P2141, L1. "the most individual model" should be "most of the individual

models".

Answer: Thank you for your suggestion. We have revised this in the manuscript (page 8, L16).

3. P2141, L15. Apparently, "relative-error ratio" (RE) means relative change.

Answer: Thank you for your suggestion. RE is actually the relative change, and we have give explanation in the revised manuscript (page 7, L10-12).

4. P2159, caption of Figure 2. "stimulated" should be "simulated"

Answer: Thank you for your suggestion. We have revised this in the manuscript.