Reply to RC C475

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 25, L4-18).

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 removed) 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 regression coefficients to the revised manuscript (page 8, L24-26).

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 15, L11-25) 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, L6-17).

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 4, L8-9).

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 9, L5).

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 9, L17-19).

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

Answer: Thank you for your suggestion. The 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 11, L15-19).

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 12, L5-8).

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 equation used to calculate the regression slope is given in the revised manuscript (page 8, L24-26). 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 17, L18-25).

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 17, L21-25).

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 17, L19-21).

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 18, L18-26).

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 22, L22-23).

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 25, L4-18).

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 26, L9-12).

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.

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 27, L2-6).

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 (Christensen et al. (2007) is not used) 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 6, L10).

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

Answer: Thank you for your suggestion. We have revised this in the manuscript (page 10, L4).

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 10, L10).

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 9, L1-2).

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

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

Reply to RC C507

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

1. P2140, lines 14-20. How are spatial correlations calculated? These values are very sensitive to autocorrelation in the residuals, which is undoubtably a problem in the snow cover field. Also, in the statement "by comparison", it is not clear what is being compared, and why or how the results are different. P2146 lines 1-5 the authors discuss correlations and partial correlations. Are these performed on detrended time series? How do the trends affect these results, and do they result in autocorrelation in the residuals which contradicts one of the assumptions of regression analysis? Also, throughout the manuscript the authors focus on absolute rather than relative changes in SWE, but never explain the advantages/disadvantages of evaluating relative versus absolute changes. By choosing to evaluate absolute changes, one skews results to areas with much more snow.

Answer: Thank you for your suggestion. We ordered all simulation grids and observations in sequence, and then calculated the spatial correlations. The term "by comparison" indicates the comparison of the correlation and standard deviation ratios across space and time, and we have deleted this in the revised manuscript to avoid confusion. The time series were not detrended for the correlation and partial correlation calculations. In the revised manuscript, the spatial, zonal, and monthly changes in SWE are analyzed in terms of the relative change (Figure 3, 4, 5).

2. P2145, lines 8-9, "the reduction in SWE during the winter half-year exceeds that in the summer half-year, in keeping with the results shown in Fig. 3." Since there is so much more snow in winter than summer, is this a trivial statement? Also, winter

half-years and summer half-years are never defined. P2145, lines 26-27, the result "This pattern implies that decreasing SWE is attributable to increasing temperature and the minor increase in precipitation" requires explanation. Another example is the recurring mention of a threshold value at which the rate of SWE reduction decreases over time throughout the 21st century: no explanation is provided, in terms of whether this local or global, based on the freezing point of water, or based on some other physical principal.

Answer: Thank you for your suggestion. Lines 8–9 have been deleted in the revised manuscript. The winter half-year ranges from December to May, and the summer half-year is from June to November.

In lines 26–27, we state that both temperature and precipitation show an increasing trend. A temperature increase leads to a reduction in SWE, and a precipitation increase causes SWE to increase. However, warming will also result in a decrease in winter snowfall and more efficient snowmelt. Therefore, the change in SWE is related to increasing temperature and precipitation. This is clearly explained in the revised manuscript (page 15, L2-10).

The threshold refers to the relationship between SWE and temperature. According to the response sensitivity of SWE to temperature during the three periods of the 21st century, a threshold may exist in the SWE–temperature relationship, however, in the revised manuscript we have deleted this section.

3. Throughout the manuscript one finds confusing references to CMIP experiments and IPCC experiments. The discussion sometimes refers to CMIP and sometimes to the IPCC AR number. For example, P2144 line 14 says that their results are different than AR5 (Stocker et al., 2013). Aren't the authors using the same models as Stocker et al.? if so, how can the results be different? This requires clarification, and further explanation. Also, p. 2145 line 15 "which is consistent with the results in AR5." If this is just a repeat of what has already been done for AR5, why is it of interest?

Answer: Thank you for your suggestion. In AR5, the results are based on reanalysis over the Northern Hemisphere during 1922–2012. By comparison, we suggest that the correlation between snow and temperature during different periods of the 21st century is stronger than that during 1922–2012. P. 2145 line 15 in the revised manuscript has been deleted.

4. Clarity of presentation is a problem even in the introduction. First, in defining the questions asked in this manuscript (P. 2139, lines 6-7). How is question 2 different than question 1? Also, the phrasing of question 2 is entirely vague ("How about the link: : :"). Second, the authors must clarify (for example on p. 2139, lines 9-16) how this study complements previous studies of CMIP5 snow simulations.

Answer: Thank you for your suggestion. Problem 1 mainly focuses on the change in SWE on different spatial and temporal scales. Problem 2 refers to the relationships between SWE and temperature, and between SWE and precipitation during the 21st century. The "link" indicates the relationship between SWE and temperature, we have explained in the revised manuscript (page 6, L30 – page 7, 3). Furthermore, previous studies that employed CMIP5 snow simulations are discussed in the revised manuscript (page 5, L1-10). We want to analyze the mechanisms that underlie the change in SWE according to the contribution of total precipitation, the fraction of solid precipitation, and the fraction of accumulated snowfall (page 25, L4-18).

SPECIFIC COMMENTS

1. Abstract, p2136, lines 10-13. Run-on sentence, should be split into two sentences

Answer: Thank you for your suggestion. We have revised this point in the manuscript (page 1, L28- page 2, L4).

2. p. 2137, lines 15-18. Define what is meant by snow cover.

Answer: Thank you for your suggestion. Snow cover represents a spatially and temporally integrated response to snowfall events, and exhibits a more direct relationship to temperature (page 4, L6-8).

3. p. 2137, line 27, "shown" should be "show"

Answer: Thank you for your suggestion. We have revised this in the manuscript (page 5, L2).

4. p. 2138, line 16, should “except” be changed to “in addition to”? “Topography” should not be capitalized.

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

5. p. 2138, line 20. What is meant by “simulated SWE actually increase with altitude”? the discussion is about rates of change, and the relevance of this statement is unclear.

Answer: Thank you for your suggestion. We have rewritten the introduction and this section has been deleted in the revised manuscript.

6. p. 2141, line 15. Define “relative-error ratio”.

Answer: Thank you for your suggestion. The “Relative-error ratio” is actually the relative change, calculated by the equation $\frac{S_i - O_i}{O_i} \times 100\%$, where S_i and O_i are the simulation results and observations, respectively, we have added the equation in the revised manuscript(page 9, L1-2).

7. p. 2141, line 23-24, what is meant by “the extent of increased springtime SWE”?

Answer: Thank you for your suggestion. The extent of increased springtime SWE is the area of positive relative change (RE>0) (page 11, L16).

8. P. 2143, lines 9-11. Regarding the unique difficulty of simulating snow over the Tibetan plateau, this requires further explanation and some reference to the literature on this issue.

Answer: Thank you for your suggestion. This has been deleted because the annual maximum SWE is not discussed in the revised manuscript.

9. 2145, line 6, what is meant by “integration cumulative errors”?

Answer: Thank you for your suggestion. Due to the difference in physical processes and the algorithm, cumulative errors will be greater later in the 21st century. However, this has been deleted in the revised manuscript.

10. p. 2146, line 14. “form” should be “from”

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

11. p. 2146, lines 14-19. Does this paragraph, which says that the sensitivity of SWE to temperature gradually increases during the 21st century, contradict previous statements?

Answer: Thank you for your suggestion. This does not contradict the previous statement. Table 2 shows that the sensitivity of SWE to temperature gradually increases from south to north at mid–high latitudes. This trend indicates that the most significant absolute change in SWE occurs at high latitudes, where the temperature increase is also significant.

12. p. 2147 line 27 – p. 2148 line 2. This is unclear and confusing.

Answer: Thank you for your suggestion. The spatial changes in SWE show that the magnitude and extent of the negative SWE trend are more significant in spring than in winter. However, positive changes in spring are less significant than in winter, which leads to a more significant reduction in spring than in winter. We have rewritten the manuscript to clarify this result (page 22, L25-30).

13. p. 2150, lines 21-24 (last sentence of manuscript). The meaning and relevant of integration truncation and intermodal differences is not explained, was not previously mentioned, and is therefore confusing.

Answer: Thank you for your suggestion. Physical processes and the algorithm (i.e., intermodal differences) may result in uncertainty. Here we only want to state that the uncertainty does not affect the overall conclusions of this study.

14. Figure 1, explain the axes, figure 2 specify which months are included.

Answer: Thank you for your suggestion. In Figure 1, the vertical axis indicates the standard deviation ratios, and the numbers along the arc are the spatial correlation. Figure 2 shows the winter (DJF) mean SWE. We have revised in the manuscript to clarify these figures.

15. Figure 6, 7. For what region is this? I assumed the entire Northern Hemisphere.

Answer: Thank you for your suggestion. The region is the Northern Hemisphere landmass where snow exists.

16. Figure 8. Cannot see range of results for all three scenarios.

Answer: Thank you for your suggestion. Due to model uncertainty, the simulated error gradually increases later in the 21st century, especially under higher-emission scenarios. Therefore, the ranges in model results for lower-emission scenarios are covered by the higher emission.

21st century changes in snow w~~W~~ater e~~E~~quivalent over Northern Hemisphere landmasses due to increasing temperature, projected with the CMIP5 m~~M~~odels

By

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Changes in snow water equivalent (SWE) over Northern Hemisphere (NH) landmasses are investigated for the early (2016−2035), middle (2046−2065) and late (2080−2099) 21st century using twenty global climate models~~, which are~~ from the Coupled Model Intercomparison Project Phase 5 (CMIP5). ~~The results show that, relative to the 1986–2005 mean~~, T~~t~~he multi-model ensemble projects a significant decrease in SWE for most regions relative to the 1986–2005 mean under three Representative Concentration Pathways (RCP), This decrease is particularly evident~~particularly~~ over the Tibetan Plateau and western North America, whereas ~~but~~ an increase occurs over~~in~~ eastern Siberia. Seasonal SWE projections show an overall decreasing trend, with the greatest reduction in spring, which is linked to the stronger inverse partial correlation between the SWE and increasing temperature. The largest relative reduction in SWE over the NH does not occur in spring but in summer. ~~Moreover,~~ Z~~z~~onal mean annual SWE exhibits

significant reductions for ~~in~~ RCPs~~three Representative Concentration Pathways(RCP)~~, and the magnitude of the reduction gradually decreases with latitude in the NH from south to north. A~~a~~ stronger linear relationship between SWE and temperature at mid–high latitudes suggests the reduction in SWE there is related to rising temperature. As temperature increases, the reduction in the fraction of solid precipitation becomes the main contributor to the change in SWE from August to May in the next year in the 21st century, and after May the reduction in SWE is controlled primarily by the decrease in accumulated snowfall. In summary, our results show a trend towards decreasing SWE, and the decreases in solid precipitation and accumulated snowfall strongly affect the change in SWE before and after May, respectively. ~~However, the rate of reduction in SWE declines gradually during the 21st century, indicating that the temperature may reach a threshold value that decreases the rate of SWE reduction. A large reduction in zonal maximum SWE (ZMSWE) between 30° and 40°N is evident in all 21st century for the three RCPs, while RCP8.5 alone indicates a further reduction at high latitudes in the late period of the century. This pattern implies that ZMSWE is affected not only by a terrain factor but also by the increasing temperature. In summary, our results show both a decreasing trend in SWE in the 21st and a decline in the rate of SWE reduction over the 21st century despite rising temperatures.~~

Key words: Coupled Model Intercomparison Project (CMIP5); Snow Water Equivalent (SWE); Model assessment and projection; Sensitivity

1 Introduction

Snow is ~~As~~ a key component of the cryosphere, ~~snow~~ and plays a fundamental role in global climate~~,~~ due to its high albedo and cooling effect (Vavrus, 2007). However, ~~as global temperatures increase,~~ terrestrial snow cover in the Northern Hemisphere (NH) is changing rapidly alongside increasing global temperatures. According to the IPCC Fifth Assessment Report (AR5) (IPCC, 2013) NH snow cover extent decreased by 1.6 [0.8 to 2.4]% per decade for March and April, and by 11.7 [8.8 to 14.6]% per decade for June, during the period 1967–2012. Furthermore, the projections show a 7% decrease in the total area of NH spring snow cover for Representative Concentration Pathway (RCP) 2.6 and a 25% decrease for RCP8.5 by the end of the 21st century. This result is consistent with results from the IPCC Fourth Assessment Report (AR4) (IPCC, 2007). Projections of mean annual NH snow cover suggest a further 13% reduction by the end of the 21st century under the B2 scenario, with individual projections ranging from 9% to 17%; i.e., despite different emission scenarios, the change in snow cover over the NH land shows the same decreasing trend. ~~According to the IPCC Third Assessment Report (TAR) (Houghton et al., 2001), the total area of snow-covered land in the NH has decreased by ~10% since the 1960s. Meanwhile, projections of mean annual NH snow cover suggest a further 13% reduction by the end of the 21st century under the B2 scenario, with individual projections ranging from 9% to 17% (Meehl et al., 2007). Furthermore, according to the IPCC Fifth Assessment Report (AR5) (Stocker et al., 2013), the total area of NH spring snow cover will decrease by 7% for Representative Concentration Pathway (RCP) 2.6 and by 25% for RCP8.5 by the end of the 21st century. From TAR to AR5, although the models' scenarios are different, the area of NH snow cover all represents a declined trend, owing to the fact that snow is highly sensitive to rising temperature.~~

~~Indeed,~~ ~~S~~Several studies have shown that marked decreases in the area and/or depth of snow have already occurred in regions such as western North America (Groisman et al., 2004; Stewart et al., 2005), central Europe (Falarz, 2002; Vojtek et al., 2003; Scherrer et al., 2004) and China (Ji et al., 2012; Wang et al., 2012), thus highlighting the need for better projections of future snow conditions.

Snow cover represents a spatially and temporally integrated response to snowfall events (Brown and Mote, 2009), and may have a direct relationship with temperature (Brutel-Vuilmet et al., 2013). Snow depth mainly reflects the magnitude of precipitation (snowfall), whereas snow water equivalent (SWE) primarily reflects the combined impact of temperature and precipitation (Räisänen, 2008).~~The snow depth mainly represents the magnitude of precipitation (snowfall) (Räisänen, 2008), snow cover possibly exhibit a more direct relationship to temperature (Brutel-Vuilmet, 2013). However~~whereas~~,~~ snow water equivalent (SWE) primarily reflects the ~~common~~ combined impact of temperature and precipitation on snow (Räisänen, 2008). According to AR5 (~~Stocker et al.~~IPCC, 2013), ~~the~~ global temperature and precipitation will ~~persistently~~ increase in the 21st century. The dependence of global warming on the RCP emission pathway is weak for the next few decades but strengthens rapidly towards the end of this century (IPCC, 2013).~~,~~ Of primary concern is the way that SWE will respond to changes in temperature and precipitation. AR5 reported that SWE responds to both temperature and precipitation, and is more sensitive to the snowfall amount at the beginning and end of the snow season (IPCC, 2013).~~in order to study the influence of temperature and precipitation on snow, SWE is arguably the most effective tool for assessing the hydrologic impact of snow cover variability (Bulygina et al., 2009), owing to the large number of studies to date. For example, SWE measurements from northwest North America were described by Clark et al (2001) and have since been used by McCabe and Dettinger (2002) to improve forecasting of seasonal streamflow. Following comparison with observational data,~~

G~~g~~lobal climate models consistently project declining SWE in many areas by the end of 21st century, while some models shows an increase in snowpack along the Arctic Rim by 2100 (Hayhoe et al., 2004; Brown and Mote, 2009). For example, a 20 km-mesh atmospheric general circulation model projects decreased SWE over much of the NH, and increased SWE over colder regions (Siberia and northernmost North America) due to increasing snowfall during the coldest ~~seasons~~months~~, although the percentage change of SWE depend on geographical features~~ (Hosaka et al., 2005). Brutel-Vuilmet et al. (2013) also indicated that the greatest relative reduction in maximum SWE at low latitudes is related to decreasing snowfall. ~~Similarly, a regional climate simulation for North America reported increased March SWE in parts of Alaska and Arctic Canada, but decreasing values farther south (Christensen et al., 2007).~~

Räisänen (2008) suggested that changes in seasonal SWE by the end of the 21st century will vary regionally and depend on local climate conditions. ~~According to the Coupled Model Intercomparison Project Phase 3 (CMIP3) projections, changes in seasonal SWE by the end of the 21st century will be spatially variable, with much depending on present local climate conditions (Räisänen, 2008). For example,~~ I~~i~~n very cold regions, for example~~,~~ ~~climate~~ warming will lead to greater winter snowfall, and thus a thicker snowpack, whereas in warm regions, higher temperatures will result in reduced snowfall. Similarly, CMIP5 experiments project declining SWE over North America south of 70°N (concentrated over the Rocky Mountains, to southern Alaska, and the eastern Canadian provinces), with maximum changes during the peak snow season (January−April), and increasing SWE north of 70°N due to enhanced precipitation (Maloney et al., 2012). ~~Except the influence of climate factor on SWE, Topography also influences variability in SWE.~~ In the mountainous regions of Europe and western North America, projected reductions in SWE are greatest at low elevations (Maloney et al., 2012).~~,~~ SWE is generally projected to decrease less with increasing altitude due to colder winter conditions,~~but decreases less with increasing altitude, owing to colder winter conditions,~~ while in some areas, simulated SWE actually increase with altitude (Scherrer et al., 2004; Mote et al., 2005; Mote, 2006). ~~Namely, the changes in SWE vary with the altitude.~~

According to AR5 (~~Stocker et al.~~IPCC, 2013), anthropogenic warming will continue beyond 2100 for all RCPs, ~~with the consequences of~~leading to an acceleration~~ng~~ of the water cycle and a changing ~~the~~ ratio of snowfall to rainfall. Moreover, increased winter precipitation likely will be insufficient to offset the greater contribution of liquid precipitation and enhanced snowmelt driven by higher average temperatures (Räisänen and Eklund, 2011~~, 2011~~). From TAR to AR5, projected linear trends in SWE under different scenarios are highly variable since SWE is dependent both on the concentration of total emissions and the duration of emissions.

The above studies show that changes in SWE generally depend on both temperature and precipitation, but their relative contributions remain debated. ~~Furthermore,~~ S~~s~~everal studies have concluded that increasing temperature plays a major role in decreasing SWE (Lemke et al., 2007; Räisänen and Eklund, 2011), whereas other studies indicate that increasing SWE is mainly related to increasing precipitation (Hosaka et al., 2005; Maloney et al., 2012). Räisänen (2008) suggested that changes in SWE depend on the competing influences of temperature and precipitation; i.e., an increase in precipitation, if acting alone, would lead to an increase in snowfall and consequently to increased amounts of snow on ground, while an increase in temperature alone would reduce the fraction of precipitation that falls as snow and increase snow melt.~~SWE variability can be attributed to either increasing precipitation (Hosaka et al., 2005; Maloney et al., 2012) or temperature (Lemke et al., 2007; Räisänen, 2011), while Räisänen (2008) suggested that the cryospheric response depends on the balance between increasing temperature and precipitation~~. Consequently, ~~our~~ the present study was motivated by the need to address the following questions: (1) ~~Throughout the NH scale,~~ how will NH

SWE respond to the different RCPs ~~projected for~~in the 21st century? (2) How will the relationships between SWE and temperature, and between SWE and precipitation change during different periods of the 21st century?~~about the link between SWE and climate change?~~

To further analyze anticipated changes in SWE, we employed output from the CMIP5 models in conjunction with GlobSnow product. ~~Here,~~ W~~w~~e focus primarily on temporal and spatial changes in SWE and on variations in the relationship between SWE and climate for each RCP ~~–~~during different periods of ~~in the~~ 21st century. The specific datasets used in this study are described in Section 2, and the simulated and observed data are compared ~~and the comparison between simulated and observed dataset are given~~ in Section 3. Temporal and spatial characteristics of SWE are projected and analyzed in Section 4, and the relationships between SWE and climate change are discussed in Section 5. The key findings of the study~~The main results~~ are summarized in Section 6

2 Datasets

To objectively quantify the changes of SWE in the 21st century, we examined 20 models participating in CMIP5 (Table1), those models ~~–~~all provide monthly SWE ~~variable~~ in ~~the~~ historical experiment and three scenarios experiments (RCP2.6, RCP4.5 and RCP8.5), and we only use the first ensemble member produced by each model (e.g., r1i1p1). While these models vary in their forcing parameters, each model includes ~~the~~ an increases in major anthropogenic aerosols observed during ~~the~~ 1850-2005 and anticipated for the future scenarios. Further details ~~are given~~can be found at http://www-pcmdi.llnl.gov.

The model simulations ~~of the models~~ cover the periods 2006−2099 and 2006−2300. Here, we describe changes in SWE during the former period, which is divided into three ~~segments~~sub-periods: the early (2016−2035: EP), middle (2045−2065: MP) and late (2080−2099: LP) 21st century. The analyses were conducted using a 1°×1° latitude–longitude grid, and re-gridding of original model grids ~~to the analysis grids~~ was conducted via bilinear interpolation.

To verify the performance of the CMIP5 models for simulating SWE, we compare~~d~~ the CMIP5 output with the monthly SWE data from European Space Agency (ESA) GlobSnow dataset (Takala et al., 2011). GlobSnow combines SWE retrieved from passive microwave~~ observation~~ and weather station observation. This is the most realistic SWE product currently available (Hancock et al., 2013) because of the improved accuracy achieved by assimilating independent sources of information~~Because of the improved accuracy achieved by assimilating independent sources of information, this is a more realistic SWE product currently available (Hancock et al., 2013)~~. The series cover the period of 1979-2010 ~~, and the SWE data have~~with a resolution ratio of 25×25 km, and is also interpolated onto a common 1°×1° grid. Hereafter, we refer to the GlobSnow dataset as the observed SWE.

In this paper, linear correlation coefficients, partial correlation analysis and regression analysis are used to investigate the relation between model simulations from different scenario experiments and observations. The equations are as follows.

Partial correlation:

$$r_{XY,Z} = \frac{r_{XY} - r_{XZ} r_{YZ}}{\sqrt{(1 - r_{XZ}^2)(1 - r_{YZ}^2)}} \qquad (1)$$

where $r_{XY,Z}$ indicates the contribution of *X* to *Y*, after removing the contribution of *Z* to *Y*.

Regression coefficient:

$$Y = b + at \qquad (2)$$

where *a* represents the linear trend of factor *Y* with time *t*.

Relative-error ratio (RE):

$$RE=\frac{S_i-O_i}{O_i}\times 100\% \qquad (3)$$

where *RE* reflects the change in a variable *S* relative to the baseline *O*.

Räisänen (2008) suggested that the change in SWE (ΔSWE) can be decomposed into four terms:

$$\Delta SWE=\underbrace{\overline{G}\int\overline{F}\Delta P dt}_{\Delta SWE(\Delta P)}+\underbrace{\overline{G}\int\Delta F\overline{P}dt}_{\Delta SWE(\Delta F)}+\underbrace{\Delta G\int\overline{F}\,\overline{P}dt}_{\Delta SWE(\Delta G)}+\underbrace{\frac{1}{4}\Delta G\int\Delta F\Delta P dt}_{\Delta SWE(NL)} \qquad (4)$$

where the first three terms on the right represent the contribution from changes in total precipitation (ΔP), fraction of solid precipitation (ΔF) and the fraction of accumulated snowfall that remains on the ground (ΔG). $\Delta SWE(NL)$ is a non-linear combination of ΔG, ΔF and ΔP. P_1 is mean total precipitation during different periods of the 21st century, and P_0 is the mean total precipitation during 1986–2005. $\overline{P}=(P_0+P_1)/2$, $\Delta P=(P_1-P_0)$, the definitions of $\overline{G},\Delta G,\overline{F},\Delta F$ can refer to $\overline{P},\Delta P$

3 Validation of CMIP5 simulations for SWE

To evaluate the simulation performance of the models used in this study, we calculated spatial correlations and standard deviation ratios for the observed and simulated winter (DJF) mean SWE (Fig.~~ure~~ 1). ~~We found that each~~ simulated SWE from each model exhibits a strong~~close~~ spatial correlation (~~P~~p<0.05) with~~ the~~ observations, and ~~the majority of~~most standard deviation ratios are close to one. ~~By comparison, most existing models have less-robust correlations and lower standard deviation ratios with the observed data in the time series from 1980 to 2005. However,~~ These results indicate that the models can reproduce the spatial characteristics of SWE. Furthermore, the multi-model ensembles can ~~evidently~~ improve simulation ~~the~~ performance, ~~which~~ and has~~ve~~ better correlation and standard deviation ratios than~~ the~~ most individual model.~~ In addition,~~ Fig.2 shows both the observed and the simulated ~~averaged~~ mean winter ~~mean~~ SWE over ~~the Northern Hemisphere~~NH land covered by the GlobSnow data. ~~is also shown in Fig. 2~~. The observed ~~average~~ mean winter ~~mean~~ SWE over ~~the northern Hemisphere~~NH is 71.6 kg m^{-2}, while the stimulation ranges from 61.0 to 111.3 kg m^{-2}. The RE ranges from −20.3% to 55.4%. ~~Significantly,~~ M~~m~~ost models overestimate SWE, and only five models (CanESM2, CSIRO-Mk3-6-0, HadGEM2-ES, MPI-ESM-LR, MPI-ESM-MR) underestimate SWE, with a RE of −20% to −0.4%. ~~compared with the observation,~~ However, ~~and~~ the multi-model mean is 80.8 kg m^{-2}, which is closer to ~~the~~ observation than ~~the~~ most of the individual model. This illustrates that the multi-model ensemble is more effective for simulating changes in SWE than individual models. From here on, all simulation values ~~denote~~ are from the multi-model means, and we take the period of 1986-2005 from the ~~in~~ historical experiment (1850-2005) as the reference period.

4 Changes in SWE in the 21st century

~~In order~~ T~~t~~o project future spatial and temporal SWE patterns, we analyze three simulatons ~~of SWE change, we analyze simulations for the three RCPs~~ (RCP2.6, RCP4.5, RCP8.5) ~~on temporal and spatial scales~~.

4.1 Spatial changes in SWE for ~~the~~ three RCPs

~~General patterns of~~ P~~p~~rojected spatial changes in SWE relative to 1986-2005 (RP) for the three periods of the 21st century are shown in Fig. 3. ~~Relative to the reference period 1986−2005 (RP),~~The mean annual SWE declines over much of the NH for all the RCPs, with the greatest changes occurring over the Tibetan Plateau (TP);~~,~~ the multi-model mean decrease in SWE exceeds 80% in the western TP. The only regions ~~Only~~ where a weak increase in SWE (RE < 20%) is observed are ~~in~~ eastern Russia and Siberia ~~does a weak increase in SWE occur~~. Over North America, ~~above~~ north of 60°N, ~~we observed~~ there is a pronounced reduction in SWE during the LP for RCP8.5~~,~~ with an ~~relative-error ratios (~~RE~~)~~ that rangs~~ing~~ from -40% to -10%.~~,~~

~~and from -20% to -10%~~ ~~F~~for both RCP2.6 and RCP4.5, the RE ranges from -20% to -10%. In contrast, i~~I~~n eastern Siberia~~,~~ the RE ~~increases to~~is from 10% to ~~≈~~20% for RCP8.5, while for both RCP2.6 and RCP4.5 the RE is <~~less than~~ 10%. This distribution suggests that the magnitude of the SWE decrease (increase in Siberia) gradually becomes larger with time and with higher emissions. ~~This pattern suggests that, as emissions rise, the intensity of decreased or increased SWE both increases. Meanwhile, we note that the decline in SWE is greater during the LP than during the EP and MP for the same emission scenario.~~

The changes in SWE in winter and spring (not shown) ~~Simulations of mean annual SWE~~ show a similar pattern to ~~those~~ that of mean annual SWE.~~winter and spring (not shown). For example,~~ ~~I~~in springtime, for example, the RE ~~of SWE~~ is between -20% and -10% over northern North America and ranges from -40% to -20% over most of Europe. In Siberia, the multi-model mean increase in SWE exceeds 10%. Over the whole NH, t~~T~~he extent of increased springtime SWE (RE > 0) is comparable to that ~~basically the same as that~~ in winter and for the annual mean. Nonetheless, the magnitude of decline of SWE in spring exceeds that in ~~other seasons~~winter so that ~~, resulting that~~ the decrease ~~of~~ in SWE in spring is ~~the~~ more~~st~~ significant than that in winter.

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As global temperatures rise, the projected reduction in SWE is most pronounced along the southern limits of seasonal snow cover. This is p~~P~~articularly apparent over the TP, ~~where is the~~a unique cold, high-altitude region ~~in the mid-latitude NH~~ (Fig. 3), where the increase in temperature is more rapid than in other mid-latitude areas (Liu, 2000; Chen, 2006; Wang et al., 2012), atmospheric warming serves to accelerate snowmelt and reduce total snowfall amounts ~~(Räisänen, 2008)~~.

~~To investigate the zonal changes in SWE,~~ Figure 4 illustrates the relative zonal changes in mean~~-~~annual SWE, precipitation and the absolute change in temperature ~~and maximum SWE and temperature~~ derived from the multi-model ~~simulations~~ mean for the three periods of the 21st century. For all variables, the temporal trends in the multi-model mean are roughly similar in different RCPs during the same period. However, the magnitude of changes in mean annual SWE, precipitation and temperature increase with emissions (RCP) and with time.

The decrease in SWE is small in the 60–70°N latitude band for all three RCPs throughout the 21st century (RE < 30%), and the magnitude of decrease in SWE gradually declines from south to north (north of 60°N), namely, the largest relative reduction in SWE occurs at the low latitude. However, the largest absolute change in SWE (not shown) appears in the high latitudes (70−80°N). Relative to the RP, the magnitude of reduction in NH SWE gradually increases over time with increased emissions. During the LP, the absolute decrease in SWE reaches −28.0 kg m^{-2} for RCP2.6, −55.7 kg m^{-2} for RCP4.5 and −77.6 kg m^{-2} for RCP8.5.

Figure 4 d–f shows that ~~Relative to RP, the projected temperature increase by the end of the 21st century will not exceed 2°C for the lower emissions pathway (RCP2.6) (Stocker et al., 2013). However, as indicated by Fig. 4 (c, f, i),~~ temperatures will increase more rapidly at high latitude than at lower latitude. AR5 also shows that anthropogenic warming will be more pronounced at high latitudes (IPCC, 2013). The temperature increase is greater over time and with higher emissions (RCP), and temperature increases more rapidly in the 50–60°N latitude band than in other areas. The temperature increase does not exceed 2°C in RCP2.6 by the end of the 21st century, which is in agreement with the results of AR5 (IPCC, 2013). Similarly, a greater increase in precipitation occurs in tropical and high-latitude regions during the EP, MP and LP for all three RCPs (Figure 4g–i). The minimum increase in precipitation occurs in the 30–40°N latitude band, which is likely related to the fact that most arid regions in the NH are located in this region. During the EP, relative changes in precipitation are the same for all three RCPs, but these grow larger with time and increased emissions. During the LP, the increase in precipitation exceeds 30% for RCP8.5 at high-latitudes

(70–80°N) whereas changes for the mid–low emission scenarios (RCP2.6, RCP4.5) are generally less than 20%.~~Viewed in greater detail, the model results are similar for all three RCPs during the EP, but diverge during the MP and LP. The maximum simulated increase in temperature occurs at high latitude during the LP for RCP8.5.~~

~~For all three RCPs, the simulations of mean annual SWE exhibit a clear decline throughout the 21st century (Figure 4 b, e, h), with the greatest reductions occurring at high latitudes (~70−80°N). Relative to RP, the decline in low-latitude SWE during the EP is minor (~ -10 kgm~~$^{-2}$~~) for all three RCPs, and the magnitude of the decline rises with increasing latitude. In contrast, the magnitude of the decline in SWE reaches -30 kg m~~$^{-2}$ ~~between 70 and 80°N in each of the three RCPs in EP. While the zonal change in mean annual SWE is highly dependent on RCPs during the MP and LP, particularly at higher latitudes. South of 60°N, the relative changes in SWE during the MP are similar for all three RCPs. However, between 70° and 80°N, the decrease in SWE is -36 kg m~~$^{-2}$ ~~for RCP2.6, -44 kg m~~$^{-2}$ ~~for RCP4.5, and -55 kg m~~$^{-2}$ ~~for RCP8.5. Moreover, the reduction in SWE is more pronounced in the LP than during the EP and MP, particularly for RCP8.5. We note that the maximum increase in temperature and decrease in SWE both occur at high latitudes, suggesting a potential relationship between decreasing SWE and increasing temperature for different RCPs.~~

~~Figure 4 (a, d, g) illustrates an intriguing pattern of zonal maximum SWE (ZMSWE) variability. Relative to RP, the ZMSWE exhibits a general decline for all RCPs over the course of the 21st century. However, the ZMSWE shows a similar pattern for the three RCPs during the EP and MP, while the amounts of decline become highly variable during the LP for the three RCPs. This pattern suggests that the change in ZMSWE depends not only on RCP but also on the different periods (e.g., EP, MP, LP). In contrast, a large reduction in ZMSWE occurs between 30° and 40°N for all three RCPs during the EP, MP and LP, and is potentially linked to the strong reduction in SWE over the TP (Figure 3).~~

~~As the only cold, high-altitude region in the mid-latitude NH, the unique topographic and cryospheric effects of the TP may have affected the performance of model simulations in this region. Nonetheless, we note the modeled output generally captured the main features of the observations (Figure 1).~~

~~We also note that a second, larger decline in ZMSWE occurs at 60–70°N during LP for RCP8.5, this change always accompanies with the amplified warming at the high latitudes, and the magnitude of this decline in SWE is greater than that at 30–40°N. But this result disagrees with the findings of Brutel-Vuilmet et al (2008), who suggested that the relative reduction in ZMSWE would be greatest at lower altitudes (20–30°N). According to that study, the low-latitude decline in ZMSWE is driven by strong snowfall reduction, and the changes are weak farther north despite the stronger warming (Brutel-Vuilmet et al., 2008). Other studies also argue that the most significant decrease in ZMSWE occurs at low elevation in mountainous regions (e.g., Maloney et al., 2012); however, the present results In this study show that the significant change in ZMSWE may also occur at higher elevations (e.g., the TP).~~

~~As shown in Figure 4 g, the magnitude of the decrease in ZMSWE during the LP for RCP8.5 is greater than for the two lower-emissions pathways (RCP2.6 and RCP4.5), particularly at higher latitude. This pattern also indicates a role for temperature in driving changes in ZMSWE, with the exception of the influence of elevation.~~

The above results show that both the relative and absolute changes in SWE show a tendency to decline with time and with increased emissions. The most significant relative reduction in SWE occurs at low latitudes, where snow may gradually disappear with the temperature increasing in the 21st century. Another significant relative and absolute change in SWE occurs in the Arctic, where significant temperature and precipitation increases are projected. This result indicates that decreasing SWE will likely lead to acceleration of the hydrologic cycle.

In general, precipitation increases will lead to an increase in SWE, however, at high latitudes SWE does not increase alongside increased precipitation in all RCPs and periods (Figure 4), which indicates that the decrease in SWE is governed by temperature. However, the Arctic (north of 70°N) is characterized by significant increases in temperature and precipitation, and a significant decrease in SWE. This result suggests that the fraction of accumulated snowfall that remains on the ground (snow cover) will decrease, and it reflects the non-linear relationships between temperature and precipitation and accumulated snowfall.

To analyze the relationships between the decrease in SWE and the increase in temperature, Table 2 shows slopes of the regression between projected interannual SWE and temperature, and the correlation coefficients for SWE and temperature at different latitude bands in the three RCPs. During the EP, linear relationships between SWE and temperature are significant in all latitude bands, which illustrates that SWE decreases alongside increasing temperature. There are also significant negative correlations between SWE and temperature; i.e., increasing temperature leads to decreasing SWE. However, for RCP2.6 this relationship is only observed in the EP, and not in the MP and LP except in the 40–50°N latitude band. Similarly, for RCP4.5 there is significant negative relationship between SWE and temperature in the EP. This relationship is observed north of 40°N in the MP, and gradually moves northward, only occurring in the 40–60°N latitude band in the LP. Of note, a significant negative relationship between SWE and temperature is observed in RCP8.5 during all three periods.

A comparison of Figure 4 with Table 2 shows that although temperature is a key factor in controlling SWE, the rate of the temperature increase is not the same as the rate of the SWE decrease. In other words, SWE decreases in response to a specific temperatures range.

~~According to AR5 (Stocker et al., 2013), anthropogenic warming will be~~

~~most pronounced at high latitude, and the temperature increase further leads to changes in water exchange and the water cycle. Additionally, such enhanced warming will influence the rainfall-to-snowfall ratio of winter precipitation, potentially driving changes in snow cover and/or SWE. Table 2 shows projected changes in the zonal relationship between mean annual SWE and temperature. Relative to RP, the rate of decline in mid-latitude SWE will increase with rising temperature for the mid–low emissions pathways. In contrast, the sensitivity of SWE to temperature gradually decreases from the EP to the LP for RCP8.5, suggesting the rate of reduction in SWE might decline as temperature increases beyond a certain level.~~

In AR4 (~~Meehl et al~~IPCC. 2007), temperatures in the 40−60°N latitude band were closely correlated with the area of springtime snow cover (*r* =-0.68). This correlation increased to -0.76 in AR5 (~~Stocker et al.~~IPCC, 2013). The present results support those findings, suggesting that the most significant changes in SWE will occur at mid to high latitudes during winter and spring (not shown). Furthermore, the correlation between SWE and temperature during different periods of 21^{st} century is stronger, even more than that reported by AR5 (~~Stocker et al.~~IPCC, 2013), indicating that SWE at mid to high latitudes will persistently decrease with the rising temperature.

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4.2 Seasonal changes in SWE

Figure 5 depicts ~~seasonal~~ monthly changes in ~~monthly~~ SWE and its relative change (RE) ~~averaged~~ over ~~the~~ NH land~~masses~~ (excluding Greenland) during different periods of the 21^{st} century.~~the RP, EP, MP and LP. The~~ M~~m~~ulti-model ensemble simulations during the RP ~~shows that simulations during the RP are consistent with the observed SWE, reproducing~~ reproduce the basic features of monthly variation in observed SWE (GlobSnoe), with the maximum values ~~during~~ in spring, and minimum ~~values~~ SWE ~~during~~ in summer (not shown). These same features are evident in simulations of the EP, MP, and LP for the three different RCPs (Figure 5a-c), although the main difference ~~being~~ is that total SWE throughout the 21^{st} century is lower than during the RP.

~~amounts are lower than those during the RP. Figure 5 (b, d, f) shows changes in SWE during the EP, MP and LP for all three RCPs, relative to RP. For all three periods of the 21st century, the greatest decrease in SWE occurs during spring, while the smallest reduction occurs in summer, contrary to the pattern of monthly SWE change. The magnitude of the decrease in SWE is similar for each RCP during the EP (Figure 5 b), that is, in the first 20 years of 21st century, the change in SWE relative to RP is the same in all three RCPs, but differences among the RCPs are evident during the MP and LP (Figure 5 d, f). During the LP, the maximum decline reaches -26.39 kg m^{-2} for RCP8.5, while the values range from -13.85 to -17.45 kg m^{-2} for RCP2.6 and RCP4.5, respectively. RCP has stronger effects on SWE change in LP than in EP and MP, although the model uncertainty caused by integration cumulative errors is enlarged from EP to LP. However, the simulation still basically reproduces the features of SWE. Thus, regardless of RCP or time period, the reduction in SWE during the winter half-year exceeds that in the summer half-year, in keeping with the results shown in Figure 3.~~

Figure 5d–f shows changes (RE) in SWE during the EP, MP and LP for all three RCPs relative to the RP. For all three periods of the 21st century, the greatest decrease in SWE occurs during summer, while the smallest reduction occurs in spring. In the first 20 years of the 21st century, the change in SWE relative to the RP is the same in all three RCPs (Figure 5d), and differences among the RCPs are more evident during the MP and LP (Figure 5e–f). During the last period of the 21st century (LP), the maximum reduction in SWE is 66.4% for RCP8.5, and ranges from 27.5% for RCP2.6 to 39.8% for RCP4.5. In contrast, the largest absolute change in SWE appears in spring, with the smallest decline in summer. The relative change in SWE is thus predicted to be markedly different to the absolute change.

~~As the dominant parameters influencing SWE,~~ T~~t~~emperature and precipitation are the dominant parameters influencing SWE, and both exhibit considerable changes in seasonality (Figure 6). Relative to the RP, temperatures are projected to rise during the EP (Figure 6a), MP (Figure 6c) and LP (Figure 6e) for all three RCPs, with the greatest warming occurring in winter and the smallest in summer. The magnitude of the temperature change increases with higher emissions over time. In the EP, the temperature increase does not exceed 2°C for all three RCPs, and larger differences emerge during the MP and LP. Moreover, a basic feature is that the temperature increase is significant in the tropics and Arctic regions during the three periods of 21st century.~~both exhibit considerable changes in seasonality (Figure 6). Relative to RP, temperatures for all three RCPs are projected to rise during the EP (Figure 6 a), MP (Figure 6 c), and LP (Figure 6 e), with the greatest warming occurring in winter, and the smallest in summer. Similar results in EP (Figure 6 a) show that the temperature increase does not exceed 2°C, which is consistent with the results in AR5. During later periods, the magnitude of warming varies according to RCP, particularly during the LP, for which the RCP8.5 simulation produces a larger change than the other two emissions pathways (Figure 6 e).~~

Precipitation also increases throughout the 21st century for all three RCPs (Figure 6d–f), and changes in precipitation during winter exceed those during summer, despite the larger absolute change in precipitation in summer. During the EP, the magnitude of precipitation increase is the same for all three RCPs, and the change gradually grows larger with increased emissions over time. A noticeable feature of the model outputs is that changes in precipitation for mid–low emissions are not significant during the MP and LP, the largest increase in precipitation occurs during winter in the LP for RCP8.5, and the RE exceeds 20%.

~~Precipitation also exhibits an increasing trend for the different RCPs, with the smallest increase occurring in spring, coincident with the largest decrease in SWE during spring. Simulated changes in precipitation are similar for the different RCPs during the EP (Figure 6 b), but diverge during the MP (Figure 6~~

~~d) and LP (Figure 6 f), indicating that the magnitude of projected precipitation changes is dependent on RCP and the time period. The most significant increase in precipitation occurs during the LP for RCP8.5. While the rise in temperature during the winter half-year is larger than that of the summer half-year, the opposite is true for precipitation, with the greatest increase taking place during the summer half-year. This pattern implies that decreasing SWE is attributable to increasing temperature and the minor increase in precipitation~~

SWE tends to decrease alongside the increase in global temperature throughout the 21st century. To further validate this finding for SWE in different RCPs, Table 2 shows the regression slope for mean annual SWE and mean temperature over different latitude bands in the NH during the RP, EP, MP and LP. The results show a significant decrease in SWE for RCP8.5 during the EP, MP and LP. However, for the mid–low emission scenario, a significant decrease in SWE at different latitude bands only occurs persistently in the EP. In the MP and LP, a significant decrease in SWE occurs mainly in the mid–high latitude band. The distribution in the linear trend of mean annual SWE (not shown) shows decreases over northern North America and the TP, and increases over Siberia. This pattern indicates that the change in mean annual SWE is spatially variable, which is consistent with the spatial change shown in Figure 3.

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~~To differentiate between the relative contributions of temperature and precipitation to SWE, we calculated partial correlations between the SWE and temperature and precipitation. Table 3 shows that for each time period of the 21st century, SWE has a strong negative partial correlation with temperature and weak correlation with precipitation. The significantly negative partial correlation for RCP8.5 decreases from EP to LP in the winter half-year, implying that the rate of decline should diminish as a consequence of rising temperature. We also note that the partial correlation between SWE and temperature during the spring uniformly passes the 90% significance test~~

~~during the EP, MP, and LP for RCP8.5, resulting in a persistent decline in springtime SWE. The largest decline in simulated SWE also occurs in spring, consistent with the results shown in Figures 3 and 5, the decrease in SWE is related to the increasing temperature. Räisänen (2008) proposed that changes in snow conditions will most likely depend on present-day temperature, in close agreement with our results.~~

~~The correlation between SWE and temperature in Table 2 reflects the relation of SWE decreasing to the increasing temperature. The sensitivity of SWE to temperature shows a gradually increase over the 21st century form the south to the north. The correlation is significant in most latitude zones (north of 30°N) in EP, but not in MP or LP, in all three RCPs, and is only significant north of 30°N under RCP8.5 in the EP, MP and LP. In addition, SWE is only weakly related to temperature in MP and LP except for several latitude zones in RCP2.6, suggesting that the temperature increase is not always linked to a decreasing SWE.~~

~~4.3 Trend changes in SWE~~

~~To further analyze the SWE changes in different RCPs, Figure 7 shows the annual and seasonal SWE trend distribution during 2006–2099 in the NH. The results show that the projected significant changes in SWE occur at mid to high latitudes, with a decreasing trend over the northern North America and the TP, and an increasing trend over Siberia. This pattern shows that the rate of SWE change is spatially variable. The CMIP5 multi-model ensemble projects a decreasing trend in SWE in most regions over the NH landmasses between 2006 and 2099 (Figure 7). For RCP2.6, the mean annual SWE is projected to decrease considerably over the TP, where the annual mean trend is less than -4 kg m^{-2}/10a, which is consistent with the temperature increasing rapidly at high elevations in mid-latitude regions. Coastal Alaska is another region where SWE changes are evident, and the trend here is between -1.5 and -1 kg m^{-2}/10a. In other regions, trends range from -0.5 to 0.5 kg m^{-2}/10a for RCP2.6. An increasing trend is projected for central Asia and eastern~~

~~Siberia.~~

~~For RCP4.5, the areal extent of the significant reduction in SWE increases over both the TP and coastal Alaska, and the notably decreasing trend over the TP reflects the decreasing SWE in response to increasing temperature, with the exception of the influence of terrain. For RCP8.5, the mean annual SWE is projected to decline over North America, particularly in western North America and eastern Canada, where the trend is smaller than -4 kg m^{-2}/10a. In the Eurasia region north of 45°N, SWE is projected to increase in the east (eastern Siberia) and decrease in the west. Another significant negative trend is located over central Russia, where the negative trend in SWE ranges from -3.5 to -3 kg m^{-2}/10a. At mid-low latitudes in Eurasia, the most significant reductions in mean annual SWE still occur over the TP. Compared with the lower-emissions pathways (RCP2.6, RCP4.5), the magnitude of decline or increase in SWE is greater for RCP8.5. Specifically, the CMIP3 models show that mean annual SWE will increase over eastern regions and decrease over western regions of Eurasia between 2003 and 2060, and that the intensity of SWE changes is greater under higher-emissions scenarios (e.g., A2) than under lower-emissions scenarios (e.g., B1) (Ma et al., 2011).~~

On~~At~~ a~~the~~ seasonal scale, ~~projected trends in SWE over the NH landmasses are weaker during the summer half-year than the winter half-year for all three RCPs. During winter, in Eurasian north of 45°N, SWE exhibits an increasing trend in the east and a decreasing trend in the west. In contrast, trends in wintertime SWE are uniformly negative over North America and the TP. From the lower emissions to the higher emissions, both the increasing and decreasing trends become more pronounced. In contrast,~~ the extent and ~~intensity~~ magnitude of the SWE increase~~mental SWE~~ in winter is larger than ~~that~~ in spring, but the ~~reduction~~ range and ~~strength~~ magnitude of SWE decrease is significantly smaller than ~~that~~ in spring. This is due to the later shift from liquid to solid precipitation in autumn and an earlier onset of snowmelt in

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spring (Räisänen, 2008). Consequently, the reduction in SWE averaged over the NH is more significant in spring than in winter.~~; consequently, the absolute scale of reduction in SWE is larger in spring than in winter.~~

~~Although ensemble simulations show that SWE decreases throughout much of the NH during the three RCPs investigated, we note that there remains a significant increasing trend in SWE across Siberia in winter and spring. Nonetheless, owing to the greater geographical extent and magnitude of the projected reductions, the average trend for the NH in the 21st century is for progressively declining SWE.~~

There is high model uncertainty of SWE simulation in the 21st century, especially for RCP8.5, this is illustrated in Figure 7, which also shows the range of uncertainty in the mid–low emission scenario. However, despite model uncertainty, ~~The projected changes in mean annual SWE over NH landmasses in the three RCPs are shown in Figure 8 and Table 4. Relative to RP, mean~~ annual SWE still ~~-~~exhibits a consistent and significant decline for each of the three RCPs, with linear trends of −0.54 kg m^{-2}/10a for RCP2.6, −1.09 kg m^{-2}/10a for RCP4.5 and −2.05 kg m^{-2}/10a for RCP8.5 ~~-0.54, -1.09, and -2.05 kg m^{-2}/10a for RCP2.6, RCP4.5, and RCP8.5~~ (Table 3~~4~~).~~, respectively. After 2040,~~ Figure 7 also shows that the negative trend in SWE gradually begins to level out for RCP2.6, and weakens somewhat for RCP4.5. For RCP8.5, however, the SWE continues to decline beyond the end of the 21st century, which agrees with projections of snow cover extent (Zhu and Dong, 2013).~~consistent with anticipated reductions in snow cover (Brutel et al., 2012).~~

Despite the fact that ensemble simulations show decreasing SWE throughout much of the NH during the three RCPs investigated, we note a significant increasing trend in SWE across Siberia in winter and spring. Nonetheless, owing to the greater geographical extent and magnitude of the projected reductions, there is an overall negative trend in NH SWE during the 21st century.

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5 Contribution analysis for SWE change~~Changes in SWE with rising temperature~~

In both seasonal and zonal contexts, rising temperatures play a fundamental role in projected SWE. Figure 6 shows that the most significant increases in temperature and precipitation occur in winter, but the largest reduction in SWE appears in summer. To ~~analyze~~ identify the relative contributions ~~impact~~ of temperature and precipitation to changes in ~~on~~ SWE ~~in the 21st century~~, we calculate the partial correlation between SWE and temperature as well as between SWE and precipitation during the RP, EP, MP and LP for three RCPs (Table 4). SWE has a strong negative partial correlation with temperature and weak correlation with precipitation throughout the 21st century. The negative partial correlation for RCP8.5 decreases from the EP to the LP in the winter half-year, indicating that the rate of the SWE decrease should decline as temperature increases. We also note that the partial correlation between SWE and temperature during the spring uniformly passes the 90% significance test during the EP, MP and LP for RCP8.5, resulting in a persistent decline in springtime SWE, despite the increase in precipitation.~~the ratios of SWE decrease to temperature increase are calculated for the three RCPs during the EP, MP, and LP (Figure 9). The ratios reflect the sensitivity of SWE to temperature. Similar linear relations have been reported for sea ice (Mahlstein and Knutti, 2012) and permafrost (Slater, 2013), indicating that increasing temperature plays a central role in cryospheric change. As shown in Figure 9, the slopes for EP, MP, and LP (-1.47 to -2.50 kg m^-2 °C^-1) are less than that for the RP (-3.17 kg m^-2 °C^-1), implying that the rate of decrease in SWE ultimately will decline with persistent~~

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~~temperature rise. Furthermore, we note that the sensitivity of SWE to temperature increases gradually from the EP to LP for a single emissions pathway, and over the same period the sensitivity decreases when moving from the lower-emissions to higher-emissions pathways. Thus, the impact of temperature on SWE is dependent on the magnitude and duration of emissions forcing.~~

Relative to 1986–2005, the largest absolute decline in simulated SWE also occurs in spring, indicating that the decrease in SWE is related to earlier temperature-driven snowmelt. This result agrees with Räisänen (2008) who proposed that changes in snow conditions would likely depend on present-day temperature. With the increasing temperature, the sensitivity of SWE to temperature averaged over the NH gradually increases from the EP to the LP for the same RCP (not shown).

Temperature increase may change the water cycle and rain–snow ratio (fraction of solid precipitation), and will act to increase the rate of snow melt (fraction of accumulated snowfall). Actually, as shown by Equation 4, SWE can be affected by changes in total precipitation, the fraction of precipitation that falls as snow and the fraction of accumulated snowfall that has not melted. Räisänen (2008) used CMIP3 model simulations to analyze the contributions of the above factors to SWE in Finland and eastern Siberia, and suggested that the major contributor to the change in SWE varies regionally. Thus, over the whole NH, how about the effect of total precipitation, snowfall and accumulated snowfall on SWE during the different periods of the 21st century.

~~Furthermore, a linear relationship between SWE and temperature is found for all three RCPs and all three periods (Table 2). The linear regression slope reflects the response of SWE to the increasing temperature. The sensitivity of SWE to temperature gradually declines over the course of the~~

~~21st century for RCP8.5, suggesting a threshold for the relationship between SWE and temperature. That is, if the temperature increases to a certain level, the rate of decline in SWE will slow down.~~

Figure 8 shows the contributions of total precipitation, snowfall and accumulated snowfall to the changes in SWE for three RCPs during three periods of 21st century. During the EP, total precipitation shows an increase in all months, but snowfall decreases in all months. This indicates that changes in total precipitation and snowfall have competing effects and lead to an increase and decrease in SWE, respectively. Because the magnitude of the decrease in snowfall is larger than the increase in total precipitation, the reduction in SWE is attributed to changes in the fraction of precipitation that falls as snow. The contributions of total precipitation, snowfall and accumulated snowfall grow larger with time. During the LP, temperature increases cause the change in accumulated snowfall to be larger than the change in snowfall after May, so that the former becomes the main control on SWE. In general, from August to May in the next year, the change in SWE is generally related to changes in snowfall, but after May increased melting efficiency dominates the change in SWE.

6 Summary and conclusions

We employed ~~twenty~~ 20 CMIP5 climate models to investigate projected changes in SWE for the 21st century~~, using~~ under three different RCPs. ~~We find that, relative to RP, mean annual SWE for all three RCPs exhibits a~~The results show a decrease in mean annual SWE for all three RCPs~~ negative trend~~ over much of the NH landmasses relative to the RP. The most significant reductions occur over the TP and ~~the majority of~~ North America, while a minor increase occurs over Siberia, however, the overall pattern in the NH is one of declining SWE. ~~.~~Moreover, we suggested that the intensity of changes in SWE is greater for RCP8.5 than for RCP4.5 and RCP2.6, and that these changes are most pronounced at mid to high latitudes. Since both the magnitude and geographic extent of the changes are much greater in spring than in winter, the overall pattern in the NH is one of declining SWE, with the most significant losses occurring in spring. The multi-model ensemble suggests that the negative trend in SWE ~~for RCP2.6 will~~ begins to level out or become stable for RCP2.6 and weakens somewhat for RCP4.5, ~~diminish after 2040,~~ whereas the declining trend continues beyond the end of the 21st century for RCP8.5. The patterns of change in SWE in spring and winter are the same with the mean annual SWE, since both the magnitude and geographic extent of the reduction in SWE are much greater in spring than in winter, the significant reduction in SWE over NH occurs in spring, however, the largest percent change in SWE does not occur in spring, but in summer, and this indicates that the change in SWE is related to baseline SWE.

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Changes in SWE are accompanied by increasing temperature and precipitation during the winter half-year~~, most notably in spring~~. SWE is not simply a function of temperature, ~~However,~~ but the partial correlations between SWE and both temperature and precipitation indicate that ~~considerable~~ decreases in SWE can be attributed primarily to increasing temperatures. Furthermore, we note that while atmospheric warming occurs primarily ~~preferentially~~ during the winter half-year, coincident with the ~~small~~ greater increase ~~projected increase~~ in precipitation, ~~but the increase~~ greater precipitation cannot compensate for the increased snowmelt due to rising temperatures.

Projections of mean annual SWE exhibit a declining trend~~s~~ and the magnitude of the SWE relative decrease is gradually reduced from south to north over NH. Namely, a more significant reduction in mean annual SWE for all three RCPs occurs at low latitudes throughout the 21st century, accompanied by an anticipated warming trend. Annual maximum SWE also has similar features to mean annual SWE, with the largest decrease observed at low latitudes. However, ~~with increasing latitude. Specifically, a more significant reduction in mean annual SWE for all three RCPs occurs between~~

~~70° and 80°N for the three time periods of the 21st century, accompanied by an anticipated warming trend. Moreover,~~ the correlation between mean annual SWE and temperature ~~is significant at high latitudes, and the data~~ suggests that a threshold of the relationship between the SWE and temperature would ~~restrain~~ mitigate the persistent ~~decline~~ decrease in SWE with increasing temperature. ~~For ZMSWE, the results also show a larger-scale decrease in ZMSWE centered between 30° and 40°N for all RCPs during the three periods investigated, which reflects the influence of terrain on SWE; and other pronounced reduction occurs at high latitude during the LP, only for RCP8.5, implying that, with the exception of topography, changes in ZMSWE are influenced primarily by temperature.~~

The 21st century temperature increases are projected to have a pronounced effect on rain–snow ratios and snowmelt. Precipitation also shows an increasing trend, however, because the magnitude of the reduction in snowfall is larger than the increase in total precipitation, the decreasing snowfall becomes the major contributor to the reduction in SWE from August to May in the next year during the 21st century. As the temperature increase, efficient snowmelt dominates the change in SWE after May, especially during the LP. ~~An intriguing feature of the modeled projections is that, although decreasing SWE invariably accompanies the increasing temperature, ratios of SWE decrease to temperature increase are highly variable among the RCPs and modeled time periods. The results suggest that this pattern reflects diminished sensitivity of SWE to temperature during the EP, MP, and LP relative to the RP. As mean annual temperature increases, the rate of decline in SWE will decrease, a pattern that is dependent not only on the specific RCP but also on the integration time period (e.g., EP, MP, LP).~~ Finally, aAlthough ~~the~~ model projection have increasing ~~results contain~~ uncertainty later in the 21st century, the trends observed in the simulations remain consistent,~~ies due to errors caused by integration truncation and inter-model differences,~~ and increased model error and bias do not appear to~~this does not~~ affect the

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~~generality or the value of the main~~ conclusions of this study.

Author contributions. C. H. Wang contributed to the idea and conception of this study, analysis of the result and arrangement the framework of the manuscript.

H. X. Shi carried out the analysis of the data and writing the manuscript with the assistance of C. H. Wang.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (2013CBA01808, 91437217, 41275061). The snow water equivalent data used in this study are from European Space Agency (ESA) GlobSnow product and CMIP5 model outputs.

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Table. 1. Models used in this study.

Number	Model	Institution	Resolution
1	BCC-CSM1-1	Beijing Climate Center, China	2.8° ×2.8°
2	BCC-CSM1-1(m)	Beijing Climate Center, China	1.3° ×1.1°
3	CanESM2	Canadian Center for Climate Modeling and Analysis, Canada	2.8° ×2.8°
4	CCSM4	National Center for Atmospheric Research, USA	1.25° ×0.94°
5	CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	1.4° ×1.4°
6	CSIRO-Mk3-6-0	CSIRO Atmospheric Research, Australia	1.875° 1.875°
7	FGOALS-g2	Chinese Academy of Sciences	1.4° ×6°
8	FIO-ESM	The First Institute of Oceanography, SOA, China	2.8° ×2.8°
9	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	2.5° ×2.0°
10	GISS-E2-H	ASA Goddard Institute for Space Studies, USA	2.5° ×2.0°
11	GISS-E2-R	NASA Goddard Institute for Space Studies, USA	2.5° ×2.0°
12	HadCEM2-ES	Met Office Hadley Centre, UK	1.875° × 1.25°
13	MIROC5	Atmosphere and Ocean Research Institute, Japan	1.4° ×1.4°
14	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, Japan	2.8° ×2.8°
15	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, Japan	2.8° ×2.8°
16	MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.9° ×1.9°
17	MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	1.875° × 1.875°
18	MRI-CGCM3	Meteorological Research Institute, Japan	1.1° ×1.1°
19	NorESM1-ME	Norwegian Climate Center, Norway	2.5° ×1.875°
20	NorESM1-M	Norwegian Climate Center, Norway	2.5° ×1.875°

Table. 2. Zonal slope (Slop) of the regression of mean annual SWE and temperature, and correlation coefficients (Cor.) ~~between~~ for mean annual SWE and ~~mean~~ temperature for three RCPs. RP, EP, MP, LP represent the periods 1986−2005, 2016−2035, 2046−2065, and 2080−2099, respectively.

		RCP2.6				**RCP4.5**			**RCP8.5**		
Lat(°N)		RP	EP	MP	LP	EP	MP	LP	EP	MP	LP
20-30	S	-0.43*	-0.22	-1.45	-0.36	-0.52*	-0.25	-0.08	-0.23*	-0.23*	-0.08
	C	-0.55*	-0.22	-0.42*	-0.14	-0.69*	-0.34	-0.03	-0.45*	-0.48*	-0.30
30-40	S	-2.15*	-4.38*	-0.74	-1.02	-3.39*	-0.85	-2.86	-3.14*	-1.64*	-0.81*
	C	-0.64*	-0.91*	-0.13	-0.13	-0.77*	-0.29	-0.25	-0.84*	-0.78*	-0.68*
40-50	S	-1.00*	-0.84	-1.60	-2.97*	-1.69*	-1.06*	-3.02*	-1.77*	-0.89*	-0.76*
	C	-0.62*	-0.44*	-0.39	-0.55*	-0.80*	-0.48*	-0.71*	-0.86*	-0.74*	-0.82*
50-60	S	-3.27*	-3.82*	-0.39	-2.68	-3.28*	-3.24*	-2.62*	-3.25*	-2.55*	-1.33*
	C	-0.71*	-0.64*	-0.08	-0.28	-0.75*	-0.65*	-0.57*	-0.80*	-0.78*	-0.67*
60-70	S	-2.87*	-2.57*	-2.84	-3.64	-3.67*	-5.10*	-3.71	-4.10*	-3.70*	-2.84*
	C	-0.66*	-0.47*	-0.32	-0.33	-0.74*	-0.76*	-0.35	-0.71*	-0.83*	-0.73*
70-80	S	-10.2*	-16.9*	-0.30	-2.40	-4.57*	-5.23*	-2.10	-8.31*	-6.16*	-4.62*
	C	-0.88*	-0.72*	-0.02	-0.35	-0.65*	-0.81*	-0.06	-0.84*	-0.91*	-0.88*

Note: * values~~indicate that the slope and correlation~~ exceed the 95% significance test.

Table. 3. Trends in SWE over Northern Hemisphere land during 2006−2099 derived from the three RCPs. All trends are significant at 95% confidence level (Mann–Kendall test).

Trend ($kg\ m^{-2}/10a$)	RCPs		
	RCP2.6	RCP4.5	RCP8.5
Autumn	-0.51	-1.17	-1.83
Winter	-0.54	-1.18	-2.18
Spring	-0.61	-1.32	-2.39
Summer	-0.50	-1.09	-1.79
Mean	-0.54	-1.09	-2.05

Table. 4~~3~~. Partial correlations between mean annual SWE and both temperature (T) and precipitation (P) over Northern Hemisphere land for three RCPs. RP, EP, MP, LP represent the periods 1986−2005, 2016−2035, 2046−2065, and 2080−2099, respectively.

			RCP2.6			RCP4.5			RCP8.5		
Month		RP	EP	MP	LP	EP	MP	LP	EP	MP	LP
Jan	T	-0.29	-0.59*	-0.25	-0.1	-0.54*	-0.44*	-0.52*	-0.45*	-0.38*	-0.31
	P	-0.13	-0.22	-0.05	-0.13	0.1	0	-0.14	0.05	-0.05	-0.05
Feb	T	-0.42*	-0.2	-0.1	-0.37*	-0.25	-0.76*	-0.38*	-0.51*	-0.39*	-0.28
	P	0.05	-0.17	-0.11	0.04	-0.11	0.18	0.09	0.02	-0.05	-0.11
Mar	T	-0.22*	-0.26	-0.24	-0.54*	-0.42*	-0.17	-0.56*	-0.4*	-0.4*	-0.4*
	P	-0.07	-0.03	-0.09	0.22	-0.05	-0.18	0.05	-0.02	-0.03	0.01
Apr	T	-0.38*	-0.31	-0.14	-0.38*	-0.37*	-0.49*	-0.51*	-0.49*	-0.38*	-0.38*
	P	-0.06	-0.1	0.02	-0.01	-0.09	0.09	0.09	0.11	-0.08	-0.05
May	T	-0.36*	-0.33	-0.31	-0.34	-0.31	-0.46*	-0.5*	-0.48*	-0.42*	-0.41*
	P	-0.07	-0.1	-0.38	-0.06	-0.2	0.07	0.09	0.1	-0.06	-0.01
Jun	T	-0.43*	-0.33	-0.57*	-0.07	-0.26	-0.46*	-0.08	-0.45*	-0.39*	-0.38*
	P	-0.07	-0.09	0.12	-0.06	-0.11	0.11	-0.27	-0.04	0.02	-0.05
Jul	T	-0.48*	-0.48*	0.27	-0.26	-0.56*	-0.54*	-0.51*	-0.04	-0.46*	-0.24
	P	-0.11	0	-0.2	-0.14	-0.08	-0.02	0.05	0.02	-0.09	-0.02
Aug	T	-0.33	-0.48*	-0.36*	-0.21	-0.48*	-0.38*	-0.29	-0.47*	-0.48*	-0.4*
	P	-0.07	-0.25	-0.06	-0.03	0	0	-0.02	-0.18	0	-0.06
Sep	T	-0.35	-0.44*	-0.39*	0.13	-0.3	-0.1	-0.59*	-0.27	-0.24	-0.34
	P	-0.05	-0.13	-0.01	-0.14	-0.17	-0.07	0.14	-0.07	-0.15	-0.04
Oct	T	-0.35	-0.53*	0.18	0.16	-0.47*	-0.21	-0.5*	-0.33	-0.28	-0.25
	P	-0.08	0	-0.09	-0.52	-0.03	0.06	0.07	-0.1	-0.06	-0.06
Nov	T	-0.43*	-0.36*	-0.07	0.01	-0.53*	-0.47*	-0.21	-0.29	-0.21	-0.33
	P	-0.05	-0.11	-0.09	-0.28	0.15	-0.05	-0.2	-0.03	-0.17	0
Dec	T	-0.25	-0.5*	-0.12	0.08	-0.27	-0.58*	-0.35	-0.34	-0.28	-0.28
	P	-0.12	-0.05	-0.01	-0.29	-0.16	-0.05	-0.19	-0.03	-0.05	0.04

Note: * ~~indicate that the partial correlation~~ values exceed~~s~~ the 95% significance test.

~~Table. 4. Trends of SWE during 2006–2099 derived from the three RCPs. Each trend is significant at 95% confidence.~~

~~Trend (kg m^{-2}/10a)~~	~~**RCPs**~~		
	~~**RCP2.6**~~	~~**RCP4.5**~~	~~**RCP8.5**~~
~~Autumn~~	~~-0.51~~	~~-1.17~~	~~-1.83~~
~~Winter~~	~~-0.54~~	~~-1.18~~	~~-2.18~~
~~Spring~~	~~-0.61~~	~~-1.32~~	~~-2.39~~
~~Summer~~	~~-0.50~~	~~-1.09~~	~~-1.79~~
~~Mean~~	~~-0.54~~	~~-1.09~~	~~-2.05~~

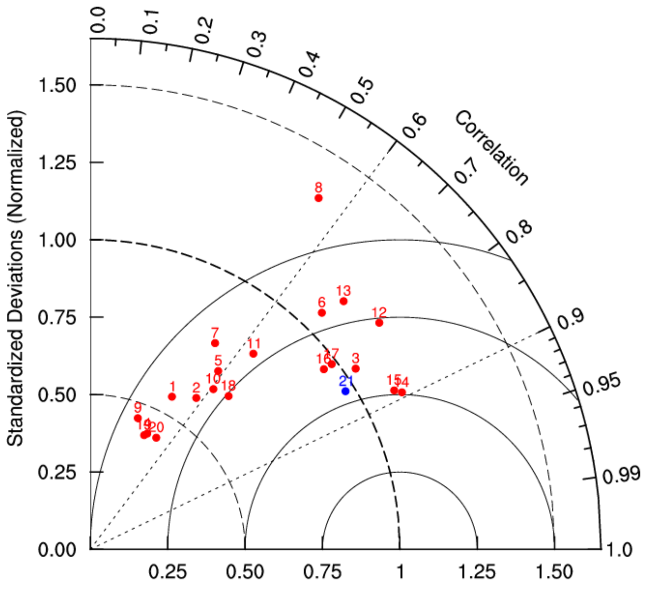


Figure. 1. Spatial correlation and standard variance ratios between observed and simulated (20 models) winter (DJF) mean SWE during 1980-2005. The numbers 1-20 ~~indicates the 20 models used in this paper, and~~ refer~~s~~ to the model names in Table 1.The number 21 indicates the multi-model ensemble. The vertical axis indicates the standard deviation ratios, and the numbers along the arc are the spatial correlation.

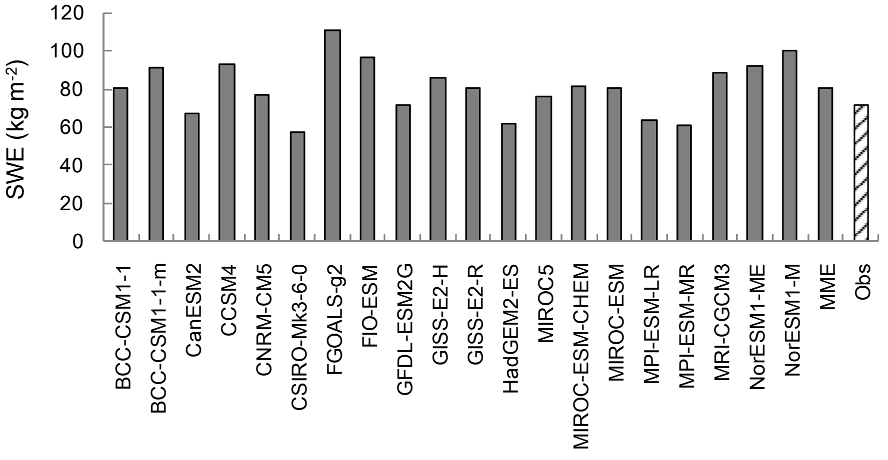
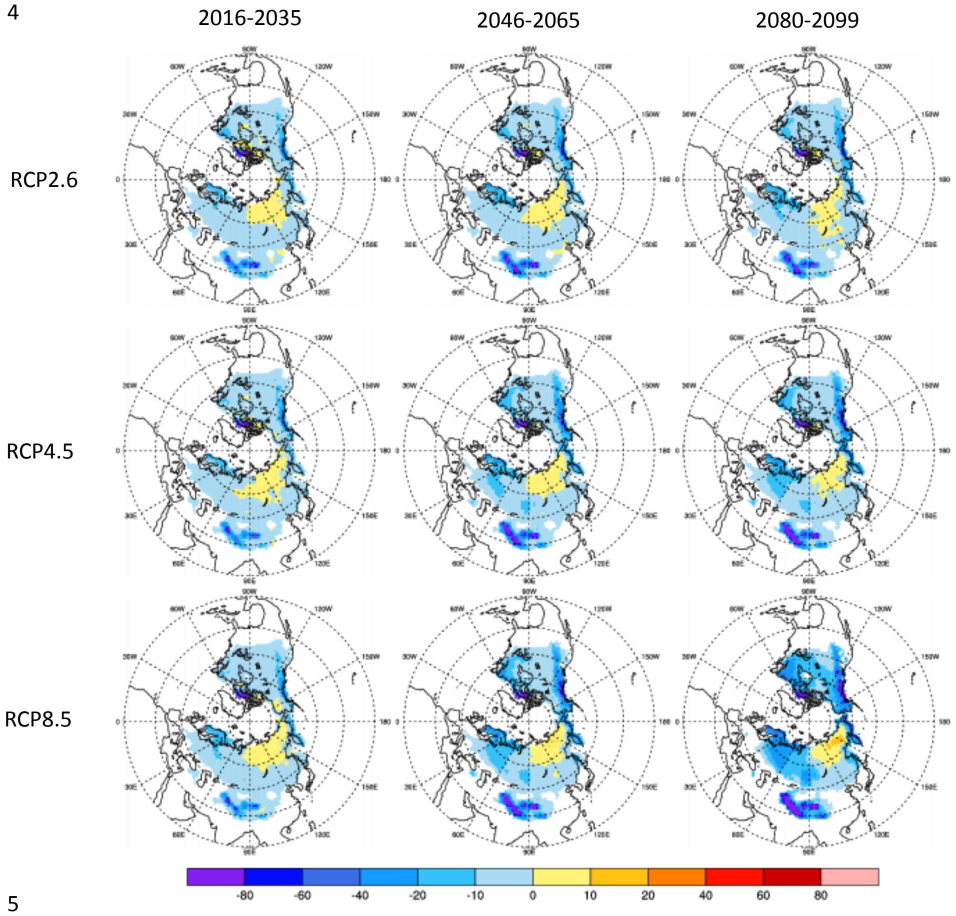


Figure. 2. The average of the observed and stimulated winter (DJF) mean SWE over the N~~n~~orthern Hemisphere land during 1980-2005. The multi-model ensemble (MME) refers to a combination of the 20 models listed in Figure 1. ~~(The 'MME' comprises the 20 preceding models listed in the figure).~~



~~Figure. 3. Changes in mean annual SWE (kg m $^{-2}$) projected by the CMIP5 ensemble, relative to the period of 1986-2005. The three rows indicated the three scenarios RCP2.6, RCP4.5, and RCP8.5, respectively, the three columns are the three periods of 2016-2035, 2046-2065 and 2080-2099, respectively.~~

Figure. 3. Relative changes in mean annual SWE (%) projected by the CMIP5 ensemble, relative to the 1986−2005 reference period.

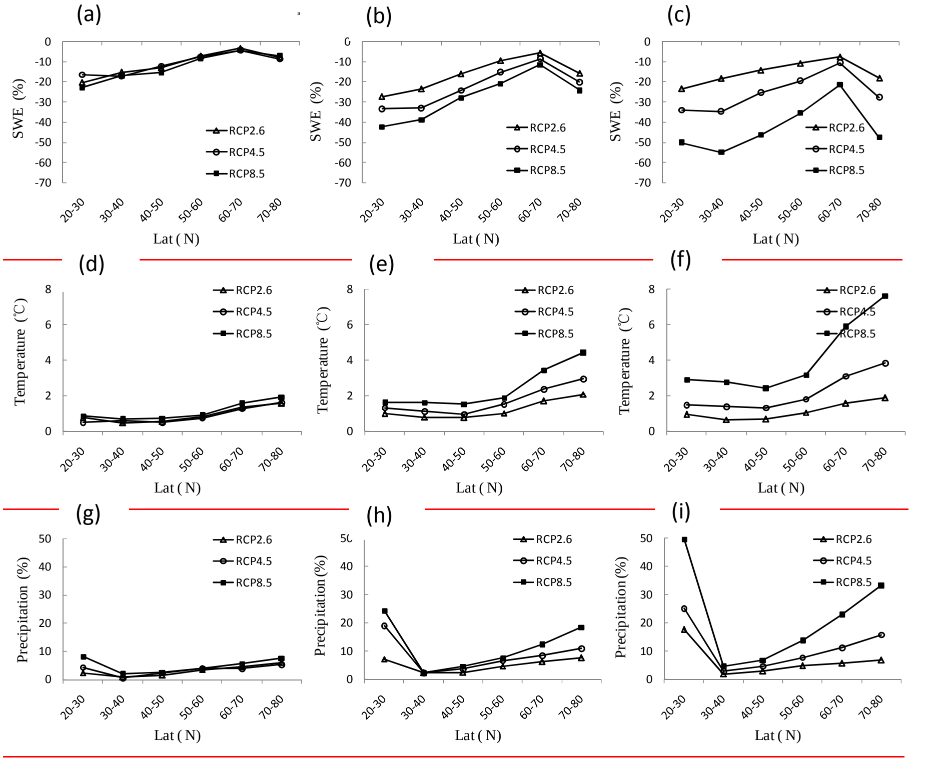
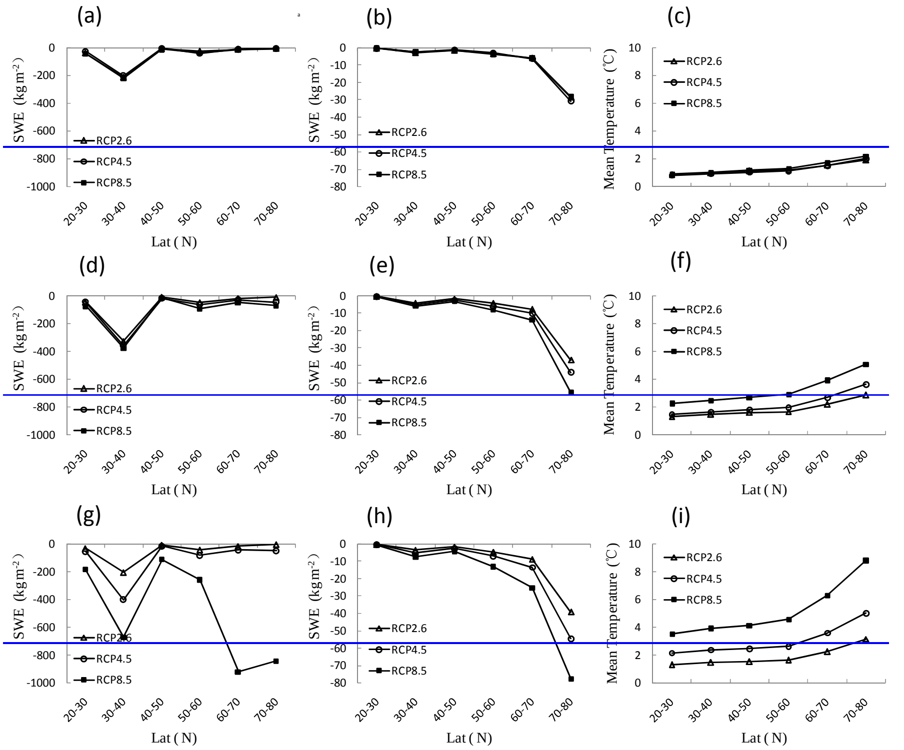


Figure 4. Relative zonal changes in mean annual SWE (a–c), mean annual air temperature (d–f) and mean annual precipitation (g–i) over Northern Hemisphere land for 2016−2035 (left), 2046−2065 (middle), and 2080−2099 (right) relative to the 1986−2005 reference period.



~~Figure. 4. Zonal changes in maximum annual SWE (panels a, d, g), mean annual SWE (panels b, e, h), and mean annual air temperature (panels c, f, i) for 2016–2035 (top), 2046–2065 (middle), and 2080–2099 (bottom), relative to the 1986–2005 mean.~~

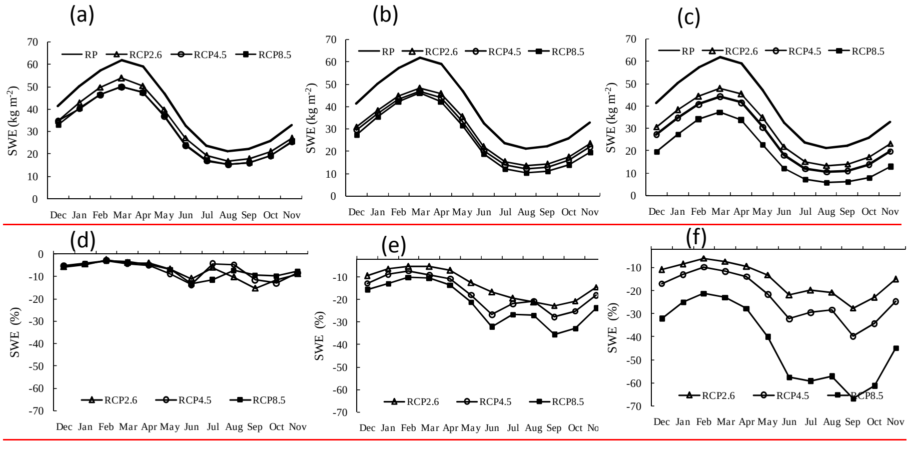
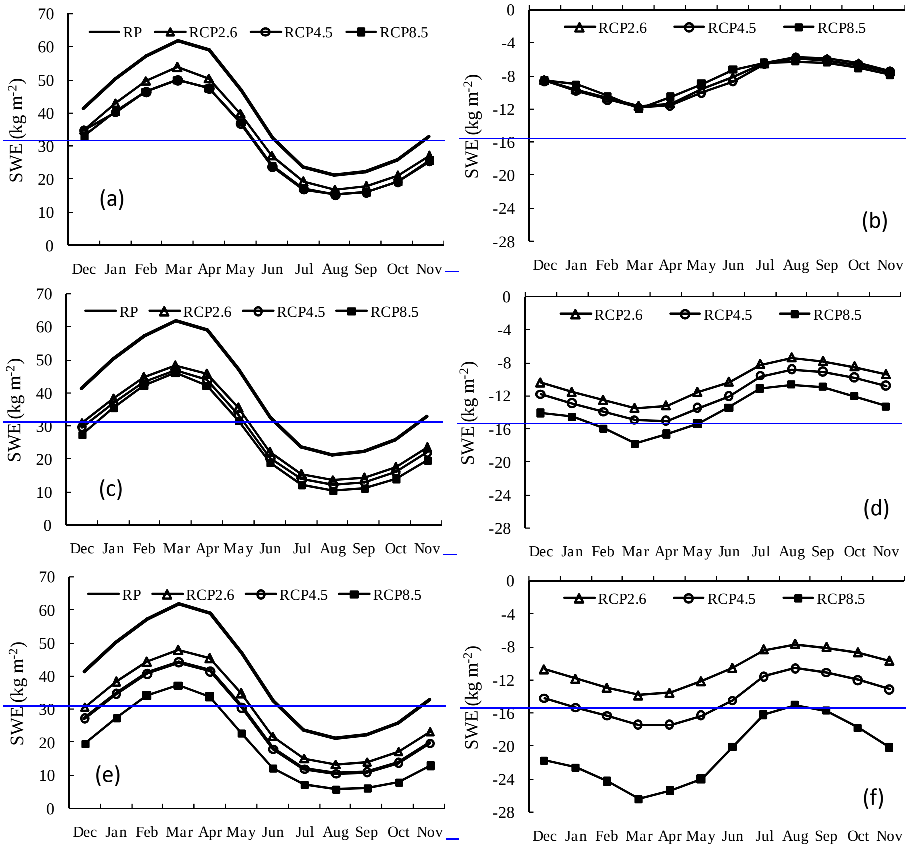


Figure 5. Projected monthly average (a–c) and relative change (RE) (d–f) in SWE over Northern Hemisphere land for 2016−2035 (left), 2046−2065 (middle), and 2080−2099 (right). Panels d–f show changes relative to the 1986−2005 reference period.



~~Figure. 5. Projected changes in monthly average SWE over NH landmasses: panels (a), (c), and (e) show the output of the RP (1986-2005), RCP2.6, RCP4.5, and RCP8.5 simulations; panels (b), (d), and (f) depict changes in SWE, relative to RP, for 2016−2035 (top), 2046−2065 (middle), and 2080−2099 (bottom).~~

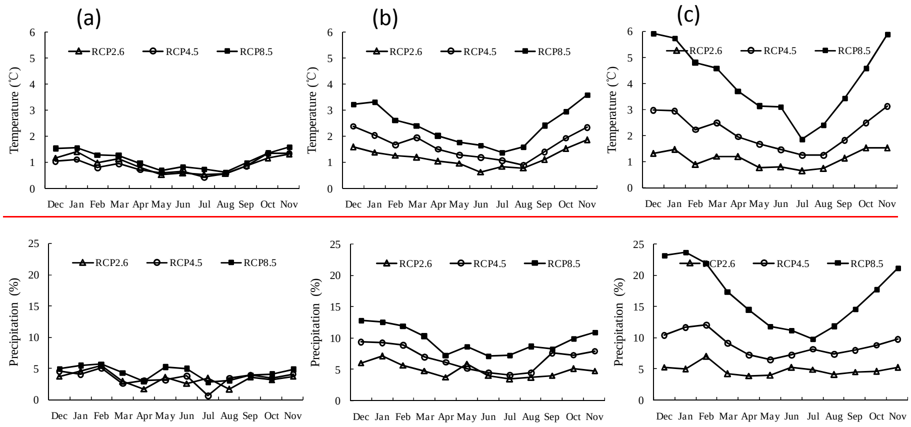
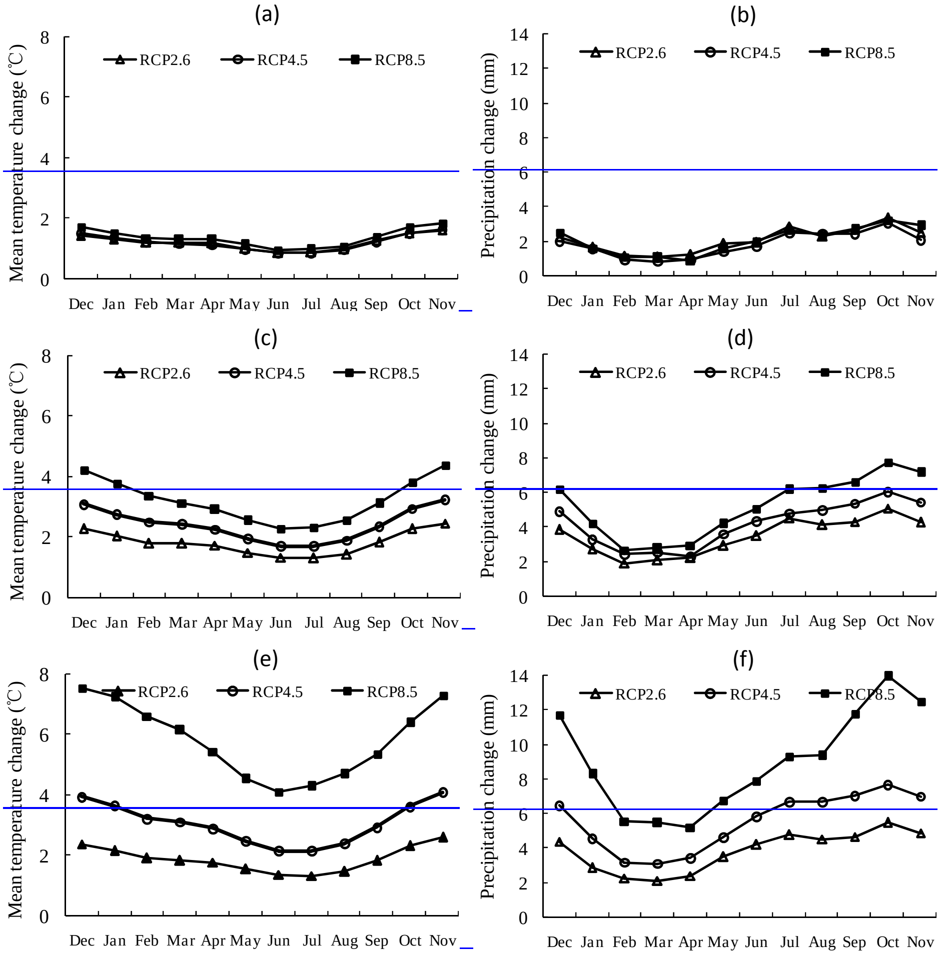
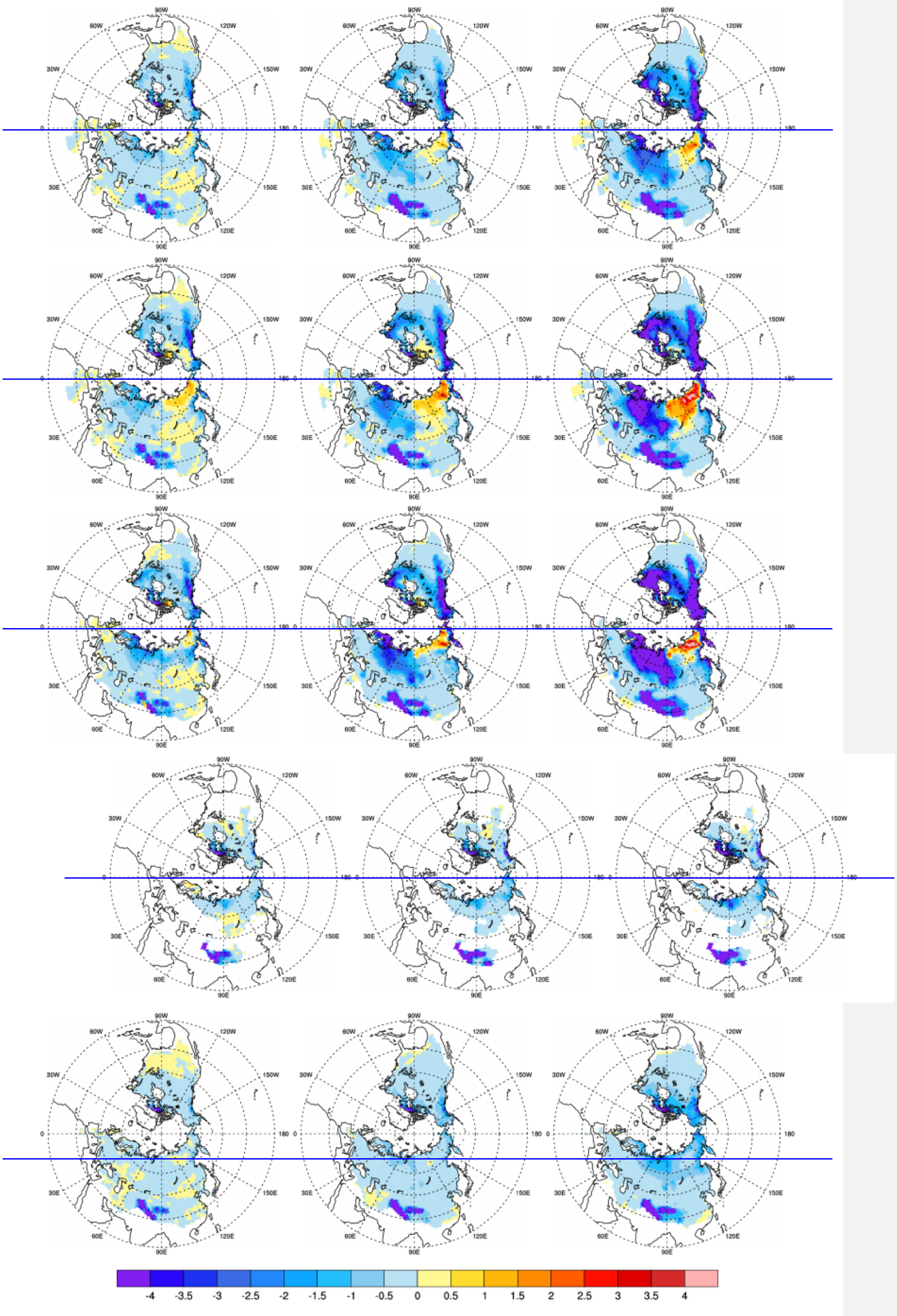


Figure 6. Changes in mean annual air temperature (a–c) and the relative change (RE) in precipitation (d–f) over Northern Hemisphere land for 2016−2035 (left), 2046−2065 (middle), and 2080−2099 (right) for three RCPs, relative to the 1986−2005 reference period.



~~Figure. 6. Changes in mean annual air temperature (left) and precipitation (right) for 2016−2035 (a, b), 2046−2065 (c, d), and 2080−2099 (e, f), relative to the 1986−2005 mean, for three RCPs.~~


-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4

~~Figure. 7. Spatial distributions of projected SWE trends (kg m^{-2}/10a) between 2006 and 2099 for the three RCPs. Shaded areas represent regions where trends reach 95% significance. The five rows indicate the annual mean, winter, spring, summer, and autumn SWE. The three columns are RCP2.6, RCP4.5, and RCP8.5.~~

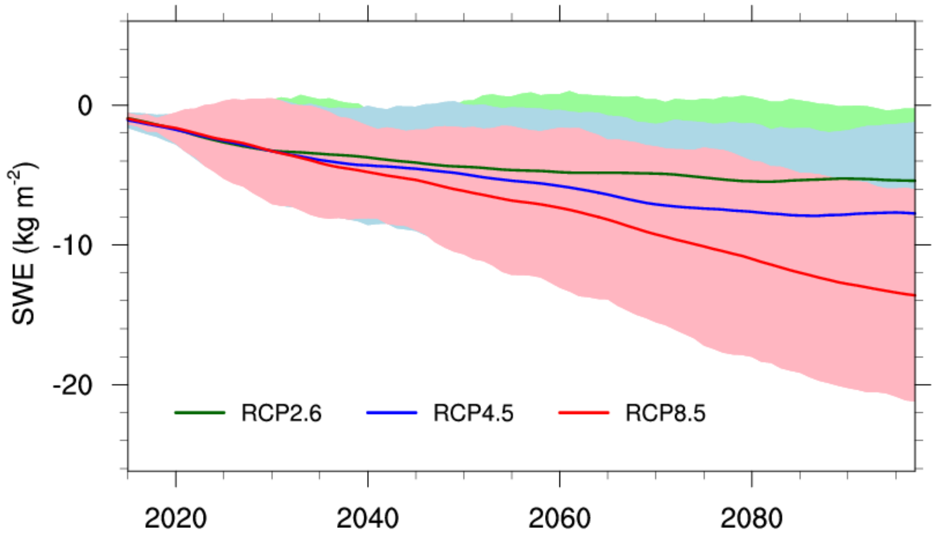


Figure. 7~~8~~. Projected changes in mean annual SWE over NH landmasses during 21st century~~, relative to RP (1986-2005),~~ for all three RCPs (green: RCP2.6; blue: RCP4.5; red: RCP8.5). The mean value for the 1986–2005 reference period is subtracted from all values. Also shown is the multi-model mean for all available models for each scenario. The 10-yr running average ~~is~~was derived for each model before calculation of the multi-model mean. Shaded areas denote the inter-model standard deviation for each ensemble mean.

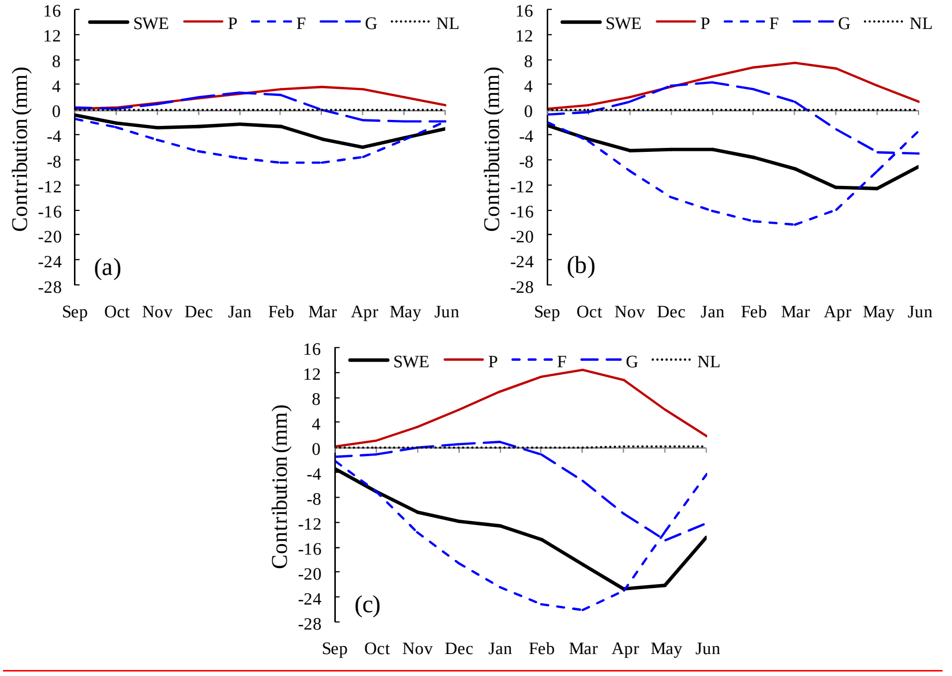
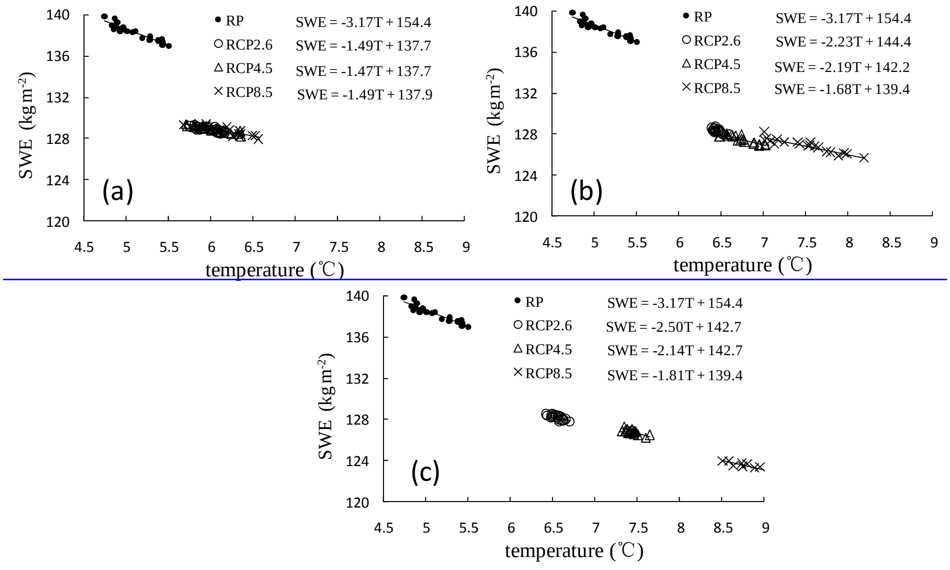


Figure 8. Mean changes in SWE decomposed using Equation (4) to show the contribution of changes in precipitation (ΔP), the fraction of solid precipitation (ΔF), the fraction of accumulated snowfall that remains on the ground (ΔG), and nonlinear terms (*NL*) during the period of 2016-2035 (a), 2046-2065 (b), and 2080-2099 (c) for RCP8.5, relative to the 1986–2005 reference period.



~~Figure. 9. Sensitivity of SWE to mean annual temperature over NH landmasses, derived from three RCPs, for the periods 2016–2035 (a), 2046–2065 (b), and 2080–2099 (c). The term 'RP' indicates the reference period of 1986–2005.~~