# Replies to reviewer 1's comments

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

1. The first major comment that I have brings in to question a number of the results and conclusions in the manuscript. Figure 5 shows observed and modeled mean SWE integrated over NH land areas (excluding Greenland) for the reference period. According to this figure, mean SWE peaks during spring at ~60kg/m2, and reaches minimum values during August and September at ~20kg/m2 (with models showing slightly lower numbers). The timing of the seasonal cycle seems realistic, but the magnitude of annual minimum SWE seems unrealistically high in comparison to the annual maximum. Previous analyses of observations and model results indicate that during the annual minimum the total snow covered area, and the total SWE, integrated over NH land areas is a much smaller fraction of the spring maximum (i.e. Takala et al. 2011, https://www.wmo.int/pages/prog/www/OSY/Meetings/GCW-IM1/Globsnow_Article.pdf; Frei et al. 2005, J. Hydrometeorology, V6, p. 681-695). It seems unlikely that integrated SWE over NH land areas (excluding Greenland) during August/September is near ~30% of the spring maximum (either in observations or models). The authors should explain clearly exactly what they are calculating and why it is realistic.

**Answer:** Thank you for your comments and suggestion. The mean SWE is calculated at all the grids over the NH. Your concerned questions are caused by different units. We also note the work of Takala et al (2011), they used snow depth (from European Centre for Medium-Range Weather Forecasts) and snow density data to calculate SWE, and estimated the mean March SWE over NH is about 2800Gt during

1982-2010, which is equal to 82.3kgm$^{-2}$. Mudryk et al (2015) took GLDAS SWE product and estimated the mean March SWE over NH to be about 2.5×1015kg (74kgm$^{-2}$) during 1981-2010. In our paper, the mean NH March SWE from the multi-model ensemble is 64kgm$^{-2}$ during 1986-2005, which is close to Takala et al (2011) and Mudryk et al (2015) estimation, except different periods and datasets. Takala et al (2011) also estimated that SWE after Jun over NH (excluding mountain regions) is about 7 kgm$^{-2}$ during 1982-2010. The mean August SWE in our paper is 20kgm$^{-2}$, which is greater than that from Takala et al (2011). This is because that Takala et al (2011) excluded mountain regions, and snow mainly exists in mountain region in summer. Hence, our estimation is reasonable.

2. The second major comment is related to the first one. The authors do not provide any literature review of previous studies that evaluated GCM snow simulations. It seems that such a review would be important in a general sense. In a more specific sense, perhaps such a review would allow the authors to explain how their calculations of NH SWE (discussed in comment #1 above) relate to results of other studies.

**Answer:** There are many studies evaluating the model performance for SWE and snow cover, such as references in this paper, Hosaka (2005), Räisänen (2008), Zhu and Dong (2013), Brutel-Vuilmet (2013), Wang et al., (2009), Wang et al., (2010) in the revised manuscript (P4L7-10) . In fact, as you suggested, this is the basis of model output application, validation of model performance for simulating SWE is provided in Sec. 3.

**Minor Comments / Clarifications**

1. Abstract: "…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." This last part

of the abstract needs clarification. First, summer temperatures are too high for significant snow even during the current climate, so their statement may be correct but seems to confuse the issue. The last sentence should be broken into two sentences to clarify.

**Answer:** Thanks for your suggestion. We have rewritten this sentence. (P2L10-12)

2. P. 3 line 25 – statement that snow depth reflects the amount of precipitation, but not temperature, requires explanation because the temperature affects the density, and therefore the depth, of snow.

**Answer:** Snow depth mainly reflects the amount of precipitation (solid) (Räisänen, 2008), temperature may influence snow density, and further affects snow depth.

3. P. 6 lines 8-10 (datasets section). Explain why they use only the first ensemble members of each model experiment, and explain whether the mention of "aerosols" refers to greenhouse gasses only or other aerosol effects.

**Answer:** Because of the numbers of model runs are not the same in CMIP5, even taking the ensemble with any techniques, which can't eliminates the error among models. In general, this manner is used to conduct the multi-models comparison (Zhu and Dong, 2013; Zhou, et al., 2012). We adopt using the first run for each model to make comparison,

The "aerosols" here means all the model design considering "major anthropogenic aerosols observed during 1850–2005 and anticipated for future scenarios", this definition comes from CMIP5, we have added reference in the revised manuscript. (P6L14) Furthermore, more details can be found at http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html

4. P. 7 lines 19-22. Explain the use of Pbar, and the meaning of line 22.

**Answer:** $\overline{P}$ is the average of total precipitation in the two periods: 1986-2005 and the any period (EP, MP, LP) of 21st century. Here, $\overline{P}$ can be regarded as reference (climate) state, the definition of $\overline{F}$ and $\overline{G}$ are similar to $\overline{P}$.

5. P. 8, top paragraph. Provide appropriate reference for the Taylor diagram, and explain how it is used here, and how conclusions are drawn from it.

**Answer:** Taylor diagram (Taylor, 2001) includes two statistical variables, the vertical axis indicates the standard deviation ratio, and the numbers along the arc are the spatial correlation.

Taylor diagram integrates the correlation and deviation among variables, which is prevailing used to compare multi-variables relation analysis. Figure 1 shows the spatial correlation of multi-models ensemble, which is more significant than any other single model with observation, and smaller standard deviation ratio than the other (individual) model. On the whole, multi-models ensemble has better performance for SWE than any single model.

6. p. 10 lines 26-27. Should the sentence state that the changes INCREASE, not decline, with time and increased emissions?

**Answer:** Here the results show the SWE has declined trend for the three emission scenarios and all periods, and the magnitude of reduction gradually increase, we have rewritten this sentence in the revised manuscript to make this point clear. (P11L6-7)

7. p. 11 lines 1-3. Why will decreasing SWE lead to an acceleration of the hydrologic cycle?

**Answer:** The original meaning is that, with temperature rising, precipitation also increases, but SWE declines due to temperature rising, and leads to the evaporation increasing. This sentence seems be redundant, we deleted that to avoid confusion.

8. p. 11 lines 4-12. Please clarify the first sentence. Also, how meaningful are the results for the land area north of 70N, since there is very little land there?

**Answer:** We have rewritten it in the revised manuscript.

The changes of SWE is calculated and compared for each zone (10 latitudes), temperature and precipitation changes are analyzed for regions north of 70°N where is belong to Arctic, we have deleted Arctic to avoid confusion.

9. p. 11 lines 13-27, and table 2. Please provide more clear explanation of these regression results. What are the independent and dependent variables? Are they “change in SWE” and “change in temperature” at all grid points in each zonal band? What are the units of the slope? How many data points are included in each regression?

**Answer:** In Table 2, SWE is dependent, temperature is independent variable. They are averaged at all the grids in each zonal band during the RP, EP, MP and LP. The units of slope is $kgm^{-2}℃^{-1}$ ,we have added units in the revised manuscript. The regression is conducted by two 20 years time series.

10. p. 11 line 30. Please clarify “SWE decreases in response to a specific temperatures range.”

**Answer:** We have rewritten this sentence to make this point clear.” (P15L5-6??)

11. p. 12 lines 4-6 “The present results support these findings, suggesting that the most significant changes in SWE will occur at mid to high latitudes during winter and spring (not shown).” Why not show a figure, and explain, what you claim are the most significant changes? Since you use the same models as AR4, isn’t it obvious that you should get the same results?

**Answer:** This indicates the absolute change in SWE, according to reviewer’s comments, all the figures for absolute change have been replaced by relative change, the relevant explanation has been deleted except necessary. We have added some exactly explanation (This sentence also can be deleted) in this revision.

Here, “most significant changes” means compare with different regions and durations .”most ” was deleted.

Despite of models title used in AR4 and AR5 are same , but the model and scenarios have been changed , for example, the scenarios is A1B, B2 etc in AR4, but in is RCPs in AR5.

12. p. 14 line 2-4. “On a seasonal scale, the extent and magnitude of the SWE increase in winter is larger than in spring, but the range and magnitude of the SWE decrease is significantly smaller than in spring.” Please clarify this statement. Do you mean that during both seasons there are some areas with SWE increasing, and some with SWE decreasing; but that when integrated over the NH the total SWE decreases more in spring than in winter?

**Answer:** Yes, you are right. The changes in SWE over the NH landmass in winter and spring can be compared by figure 7 in the previous manuscript. When integrated over the NH the total SWE decreases more in spring than in winter

13. p. 14 lines 8-10, and figure 7. In figure 7 the ranges of uncertainty for different scenarios are not visible.

**Answer:** Yes，because of changes range(uncertainly) in lower emission(RCP2.6) is smaller than higher emission(RCP8.5), which is shaded by RCP8.5. We replotted this figure.

14. p. 14 line 29 – page 15 line 1. “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.” The authors seem to imply that an increase in total precipitation leads to an increase in SWE, but that is not the case when temperatures are changing. Please clarify.

**Answer:** The increase in precipitation, if acting alone, would lead to an increase in snowfall and consequently to increase amount of snow on ground, and increase SWE. Temperature increasing will cause the reducing of fraction of precipitation that falls as snow and to increase the melting snow. Therefore, whether the SWE will be actually increase or decrease depends on the balance between these competing processes( Ra¨isa¨nen ,2008)

15. p. 16 lines 23-25. This last sentence of the paragraph seems trivial - if there is almost no snow to begin with, a small absolute change results in a large relative change. It seems that many of the results for summer need to be put in context of the fact that there is very little snow to begin with, as well as in context of the values shown in figure 5 (see Major Comment #1 above).

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

16. p. 17 lines 1-4. "… we note that while atmospheric warming occurs primarily during the winter half-year, coincident with the greater increase in precipitation, greater precipitation cannot compensate for increased snowmelt due to rising temperatures." Greater precipitation would not be expected to have a compensatory effect, not only because of increased snow melt, but because there will be more liquid precipitation, except over Siberia.

**Answer:** Thank you for your suggestion. You are right, and we have rewritten this sentence.（P21L21-22？？）

17. p. 17 lines 11-14. "…However, the correlation between mean annual SWE and temperature suggests that a threshold in the relationship between the SWE and temperature would mitigate the persistent decrease in SWE with increasing temperature" This statement requires clarification. Are the authors referring here to the non-linearity associated with the freezing point of water, which should be obvious and should be discussed earlier in the manuscript.

**Answer:** We have rewritten this sentence as " …suggests that the relationship between the SWE and temperature is not linear, it would mitigate the persistent decrease in SWE with increasing temperature, when temperature increases to a certain level."（P22L8-10）

# Replies to Reviewer2's Comments

**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. p12, line 21 : « temperature increases more rapidly in the 50–60°N latitude band than in other areas ». No, temperature increases more rapidly in the high latitudes (60-80°N).

**Answer**: Thank you for your suggestion. We have revised this in the manuscript. (P13L2)

2. p12, lines 24-25 : « a greater increase in precipitation occurs in tropical and high-latitude regions during the EP, MP and LP for all three RCPs». In high-lalitudes region, precipitation (relative and absolute values) increases In low-latitude regions, the relative change of precipitation increases, but the absolute precipitation is very regionally dependant…

**Answer:** Here should be "a greater relative increase in ….", we have corrected this in the revised manuscript.(P13L4-5)

3. p14, line 30: What do you mean by « decreasing SWE will likely lead to acceleration of the hydrologic cycle » ?

**Answer:** The original meaning is that, with temperature rising, precipitation also increases, but SWE declines due to temperature rising, and leads to the evaporation increasing. This sentence seems to be redundant, we deleted that to avoid confusion.

4. p16, line 15 : «the most significant changes in SWE will occur at mid to high latitudes during winter and spring (not shown)» In contradiction with Figure 4 : at mid latitudes, the relative changes in SWE are lower than at low or high latitudes. This

sentence should be clarified and developped, or deleted.

**Answer:** The sentence indicates absolute changes. We deleted it in the revised manuscript.

5. p17, lines 18-28 and Figure 5 : It may be more relevant to plot the difference DSWE=SWE_RP – SWE_RCP (done in the previous version of the manuscript), because it seems that DSWE is greater in spring than in summer, whereas the relative change in SWE is greater in summer (when the snow extend is smaller and the snow pack thinner).

**Answer:** Yes，we agree with your suggestion, but previous reviewer asked to replace the absolute change with relative change, considering the baseline of SWE with latitude; relative change also contains similar DSWE information, hence, we adopted former suggestion, we sincerely hope understanding. We also added some analysis and explanation for absolute change to make our point clear. (P15L20-22)

6. p18, lines 7-9 : I do not understand this statement. The temperature increase is significant for all latitudes, and it is particulary strong at high latitudes (polar amplification).

**Answer: W**e accepted your suggestion and have revised this statement in the manuscript. (P17L2-3)

7. p18, line 18 : What do you mean by « precipitation » ? Solid+liquid precipitation ?

**Answer**: Yes, precipitation includes both the solid and liquid precipitation in this manuscript. This definition gives the paragraph follow eq.(4) in revised paper.

8. p18, lines 18-20 : for RCP2.6 changes in precipitation are quite similar during winter and summer.

**Answer**: In figure 6, due to the uniform scale, the change in precipitation in winter and summer are seemingly similar for RCP2.6. Actually, the magnitude of relative change in precipitation in winter is larger than that in summer for RCP2.6.

9. p19, lines 14-17 : it is very difficult to conclude something for low emission

**Answer**: Thanks for your suggestion. As a whole, decrease trend in SWE appears in different latitude for low emission during EP, and this significant feature gradually disappears from MP to LP, we have rewritten this sentence. (P17L21-22)

10. p19, lines 17-20 : delete this comment if you don't want to show the figure (Figure 7 in the previous version of the manuscript) significant test.

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

11. p22, line 17 : How have been computed this trends ? over 100years ? over the last 10 years of the 21st century ?

**Answer**: This trend is calculated by the regression analysis during 2006-2099.

12. p22, l22 : you could add the reference to (Brutel-Vuilmet et al., 2013)

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

13. p22, lines 25-30 : delete this comment if you don't want to show the figure (Figure 7 in the previous version of the manuscript)

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

14. p23, line 6 : « largest reduction in SWE appears in summer ». Ok for the relative change in SWE. But DSWE is higher in spring.

**Answer**: The largest relative reduction in SWE occurs in summer, and the larger absolute reduction in spring, we have revised in the manuscript.(P18L20-22)

15. p23, line10 : strong negative correlation with temperature, and weak (positive ?) correlation precipitation

**Answer**: The correlations between SWE and precipitation, no matter the positive or negative, none passes significant test. We have made further explanation in the revised paper. (P19L5-6)

16. P25, lines 4-18 and Figure 8 : It seems that the SWE curve follows the solid precipition curve in winter and spring. So, It is maybe more interesting to study the correlation between SWE and solid precipitation ? (Table 4, Figures 4&6). Moreover, the precipitation changes are very regionally dependant, so the region analyse should be more relevant...

**Answer**: Yes, you suggested an interesting topic, which can be our next work. SWE should be closed to solid precipitation, however, solid precipitation data has large uncertainly, firstly, solid precipitation observation is rarely, and snow definition (parameter scheme) in model is also different. Furthermore, this manuscript mainly focuses on SWE characteristics at large scale.

17. Table 3 :Trends are greater for spring, which is consistant with my previous comment. Trends for RCP4.5 are < -1,09 kg m-2/10a for every season, and the mean value is = -1,09 kg m-2/10a. Should be an error, no? For which period are computed the trends ? 2006-2099 ?

**Answer**: Sorry, it is a typo, the mean trend for RCP4.5 is -1.18 $m^{-2}$/10a, we have corrected it in the revised manuscript. The trend is average on analysis period, which is calculated during 2006-2099.

18. Table 4 : The data may be more relevant if computed by seasons (as in Table 3) than by months. What do you mean by Precipitation ? Solid+liquid precipitation ?

**Answer**: Thank you for your suggestion. We calculated the correlation on seasonal scale, but the differences are too large in month to express the regularity, so we still keep original form in the revised manuscript. The precipitation includes the solid and liquid precipitation.

19. Figure. 4 : Could you explain why the temperature curves are different too the temperature curves presented in the previous version of your manuscript?

**Answer**: In the previous manuscript, the temperature is averaged over the NH where SWE >0 and SWE <1000. in the revised manuscript, due to analyzing the contribution of SWE change requiring SWE >10mm on August, we have recalculated the temperature over the NH.

20. Figure. 6 : Could you explain why the temperature curves are differents too the temperature curves presented in the previous version of your manuscript?

**Answer**: The explanation is the same as the above

**Technical Comments**

1. p4, lines 13-14-15 : this sentence is written 2 times.

**Answer**: Thanks. Corrected.

2. p27, line 27 : « uncertainty » should be « uncertainties »

**Answer**: We have corrected it (P18L7).

3. Caption of Figure 2 : « models listed in Figure 1 ». should be « in Table 1»

**Answer**: We have corrected it in the manuscript.(P27L4)

4. Table 2 : « S » and « C » should be « Slop » and « Cor » in the table. Could you indicate the slop unit ?

**Answer**: " S" and " C " are " Slop " and " Cor" in the table, the slop unit has been added in the revised manuscript. (P23L2)

5. Figure. 4 : What do you mean by « Precipitation (%)» ? Solid, Liquid, or Solid+Liquid precipitation ? Relative change or Absolute mean annual precipitation ?

**Answer**: Precipitation (%) indicates the relative change in mean annual precipitation. Precipitation is sum of solid and liquid precipitation in the whole manuscript.

6. Use the same referencing for figures and tables all over the manuscript. Fig.N or Figure N.

**Answer**: we have uniformed in the revised manuscript.