Responses to reviewer's comment

We are grateful to anonymous reviewers for their helpful and constructive suggestions and comments. We have tried our best to address all issues raised by them, which we believe improve the manuscript substantially. The revised contents and detailed responses to the valuable questions are as follows:

Reviewer 1 stated that;

P1L21-23: The abstract contains quite a few abbreviations which make it somewhat difficult to quickly grasp the major points of the manuscript. None of the different freeze-thaw stages are defined nor the abbreviations explained.

The reviewer made a valid point, and we spelled out the words and the corresponding abbreviations of the different freeze-thaw stages. The revised abstract is as follows:
"Freezing and thawing action of the active layer plays a significant role in soil respiration (R_s) in permafrost regions. However, little is known about how the freeze-thaw process regulates the R_s dynamics in different stages for the alpine meadow underlain by permafrost on the Qinghai-Tibet Plateau (QTP). We conducted continuous in-situ measurements of R_s and freeze-thaw process of the active layer at an alpine meadow site in the Beiluhe permafrost region of QTP to determine the regulatory mechanisms of the different freeze-thaw stages of the active layer on the R_s. We found that the freezing and thawing process of active layer modified the R_s dynamics differently in different freeze-thaw stages. The mean R_s ranged from 0.56 to 1.75μmol/m^{2}s across the stages, with the lowest value in the spring warming (SW) stage and highest value in the summer thawing stage (ST); and Q_{10} among the different freeze-thaw stages changed greatly, with maximum (4.9) in the winter cooling stage (WC) and minimum (1.7) in the SW stage. Patterns of R_s among the ST, autumn freezing (AF), WC, and SW stages differed, and the corresponding contribution percentages of cumulative R_s to annual total R_s were 61.54, 8.89, 18.35, and 11.2%, respectively. Soil temperature (T_s) was the most important driver of R_s regardless of soil water status in all stages. Our results suggest that as the climate warming and permafrost degradation continue, great changes in freeze-thaw process patterns may trigger more R_s emissions from this ecosystem because of prolonged ST stage."

P4L143-150: Some more information about chamber volume, chamber closing time, and flux calculations might be beneficial. What was the minimum flux the chamber system was able to detect? Did you have to increase the chamber closing time in winter in order to achieve the needed minimum change in CO_2 concentration for flux calculations? Do you have any concerns about the disturbance caused by collar installation and above-ground plant removal for the determination of soil respiration? What about the roots left in the soil after plant removal? It has been shown that roots respiration as well as the decomposition of dying/dead roots can affect soil respiration for some time after plant removal (e.g. Subke et al., 2006).

To clarify them, we added additional explanations and elaborate the method section. In our

experiment, we used the LI-8100A Automated Soil Gas Flux System to determine the soil respiration (CO_2 flux). The smart chamber is a portable, self-powered 20 cm survey chamber featuring an embedded microprocessor and internal storage for real-time flux calculations when configured with LI-COR gas analyzers. The LI-8100A is a very popular survey measurement device for CO_2, CH_4, N_2O and other trace gases depending on the trace gas analyzer installed. In our experiment, the LI-8100A was only assembled with a CO_2 gas analyzer. The measuring range for CO_2 that the infrared gas analyzer can detect is from 0 to 20000μmol/mol with accuracy 1.5% of reading.

Throughout the measurements, we adopted the recommended settings by the LI-COR to determine the soil respiration flux. A typical measurement protocol was applied: Obs. Length: 2 mins, Dead band: 25 seconds, Pre-purge: 30 seconds, Post-purge: 45 seconds, Chamber Volume: automated, IRGA volume/total volume: automated. Chamber offset of the program was adjusted to 2 cm.

During the experiment, we carefully designed the experiment and gave full consideration to the potential disturbance to soil respiration caused by collar installation and plant removal. In order to minimize the disturbance for the determination of soil respiration, we installed the collars one month before the experiment and left all the collars permanently inserted into the soil. In addition, after the above-plant was clipped and left undisturbed for more than 24 hours before we initiate the measurement for soil respiration. This "resting time" allowed the removal of any excess CO_2 released by roots disturbed during above-plant removed.

Soil respiration includes CO_2 produced from processes such as root expansion, mycorrhizal exploration, and microbial decomposition of litter and soil organic matter (Phillips and Nickerson, 2015). We did consider the paper entitled with "Trends and methodological impacts in soil CO_2 efflux partitioning: A meta-analytical review" by Subke et al. (2006) that was appeared in Global Change Biology. They summarized impacts of different methodologies on soil CO_2 efflux partitioning and found there was no coincident influences of plant removal on soil respiration. However, Guo et al. (2011) found that mowing of meadow would increase soil respiration (appeared in Journal of Acta Agrestia Sinica). Thus, the above-plant removal in our experiment could have increased soil respiration and our results may have overestimated soil respiration due to disturbance of the plots. In order to minimize the disturbance to soil respiration, the living plants inside the collar were carefully removed at the soil surface at least 1 day prior to the measurement.

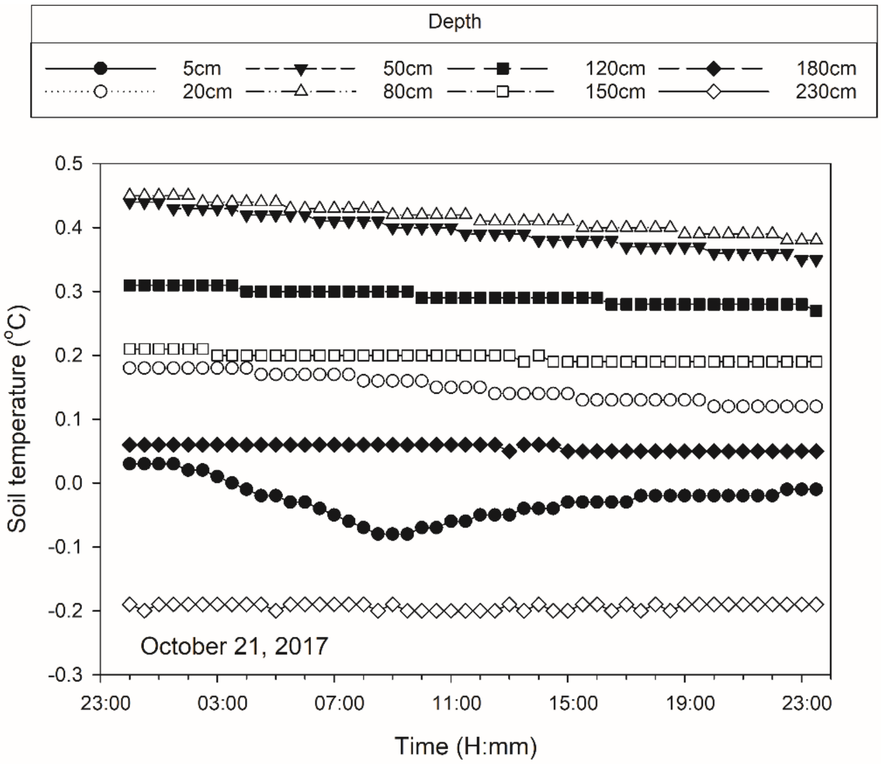
In addition, we supplemented detailed information of the measurement protocol for determining soil respiration using LI-8100A device in the manuscript.

P9: During the ZC sub-stage, several possible scenarios are offered for the sudden increase in Rs. How many in situ measurement points actually fall within this very short period? From Figure 2 it looks like only one, maybe two points. How does this affect uncertainty for the developed Rs model? Did you also measure a diurnal freeze-thaw pattern during this period? How long after thaw during the day did you do the Rs measurement? Could substrate availability and soil aggregation be affected by freeze-thaw cycles and thus affect microbial activity during this stage?

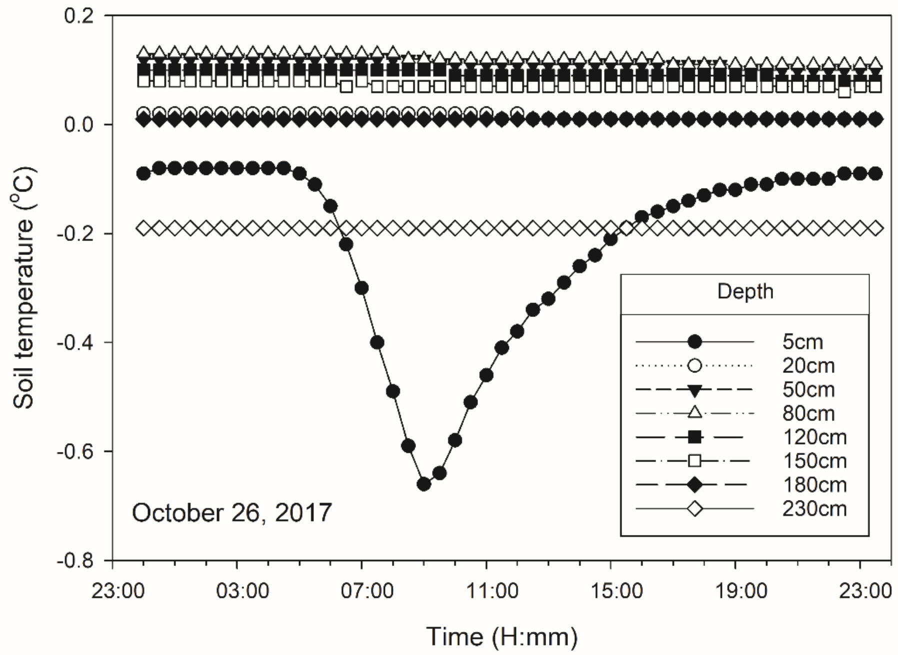
We would like to point out that each open circle in Figure 2 represents the average R_s obtained

from six plots on each sampling day. The daily average R_s flux between the sampling dates was obtained by interpolating the average R_s flux rate. Using the observed data and interpolated data, coupled with soil temperatures at different layers recorded every 30 min by a data logger, we developed the R_s model at different freeze-thaw stages. We ran regression analysis, and found that the value of adjusted R was high enough that the R_s model was accurate and reliable at 95% confidence level.

At our study site, we used a data-logger powered by solar panel to automatically record the soil temperatures at different layers every 30 min. The depths for the soil temperature measurement were 5, 20, 50, 80, 120, 150, 180 and 230 cm. We believe that the diurnal freeze-thaw changes were clearly detected during the ZC sub-stage. For example, October 21, 2017 and October 26, 2017 were the earlier date before the ZC substage began, and October 26, 2017 was the middle date of the ZC substage. The diurnal freeze-thaw patterns of the earlier and middle ZC substage were exhibited as the following figures:



Diurnal freeze-thaw changes of soil temperatures at different depths at the earlier ZC substage



Diurnal freeze-thaw changes of soil temperatures at different depths at the middle ZC substage

These figures show that the surface soil (5 cm) still underwent a diurnal freezing-thawing cycle process at the earlier time before the ZC substage began (October 21); The bottom soil was frozen while the middle layers still remained a thawed state. As the ZC substage process went on and approached the middle of the substage (October 26), while the soil temperatures of shallow and bottom of active layer were negative and the diurnal change soil temperature at 5 cm was discernible, all the other layers' temperatures were positive or near to 0°C. This indicates that active layer was frozen bi-directionally.

As surface soil is frozen throughout the day at the ZC substage, as noted in winter season (Zhang et al., 2015), we measured the R_s between 9:00 and 11:30 a.m. local time.

During the ZC substage, the active layer was frozen bi-directionally and temperatures in the active layer were higher in its middle part and lowering upwards and downwards from there. However, the upper freezing front rapidly moved downward within several days, while the lower one moved upwards slowly. At the same time, moisture in the thawed part in the middle of the active layer was migrating to both of the upper and lower freezing fronts and freezing there. Meanwhile, heat was transferred to both of the freezing fronts similarly during the moisture migration and freezing process. Because the moisture and heat migrated fast especially when the upper freezing front moved downward rapidly and the moisture content at freezing front was relatively high, the soil substrate availability and soil aggregation must be affected by this process, which could influence microbial activities substantially.

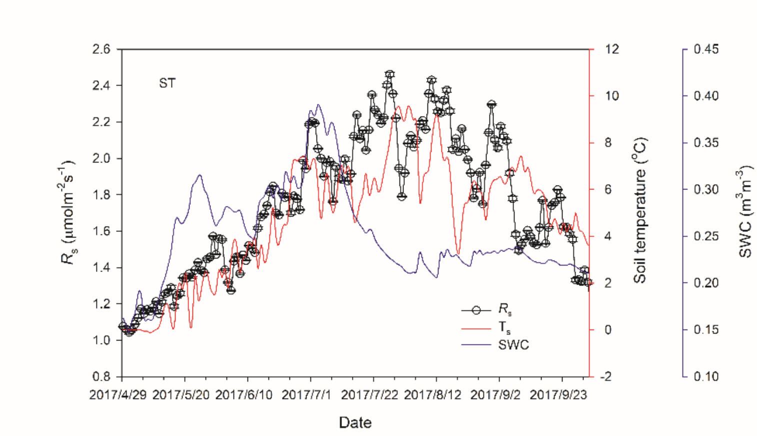
Figure 4: Are these results based on the Rs model? Can you give an uncertainty range? On how may measurement points is the AF stage based? On the y-axis; should it read Rs and μmol? Is SWC the same as volumetric water content, i.e. ratio of water volume to soil volume? What is the dotted line in the AF subplot?

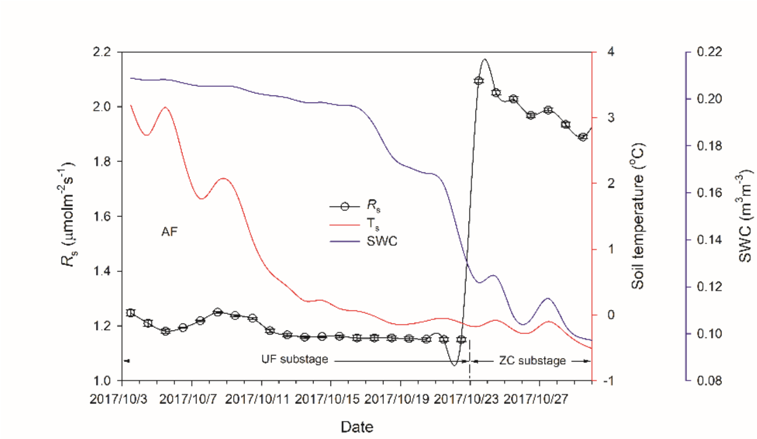
In Figure 4, the R_s fluxes were derived from the fitted R_s equations (Table 2) at the different freeze-thaw stages. In order to better illustrate how the freeze-thaw process regulated the R_s, we plotted the variations of R_s, soil temperature and moisture of the different freeze-thaw stages, respectively. The lines in the Figure 4 were smoothed when plotted.

We reconstructed the Figure 4 and gave an uncertainty range of the R_s each day.

During the AF stage, we measured the R_s fluxes 54 times from the six plots on three sampling days and obtained the other daily R_s by interpolating methods basing on the measuring results.

The reviewer made a valid point, we made a mistake with the title of y-axis. It should read R_s and the unit should be μmolm^{-2}s^{-1}, which are reflected in the revised manuscript. In Figure 4, the SWC represents volumetric water content. For the dotted line in the AF subplot, we originally meant to mark the UF substage and the ZC substage, with UF substage on the left y-axis and ZC substage on the right y-axis. We replotted the figure to correct the misleading marks.





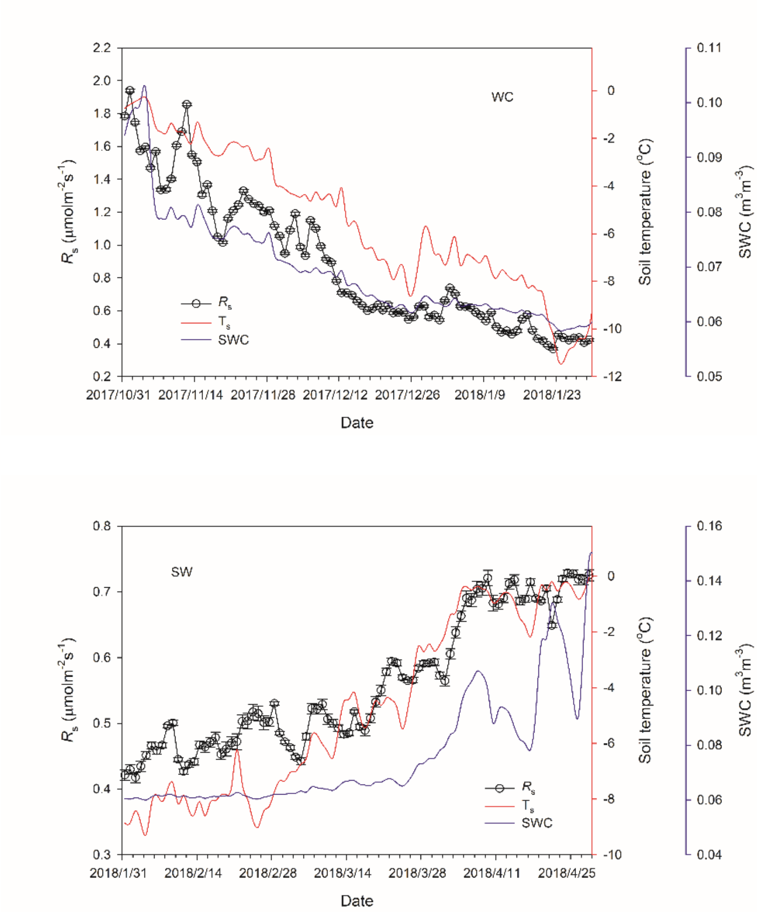


Figure 4. Variations in soil respiration (R_s), soil temperature (T_s) and soil water content (SWC) for the four freeze-thaw stages including summer thawing stage (ST), autumn freezing stage (AF), winter cooling stage (WC), and spring warming stage (SW) (from late April 2017 to late April 2018). The SWC unit stands for water volume per total soil volume. Error bars show standard error (n=6).

Using the different freeze stages and the developed Rs model in combination with the observed changes in active layer dynamics described by Wu et al. (2015) for the site, can you estimate or comment on by how much Rs has changed (or will change) and what period/freeze stage the changes are largest?

According to the results on the changes in active layer thickness and near-surface permafrost in alpine ecosystems on the Qinghai-Xizang (Tibet) Plateau reported by Wu et al. (2015), the onset of spring thawing advanced and the duration of thaw increased, which meant that the durations of spring warming process and summer thawing process would extend, and those of autumn freezing process and winter cooling process would be shortened. Combining with our results, under the current scenario, the summer thawing stage would have the largest change. The variations of the freeze-thaw pattern will accelerate the R_s and the contribution of CO_2 emitted during the summer thawing and spring warming stages to annual R_s will increase further. Certainly, as the spring warming and summer thawing processes extend, the vegetation growing period will also increase and more CO_2 will be fixed by photosynthesis. To better understand the full changes in CO_2 budget in different freeze-thaw stages, further

research is warranted which we will carry out next year.

Other minor comments:

The usage of units differs between the text and figures. The date format between Figure 1, 2, and 4 is inconsistent.

We carefully checked them throughout the manuscript including figures, and corrected them accordingly. The data format was unified into yyyy/m/d.

P1L39: I suggest to start the sentence with "Furthermore, […]"

We agree to the point and revised it accordingly.

P2L47: […] on the northern hemisphere […]

We added the article "the".

P2L47-50: The numbers for the circumpolar SOC stocks mentioned here seem to be the numbers from Tarnocai et al. (2009)? Then they should be referenced. You could also consider updating the numbers published by Hugelius et al. (2014).

The reviewer made a valid point, and we replaced the reference with Tarnocai et al., 2009. We also updated the amount of SOC according to the paper by Hugelius et al. (2014),

P2L50: Do you mean "sensitivity"?

We corrected the mistake.

P2L57: What do you mean with "completed"?

Here we want to express the meaning that the exchange of energy and water in permafrost regions between the earth and the atmosphere is mainly done through the active layer. To clarify this, we revised the sentence in the manuscript as follows "The exchange of energy and water in permafrost regions between the earth and the atmosphere is mainly mediated through the active layer."

P3L91-93: If this is the hypothesis of this manuscript, I suggest using "should" instead of "must"

We agree to the point, and corrected it accordingly.

P3L106: Is all that precipitation falling as rain? Is the study site covered in snow in the winter?

In our study site, the precipitation falls mainly as rain or sleet, sometimes mixed with small hails from May to September; during this period, the hail and sleet will melt quickly due to the near surface temperature rising. In winter, some precipitation falls as snow; due to high wind and low air temperature, the snow on the soil surface is quickly blown away and sublimated. Therefore, our measurement plots are rarely covered by snow in winter.

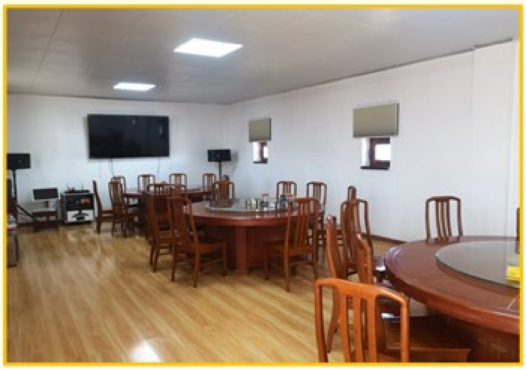
P3L116: How large is the chosen terrain? Does the active layer observation site contain one or multiple locations with soil temperature and moisture probes?

The terrain we chose as our study site is distributed with typical alpine meadow ecosystem and its area is about 13 km^2. Ground penetrating radar (GPR) scan results showed that the geological conditions in this area were relatively uniform, and therefore our intensive measurements of temperatures and moisture at various depths in one active layer can cover fairly large spatial scale. We supplemented the soil type and frozen soil information of the

study site in the manuscript.

P4L147: Did you use an automated system or manual measurement?. Nevertheless, a measuring interval of 3-7 days is still quite impressive, especially during the frozen periods.

We appreciate the comment. During our experiment, we used an LI-8100A automated soil gas flux system (LI-COR Inc., Lincoln, NE, USA) to measure the soil respiration and a standard LI-COR® 20-cm head was applied for the measurements. On the sampling days, the LI-8100A instrument was carried to the study site manually and the plots were sampled one by one. We relied on the Beiluhe Observation Station of Frozen Soil Environment and Engineering to carry out this work. The station is guarded all the year round, where the logistics support such as water, electricity and heating are complete. Here are a few photos of the station.


P4L156-157: Was SWC determined at every measurement day, including when the soil and/or the soil water was frozen? Does the soil moisture probe detect only liquid water? Is SWC based on soil or on pore volume?

The soil temperatures and moisture contents were measured automatically every 30 min each day by a data logger powered by solar panel (CR3000, Campbell Co., USA) even when the soil

was frozen. According to the measurement principle of soil moisture sensor applied in our experiment, the probe only can determine the liquid water content and the SWC unit in m^3/m^3 stands for liquid water volume per total soil volume.

P5L179: Do you present and/or discuss the ANOVA results in the manuscript?

We discussed the ANOVA results in the manuscript but didn't clearly expressed them. We included addition description about the ANOVA test in the manuscript. Something like: P1 L20 ($P < 0.05$), P7 L279 (P=0.0079), P8 L296 ($P < 0.05$), P8 L325 (R^2>0.5), et al.

Section 3.1. A summary table with an explicit definition of the different stages, a description of the characteristic temperature and soil moisture profiles as well as the timing and length of each freezing stage might be beneficial. You could also include the number of measuring points for each period.

The reviewer made a valid point and we included an additional table. We summarized the definition of the different freeze-thaw stages, described the characteristics of soil temperature and moisture as well as the start-end time of the different stages, and listed the number of measurement data according to the ground temperature and moisture monitoring program in a table.

Table B. Characteristics of the different freeze-thaw stages

Stage	Definition	Start and end time	Soil temperature/moisture features	Number of measuring points
ST	Summer thawing stage	Started in late April when the active layer began to thaw downwards from the ground surface; Ended in early October when the thawing process reached its maximum depth.	Soil temperatures in the active layer decrease from ground surface downwards; Moistures migrates downwards accompanied with the downward movement of the thawing front.	eight soil depths with 60288 temperature data; seven soil depths with 52752 moisture data
AF (UF, ZC)	Autumn freezing stage, including unidirectional freezing substage (UF) and zero curtain substage (ZC)	Started when the active layer reached its maximum thawing depth; Ended when the whole active layer became frozen. Among which, UF started when the active layer began to freeze upwards from the permafrost table and ended when the stable	At the UF substage: temperatures of active layer were lower in its bottom and higher in its middle or upper part; moisture in the lower part migrated from the thawed part to the freezing front. At the ZC substage: temperatures in the active layer were higher in its middle part and lowering upwards and downwards from there, and the middle part was in the unfrozen state	eight soil depths with 7680 temperature data and seven soil depths with 6720 moisture data in UF; eight soil depths with 3072 temperature

		frozen ground surface was formed; ZC started when the surface soil was stably frozen and ended when the whole freezing process was done.	with temperatures of 0°C or a little above 0°C; Moisture in the thawed part of active layer migrated to both of the upper and lower freezing fronts and froze there.	data and seven soil depths with 2688 moisture data in ZC
WC	Winter cooling stage	Started when the freezing process finished in late October; Ended in the mid-late January of the next year.	Temperatures of active layer increased with the increasing depth. Moisture migration was not high due to low ground temperatures.	eight soil depths with 35328 temperature data; seven soil depths with 30912 moisture data
SW	Spring warming stage	Started in early February; Ended in late April.	Daily freezing and thawing cycles appeared on ground surface in late April. Ground temperature gradient decreased and the rate of unfrozen water migration decreased gradually. Moisture content near the ground surface showed a decreasing trend.	eight soil depths with 34176 temperature data; seven soil depths with 29904 moisture data

P6L28: What do you mean with "regularly"?

Here we originally intended to express that the variations of R_s flux had the characteristics that it fluctuated at a low level in the spring warming stage (SW), increased and changed dramatically at a high level in the summer thawing stage (ST) and the autumn freezing stage (AF), and decreased sharply with the arrival of the winter cooling stage (WC). In two years the R_s flux had the same pattern of change as the freeze-thaw process of the active layer developed. To avoid misleading, we deleted the word in the manuscript.

Section 3.3: Table 2 was missing from the manuscript. However, a summary table of the Q10, mean (min/max) Rs rates, SR, and contribution to the annual balance would be helpful. Then the numbers do not necessarily have to be mentioned in the text, which could help with readability. Figure 3 could then possibly be presented in Table 2 as well? For Q10, it would also be important to indicate the range of soil temperatures during the different stages, since the effect of low temperature on temperature sensitivity and Q10 is later discussed in the text.

We have to address this, I suppose…..

P7L274: "shown"

We have corrected it.

P7L286-287: Did you test the effect of soil moisture on Rs? In the manuscript you state that Ts is the most important factor.

Yes, we did test the effects of soil moistures of different depths on the R_s. However, the results showed that the relationship between soil temperature and R_s was strongest with the highest values of R^2, especially the soil temperature of 5cm depth, compared to the soil moisture contents.

P8L312: Is the exponential increase in abundance of microbes, which are adapted to freezing conditions, with increasing temperature true for all freezing stages? Would that mean that these microbes also dominate during the summer?

"As we did not analyze microbial community structures in this study we are not sure what kinds of microbes would dominate at different stages. However, recent studies have suggested that microbial community structures and their activities are distinctive in summer and winter (Schostag et al., 2015). As such, we speculate that microbes that are well adapted in cold conditions may not dominate in summer.

P8L320: I would assume that a higher Q10 would then specifically matter in winter if the winter was warming more than the summer?

Yes, a higher Q_{10} would be greater importance in the condition that winter warming is higher than summer warming. As winter warming can activate respiration without affecting primary production, a strong positive feedback to climate change can happen by winter warming. However, R_s in summer warming could be offset by the increase in biomass production, resulting in a stronger C sink by summer warming.

P8L325: What was the limit for soil water content to be "sufficient"?

We think the limit of soil water content to be "sufficient" varied for the soil microbial activities during the different freezing and thawing stages. At a soil water content level that the soil nutrient matrix can dissolve and migrates and at the same time the soil does not appear anaerobic state, the water moisture maybe is "sufficient".

P14L11: "[…] late April 2017 […]"

We corrected the mistake.

Reference list need checking. Some references are not edited correctly (e.g. Grogan, P., and Chapin III, 2000)

We have checked references thoroughly, and corrected subscripts, units, and middle names.

Figure 1: It could be more intuitive to reverse the y-axis to indicate soil depth. In addition, it would be helpful to also indicate the timing of the different stages along the x-axis (similar to Figure 2)

The reviewer made a valid point, and we have replotted Fig.1 and added the different stages along the x-axis and reversed the y-axis.

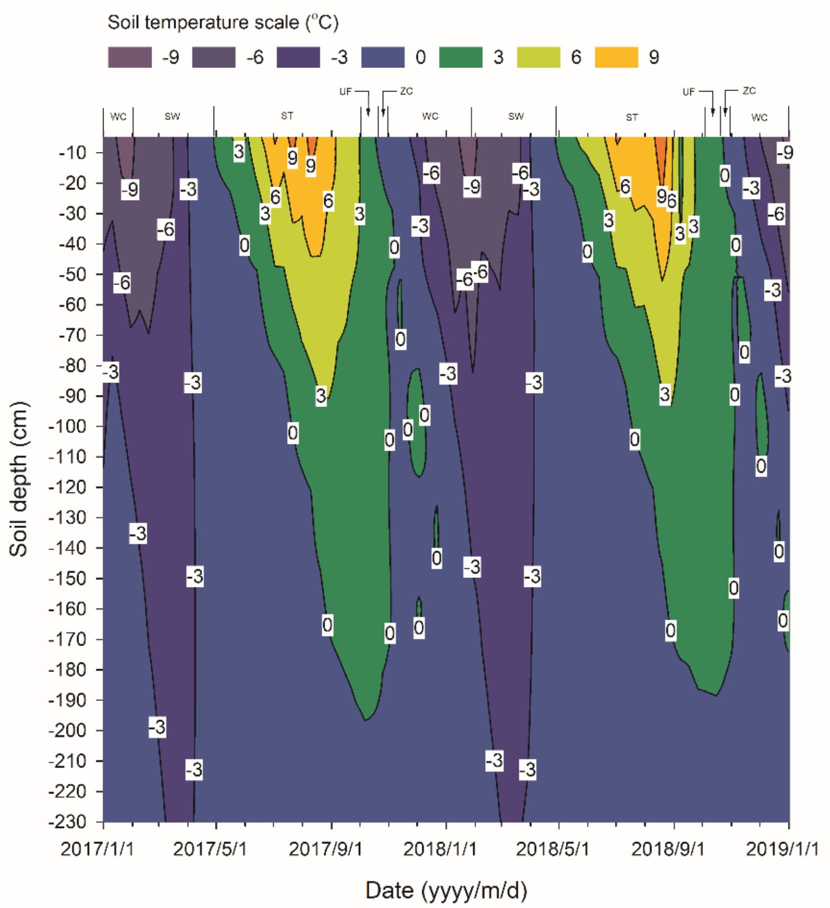


Figure 1. Soil temperature contour outlines of the experimental site in 2017 and 2018