Response Letter

The manuscript has been revised and improved again according to the comments raised by two reviewers and the Editor and highlighted in blue in this version of the manuscript. A list of responses is itemized as follows.

Sincerely,
Guoyu Li, Huijun Jin and Fei Wang

Comment 1

I am satisfied with the revision, which took into account most of my initial comments. The quality of the manuscript is much improved.
Other comments:
Lines 248 to 266 and figure 9: they are about the cooling effect of thermosyphons and thermal disturbance from the warm pipeline. If I am correct, these four boreholes are all affected by both the thermosyphons and pipeline. It would be more convincing if there was an undisturbed borehole as a control to distinguish the effect of the pipeline.

Yes. Four instrumented cross sections were established perpendicular to the CRCOP I at the JB permafrost site, as shown in Figure 3C (Appendix C). Ground temperatures in the boreholes of JB-B-1 (on-ROW, 2 m away from the pipe) and JB-B-II (off-ROW, 16.6 m away from the pipe) are used as the reference values to analyze the thermal disturbance of pipeline and cooling performance of the thermosyphons, which are analyzed and discussed in Section 3.2.1 and Section 3.2.2 in detail.

Figure 6, better to remove the shadows under the labels. In (b), I suggest using x in place of a in the equations. Otherwise, you need to explain what is the variable a.

Thanks. This figure has been revised according to your suggestions.

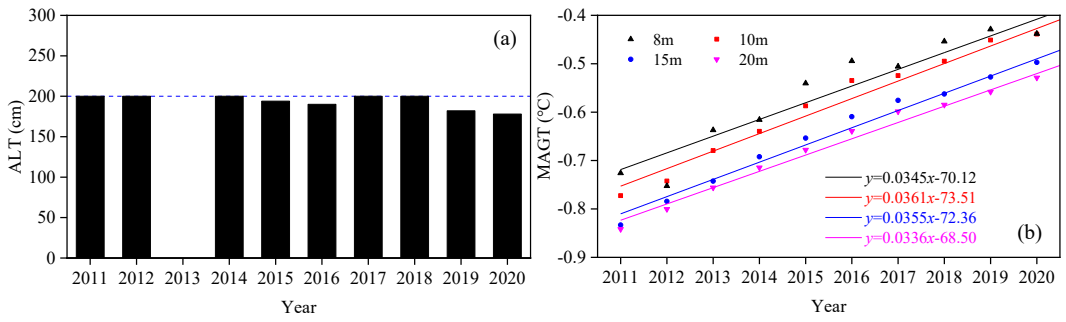

Figure 6. Variations in the active layer thickness (ALT) (a) and mean annual ground temperature (MAGT) (b) in borehole JB-B-II at the JB site along the China-Russia Crude Oil Pipeline (CRCOP) I in northern part of Northeast China from 2011 to 2020.

Figure 8, please explain k in the figure caption.

The ‘k’ in Fig.8 denotes the rates of the permafrost table depth increasing and the

supra-permafrost subaerial talik thickening. The sentence 'Where k denotes the increasing rate, has been added and highlighted in blue in the new manuscript.

Figure 9, the term "Time series of temperature contours" is weird. In many occasions it is called time contour plots or depth-time contour plots.

We are sorry for this vague statement. The caption has been revised as

'*Depth-time contour plots of ground temperature (°C), derived from the boreholes JB-B-2 (a), JB-B-3 (b), JB-B-6 (c), and JB-B-9 (d) at the JB site along the China-Russia Crude Oil Pipeline (CRCOP) I in the northern part of Northeast China. The blank gap indicates the missing data*'

Comment 2

The detailed response to review comments provided by the authors is much appreciated. Most of the comments have been adequately addressed. Additional information and clarifications have been provided that have improved the manuscript. A better description of the instrumentation and its location with relative to the pipeline ROW, has been provided to the reader. Additional minor revisions however are required for the paper to be acceptable for publication. Some of the comments are related to new text or figures included in the revised draft (see below). I have also provided a number of suggestions for editorial revisions that should also improve the paper.
Specific Comments
L49-50 – The development of taliks is part of shrinking permafrost extent. I suggest your rewrite the sentence: "…thickening active layer, development of taliks, shrinking permafrost extent and increases in thaw-related landscape change and hazards such as ground surface subsidence, settlement of foundation soils and thermokarst."

Thanks for your better suggestions. This sentence has been revised as suggested and highlighted in blue in the new manuscript.

L55-56 – This sentence seems out of place as the previous few sentences are commenting on expected change rather than current extent. You could consider moving this sentence to the beginning of the paragraph where you are discussing the distribution of permafrost in the region.

Thanks. This sentence has been moved to L44-45 and also highlighted in blue.

L63 – You should probably say something about when the pipelines were constructed and when operation started.

Thanks. The CRCOP I was constructed during the two cold seasons in 2009–2010 using a conventional burial construction method and became operational in January 2011. The CRCOP II, nearly parallel to CRCOP I, was built in 2017 and began operation in January 2018. The separation distance between the two parallel pipelines is generally limited to approximately 10 m. The two sentences have been added in L65-66 in the new version according to your comments.

'*The CRCOP I was constructed during the two cold seasons in 2009-2010 and began operation in January 2011. In January 2018, CRCOP II was completed and began to operate.*'.

L67 – Any references for Nadym-Pur-Taz pipeline?

The reference has been added.

Seligman B J. Long-term variability of pipeline-permafrost interactions in north-west Siberia. Permafrost and Periglacial Processes, 2000, 11(1): 5-22.

L92 – Is the permafrost thickness >60 m everywhere in the region? You might want to give a range, i.e. from Xm to more than 60 m thick.

Thanks. This sentence was revised as '*The permafrost thickness varies from 0 to more than 60 m, ...*', based on the published papers from Jin et al. (2007) and Wang et al. (2019).

Jin H, Hao J, Chang X, et al. Zonation and assessment of frozen-ground conditions for engineering geology along the China–Russia crude oil pipeline route from Mo'he to Daqing, Northeastern China. Cold Regions Science and Technology, 2010, 64(3): 213-225.
Wang F, Li G, Ma W, et al. Pipeline–permafrost interaction monitoring system along the China–Russia crude oil pipeline. Engineering Geology, 2019, 254: 113-125

L95 – replace "where" with "and"

It was changed.

L106 – Table 1 notes – specify if MAGT measured at DZAA

Thanks. It was revised as '*MAGT, mean annual ground temperature of permafrost at the depth of zero annual amplitude, ...*' according to the comment.

L118 – Table 2 – Accuracy and Resolution (Precision) are not the same thing so there should be two values provided.

Thanks for pointing out this issue. The accuracies for sensors are given in Table 2 and the word 'resolution' in Table 2 has been deleted.

L126-127 – Revision suggested: "….at ambient temperature of 20 °C, but only +/-0.34 °C at…"

It has been revised and highlighted in blue.

L137 – Do you also have to adjust the daytime readings – do the have the same systematic error?

In the processing of total solar radiation data measured by the LI200X pyranometer, the negative values are set to zero and other values keep invariant (refer to the instruction manual, https://www.campbellsci.com/li200x-l).

L151-152 – It isn't clear from Table 3 if JB-B-1 is on or off the ROW because it appears under both categories in the table.
L153-154 – SL-B-1 – located both on and off the ROW? Check borehole numbers.
L155-157 – Similar comment to above. You seem to be indicating that JS-B-1 is located both on and off the ROW.
L162 Table 3 – See previous comments. The same borehole seems to be identified as being both on and of the ROW. Be clear on location of sites in both the text and table.

The boreholes have been named according to where they exist. For example, for JB-B-1 the -B- indicates that is a 'borehole', and the prefix JB is an abbreviation for the site name. To distinguish

whether the borehole is on the pipeline ROW, Arabic numerals are used to name the boreholes on-ROW (e.g., JB-B-1) and the off-ROW boreholes are numbered using Roman numerals (e.g., JB-B-I). Thus, the locations of boreholes can be determined by their name prefixes and suffixes. For example, 'XA-B-I' indicates the borehole is located off the pipeline ROW at the XA site.

L174 – Delete "Besides"

It was deleted.

L184-185 – Delete "dynamic". Also revise to "..but the amplitude decreased with depth, with the magnitude of the decrease varying between sites."

Thanks. This sentence has been revised as you suggested.

L186-188 – You are confusing amplitude and range. The values given are the range in temperature. Note amplitude is measured from the mean value. Revise text to: "..maximum annual range of GT…….XT had the maximum range in GT…."

We are sorry for this serious mistake. Thanks for your comments. It was revised and highlighted in blue.

L189 – What is meant by "at a particular depth" – upper few metres?

It was an unhappy choice of words and revised as '*at a certain depth*'.

L192 – Figure 3 – Which JB site is being shown, JB-B-1 or JB-B-11? In my comments on the earlier draft, I had asked whether the variation in the deeper temperatures might be due to an issue with a sensor. For JB there appear to be spikes (sharp increases) in the temperature record. We see these periodically in our data and it is likely due to some electrical glitch with sensor and logger. This fluctuation of up to 0.5°C at depths of 10-20 m does not seem to show up in the profiles shown in Figure 5. For JS, the "noise" for the deeper sensors seems to be greater than that for the shallower sensors. The record also doesn't appear to be continuous and perhaps the authors have removed data points they determined were erroneous. If the temperatures measured by the deeper sensors are correct then it would seem that the temperature does not stay below 0°C throughout the year at any depth so perhaps no permafrost present?

Up to 38% of the temperature data in borehole JB-B-II were missing in 2019 (between late March and early August) due to the detachment of the thermistor cable from the CR3000 data logger. Therefore, the GTs measured in borehole JB-B-I are graphed in Fig.3, considering continuity and long time series of data. The sharp increase in the deeper temperatures might be due to some electrical glitch with the sensor and logger, as you stated. For assessment of the inter-annual trend of permafrost off the ROW, a decade record of GTs in borehole JB-B-II was used. Fig.5 shows the monthly average GTs in 2018 in this borehole. Therefore, abnormal fluctuation in temperatures at depths of 10-20 m does not show up in the temperature profiles.

At the JS site, the off-ROW borehole JS-B-I and two on-ROW boreholes of JS-B-1 and JS-B-2 are all connected to a data logger. For these two boreholes on-ROW, high-quality temperature data series were collected. Thus, the sharp increase in the deeper temperatures for the JS-B-I borehole in the summers of 2019 and 2020 was not caused by the data logger. The phenomenon of temperature increase at depths of 10-20 m was observed for two consecutive years (Fig.R1),

which would seem to indicate that the failure of the thermistors is impossible. As Fig. R2 show, Large surface runoff occurs in low-lying areas at this site in mid-June, resulting in occasional floods and waterlogging. Meanwhile, the strata of this site (obtained from the JS-B-I borehole) are composed of peaty soil (0-0.8 m), grey silty clay (0.8-2.0 m), yellowish-brown gravel (2.0-5.5 m), and strong weathered granite (5.5-20.0 m). The presence of the rock layers with high permeability provides a channel for the movement of supra- and/or intra-permafrost groundwater. For the above-mentioned reasons, we conclude the positive temperatures that occurred from late June to September are probably due to the thermal disturbance of supra- and/or intra-permafrost groundwater.

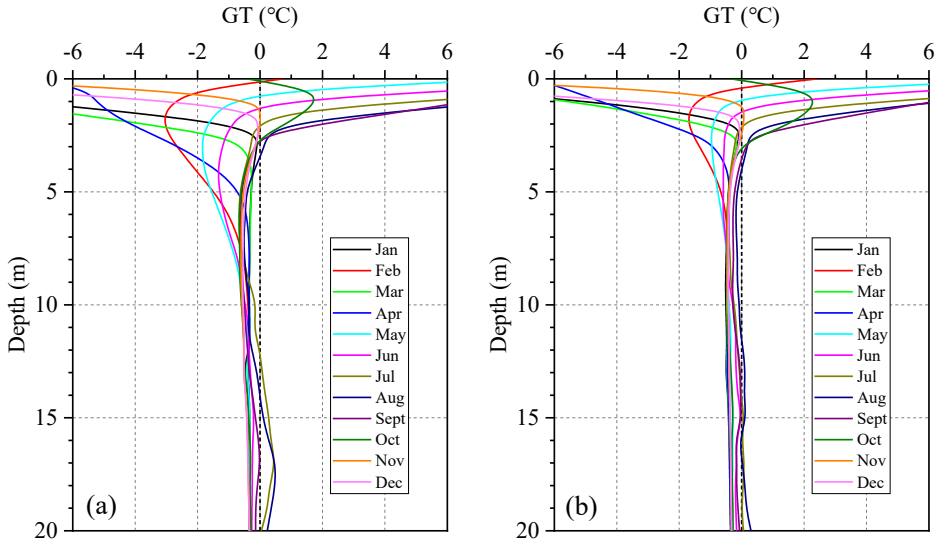

Figure R1. Monthly average ground temperatures at depths of 0-20 m recorded in the JS-B-I borehole at the JS site in 2019 (a) and 2020 (b).

Figure R2. Waterlogging on the ground surface at the JS site on June 17, 2021.

L195 – Revise to "Seasonal variations in GTs…."
L199-200 – Revision suggested: "…decreased northward. However there is substantial scatter in the relationship between GT and latitude (Fig. 4)."

They were revised based on the above suggestions.

L202 – Fig. 4 – Why is JS not included?

Thanks. As shown in Fig.R1 and R2, positive temperatures (at depths of 12 -20 m) were observed in the summers of 2019 and 2020, therefore, the data for the JS site was not graphed in Fig.4.

L204 – Delete "under a warming climate" (this refers more to attribution of the trend rather than

determining the direction and magnitude of the trend)

Thanks for your precious comments. It was deleted.

L205-206 – Do you mean the profile is isothermal? This has been shown for warm permafrost in other regions – see for example Smith et al (2010, DOI: 10.1002/ppp.690); Romanovsky et al. (2010, DOI: 10.1002/ppp.683)

Thanks for pointing out this issue. Figure3 shows that large annual variation in temperatures near the surface decreases to little amplitudes at the depth of 1 m of the ground. At depths from 1 to 2 m, the monthly average GTs in 2018 was fluctuating in proximity to 0 °C, which allow permafrost to persist for decades due to latent heat effects. These two references have been added in the revised manuscript.

L209 – This also depends on the thermal properties of the material.

According to the comment, this sentence has been revised as '*…layer and thermal properties of soil deposits.*'.

L223 – Revision suggested: "….buried at a depth of 1.6 – 2.4 m…."
L225 – Delete "ambient"
L228 – Delete "Besides"

They have been revised in the new manuscript.

L232-233 – The information on construction and start of operation of pipeline should have been mentioned earlier in the paper. Revision suggested: "…since initiation of CRCOP 1 operation in 2011,…."

According to the above comments, the related information has been added in L65-66 in the new manuscript. The sentence was also revised as you suggested and highlighted in blue.

L238-240 – If the ground is ice-rich there would also be significant settlement of the ground surface accompanying the increase in thaw depth as has been shown for other pipelines.

Agree. Significant ground surface subsidence within the trench of the pipeline occurred along the CRCOPs, particularly in warm and ice-rich permafrost zones. Up to 1 m of surface subsidence within the trench area had been measured just ten months after the initiation of CRCOP 1 operation (i.e., in October 2011) during the field surveys. So the sentence has been revised as '*…led to significant subsidence of the ground surface within the trench area and…*'.

L253-255 – In response to review comment regarding use of "artificial permafrost table", the authors indicated that this was revised to just refer to "permafrost table". However the term is still used here.

The term of "artificial permafrost table", less frequently used, is used to define the changing permafrost table under the influence of engineering activities (e.g., Wu et al., 2016). We are very sorry that this term had not been revised in this paragraph. In this revision, this term has been revised and its abbreviation in Appendix A is deleted.

Wu Q, Zhang Z, Gao S, et al. Thermal impacts of engineering activities and vegetation layer on

permafrost in different alpine ecosystems of the Qinghai–Tibet Plateau, China[J]. The Cryosphere, 2016, 10(4): 1695-1706.

L255 – Revision required: "Overall the depth of…." (need to be clear it is the depth of the permafrost table that is increasing).
L258 – Delete "Besides"

They have been revised.

L259-260 – The lateral extent of the thermal disturbance isn't clearly shown by these types of figures. A figure showing the temperature distribution across the ROW would be more effective, i.e. something comparable to the ERT figure.

As shown in Figure C3 (Appendix C), the boreholes of JB-B-3, JB-B-6, and JB-B-9 are located along the same cross-section of the pipeline, which are 2, 3, and 4 m away from the pipeline centerline, respectively. The increasing rate of the permafrost table depth in the JB-B-9 borehole is still greater than that of off-ROW borehole of JB-B-II over the observational period, suggesting the thermal disturbed range of the warm pipeline is greater than 4.0 m.

L263-264 – What is meant by unexpectedly warmer oil temperature? Was the temperature higher than the original design values?

Yes. The oil temperature at the first pump station of CRCOP during the preliminary design stage varied from −6 to 10 °C, and later it was changed to −3.65 to 6.41 °C. However, the oil temperature is all above 0 °C year-round, ranging from 0.4 to 28 °C. Besides, it shows a slow increase trend with operational time increases.

L263-266 – Sentence isn't clear. Are you referring to surface settlement and the resulting ponding of water that occurs with thawing of ice-rich permafrost? Given the high temperature of the pipe, how important is the effect of climate change over this relatively short time period? Isn't the low performance of the thermosyphons mostly due the significant heat source (the pipe) that is present throughout the year?

Thanks. The heat dissipated from the pipeline led to rapid permafrost thawing and thaw bulb development around the pipe. Following the permafrost thawing and the thaw bulb expanding, ground settlement within the trench of the pipeline developed gradually due to the thaw consolidation of permafrost layers. Then, rainfall, surface water, and groundwater accumulated within the sinking trench of the pipeline in summer times, which would infiltrate to the permafrost table along the longitudinal cracks developed at the two shoulders of the trench and accelerated thawing. This phenomenon is very common and serious in the permafrost wetlands along the CRCOPs route. The warm oil temperature and thermal erosion of surface water ponding on-ROW are the two main causes of permafrost thaw around the CRCOPs, and are also responsible for the unsatisfactory cooling effect of thermosyphons on the pipeline foundation soils. Based on the above-mentioned comments, the sentence has been revised as "*The unexpectedly warmer oil temperature, thermal erosion of surface water ponding on the ROW, and lowering thermosyphon performance are responsible for the unsatisfactory cooling effect of thermosyphons on the pipeline foundation soils.*".

L273 – "soil layers" could be deleted.

Deleted as suggested.

L273-274 – VWC could be given as a %

It was changed and Figure 10 has been revised.

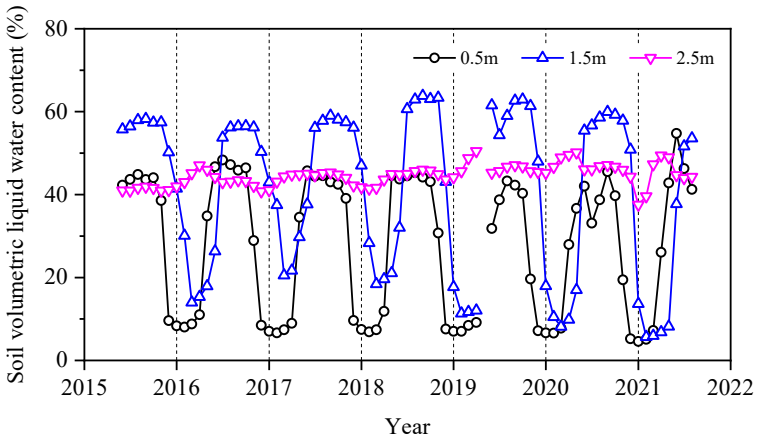

Figure 10. Temporal history of soil volumetric liquid water content at depths of 0.5, 1.5, and 2.5 m at the JB site along the China-Russia Crude Oil Pipeline (CRCOP) I in the northern part of Northeast China during 2015-2021.

L274 – revision suggested: "…is less variable with an ….."
L284-286 – revision suggested: " ERT can be utilized to delineate frozen and unfrozen ground along the….."

Thanks, they were revised according to the above comments.

L286 – If surveys were done in April then maximum thaw would not have occurred yet.

Yes. This fieldwork was conducted when the snow on the ground surface was completely melted because the freezing depth of strata often reached its maximum in March-April in Northeast China.

L289 – insert "steel" between "stainless" and "electrodes"

Added as you suggested.

L291-292 – Repetition of information in previous paragraph – you could modify the text in the previous paragraph to mention inverted ERT results and reduce repetition.

Thanks for pointing out this issue. This sentence has been deleted and the associated sentence in the previous paragraph has been revised as '*The ER distribution within the subsurface can be visualized by ERT. The inverted ERT results provide a continuous transect of the characteristics of the active layer and near-surface permafrost to delineate the shape and size of talik (unfrozen ground in permafrost regions) or permafrost islands along the CRCOPs route (Zhang, 2011).*'.

L293-295 – Figure 12 appears to indicate that values >300 m aren't necessarily associated with frozen ground. Was the resistivity and ground temperature measured at the same time? The ERT surveys were done in April but the temperature profile in figure 11 would appear to be from later in the thaw season. Material type is also important. For example, Lewkowicz et al. (2011, DOI:

10.1002/ppp.703) noted that for some of their surveys in the Yukon, moderate resistivity values were associated with bedrock or gravel rather than being an indicator of frozen ground. It isn't clear if you have utilized information on lithology in the interpretation of ground thermal conditions in figure 11. Holloway and Lewkowicz (2019, Cold Regions Engineering 2019 & 8th Can. Permafrost conf. https://doi.org/10.1061/9780784482599) also observed high values of resistivity for unfrozen silt and peat. Some additional explanation regarding the basis for use of 300 m is probably required here.

Thanks for pointing out this issue. The ERs of some rock and soil deposits have a clear range at room temperatures, such as clay (0.1–10 Ωm), mudstone (10–100 Ωm), and basalt (100–10^5 Ωm). Moisture content, salt content, pore structure, soil texture, temperature, whether the pore water is frozen, and other factors all influence a geotechnical material's resistivity (Kneisel, 2006; Hauck, 2013; Lewkowicz et al., 2011). The significant difference in ER value of soils in the frozen and thawed states (e.g., ER value of ice-rich permafrost is typically 10-100 times higher than that of unfrozen soils) makes the ERT be used in permafrost surveys widely. For interpreting the ERT results and improving interpretation accuracy, borehole drilling and ground temperature data are commonly used. For example, based on the relationship among ER of soils, stratum lithology, and ground temperature in boreholes, an ER value of 500 Ωm was used as the critical value to interpret permafrost islands above the thawed zone (Li et al., 2021). In our study, according to the ERT detection in Northeast China made by previous scholars (Hu and Shan, 2016; Li et al., 2021) and profile characteristics in boreholes, an ER value of 300 Ωm was chosen as the critical value to identify the boundary between frozen and unfrozen zones. The sentence has been revised as '*Here, an ER value of 300 Ωm was used as the critical value to identify the boundary between frozen and unfrozen zones combined with the profile characteristics of resistivity, GT, water/ice content, lithology (obtained from borehole drilling, Fig.12), and other ERT surveys in Northeast China made by previous scholars (Hu and Shan, 2016; Li et al., 2021).*' and the related references have been added.

Hauck C. New concepts in geophysical surveying and data interpretation for permafrost terrain. Permafrost and Periglacial Processes, 2013, 24(2): 131-137.
Hu Z, Shan W. Landslide investigations in the northwest section of the lesser Khingan range in China using combined HDR and GPR methods. Bulletin of Engineering Geology and the Environment, 2016, 75(2): 591-603.
Kneisel C. Assessment of subsurface lithology in mountain environments using 2D resistivity imaging. Geomorphology, 2006, 80(1-2): 32-44.
Lewkowicz A G, Etzelmüller B, Smith S L. Characteristics of discontinuous permafrost based on ground temperature measurements and electrical resistivity tomography, southern Yukon, Canada. Permafrost and Periglacial Processes, 2011, 22(4): 320-342.
Li X, Jin X, Wang X, et al. Investigation of permafrost engineering geological environment with electrical resistivity tomography: A case study along the China-Russia crude oil pipelines. Engineering Geology, 2021, 291: 106237.

L297 – permafrost thaw around the pipe?

Yes, the buried pipeline running at a positive temperature (up to 28°C), acting as a heat source, led to the permafrost around it thawing.

L299-230 – The profile seems to indicate that near the surface, frozen conditions exist and therefore difficult to see effect of ROW clearing. Given that the profile was done early in the thaw season it will be difficult to determine the overall effect on depth of thaw. The paper really doesn't mention much about surface disturbance during construction. The thermal effect of the pipe would appear to be the main influence on the ground thermal regime.

Thanks. This sentence has been deleted according to the comment.

L305- Fig. 12 – See previous comments on relationship between resistivity and temperature. What site are the data in the figure from? Are there borehole logs similar to this for all boreholes drilled? It would be useful to include the lithology and other information on material characteristics in the database.

The profile of soil resistivity, ground temperature, and lithology in borehole JB-B-1 are plotted in Fig.12 for interpreting ERT inversion results in Fig.11. The stratigraphy information obtained from borehole drilling at these monitoring sites was introduced in a paper published in the journal Engineering Geology in detail (Wang et al., 2019). According to the comment, the lithology of strata was added to ER dataset.

L314 – Typo – "60.6 m deep"

Revised as you suggested.

L314-315 – According to Table 3, volumetric water contents only appears to be available for 3 boreholes at the JB site rather than for all sites as the sentence implies. Meteorological data are also only collected at the JB site. You should rewrite the sentence to indicate that only the ground temperatures and ERT span the range in latitudes given. You should also specify that ground temperature and moisture content data were collected beneath the ROW and in undisturbed terrain off the ROW.

L318-319 – Revision suggested: "Analysis of data compiled indicates permafrost conditions along the eastern flank… Mountains are controlled…"

This sentence has been revised as you suggested.

L322-324 – Are you referring to the undisturbed sites here or those on the ROW? You need to be clear.

Thanks for pointing out this issue. Sorry for the unclear statement. This sentence has been revised as '*…GT measurements off the ROW indicates…*'.

L326 – revision suggested: "…leading to talik formation to a maximum depth…"

Revised as you suggested.

L327 – Poor sentence – revision required.

The sentence has been changed to '*This permafrost disturbance is still expanding and can persist for decades.*'.

L328 – Revision suggested: "…..permafrost beneath the pipeline ROW cannot be prevented but

can be significantly reduced by installing insulation or thermosyphons.”

Revised as you suggested.