Response to Referee #2

Thank you very much for your comments concerning our manuscript entitled "A New Map of The Permafrost Distribution on The Tibetan Plateau" (MS No.: tc-2016-187). Those comments are valuable and helpful for improving our manuscript. We followed all comments and made revision and answers carefully. The changes are marked in red in the revised manuscript. The page, line, and figure numbers refer to our revised manuscript. And, a point-by-point reply to the comments are as following:

1. MODIS LST. The authors use MODIS LSTs as the key input for their model of permafrost distribution. However, MODIS LSTs measure a combination of different surfaces including the snow surface. If, as the authors postulate, there is only minimal snow cover across the region and correspondingly that MODIS LSTs can be used in the winter then this is all fine. However, the authors have not shown conclusively that snow cover impacts on LST retrievals can be ignored for their region. Addressing this point is a necessity for this manuscript to be considered suitable for publication in The Cryosphere. Likewise, there is certainly some effect of canopy cover in the summer which has been ignored by the authors. It would be useful if the authors examined the ecotype related impacts on the LST and correspondingly how this may affect the distribution of permafrost in the region. I also suggest that the authors produce an additional figure which shows a 1st panel with the estimated regional snow depth across the area (either from reanalysis or other datasets) and a 2nd panel that shows the spatial distribution of vegetation classes (broadly) across the region so that as reviewers we can determine the degree to which this issue may be problematic. Another issue with the MODIS LST that I find concerning is that the authors make the claim that MODIS is preferable to interpolation for temperature (it seems to be in the context of air temperature). A number of studies have found issues with MODIS-derived (or aided) air temperature products with only minimal improvements being observed (if at all) in terms of cross-validation.

   Although I do think that MODIS products have utility for permafrost purposes, more work must be done to demonstrate that these products offer improvement over high resolution interpolation of station-based temperature products. It is important that the permafrost community ensures that the usage of LSTs from MODIS for driving permafrost models is assessed at each usage given the spatial heterogeneity of the factors influencing MODIS LSTs.

Response:

It is a very good question that also raised by another reviewer. The snow and vegetation might play significant influences on the relationship between the remote sensing LST and the ground surface temperature (GST), the influences is depending on the snow depth and duration (Zhang, 2005), vegetation height and coverage. On the Tibetan Plateau (TP), the most wide-spread snow cover were found in the southeastern region and some alpine regions with the elevation higher than 6000 m (Qin et al., 2006; Pu et

al., 2007). In the vast interior and northern TP, where the permafrost most developed and is our major study area in this manuscript, the snow cover is rare, shallow (< 3 cm) and existed in a short duration, mostly existed in several hours for one single snow event, due to very strong solar radiation and wind (Che et al., 2008; Huang et al., 2017). In this case, the thin snow cover with short duration mainly has a cooling effect on LST due to the high surface albedo of fresh snow and a rapid process of snowmelt. The duration of the cooling effect may be very short, thus it may have very little effect on the LST in average for certain period of time (Zhang, 2005). Generally, the soil surface beneath the vegetation layer have a higher temperature than the canopy surface, depending on the height and coverage. The alpine ecosystem in permafrost regions and its vicinity are all composed of grassland, characterized by dwarf and sparse plants. The vegetation coverage in most of the permafrost region was less than 30% (Lehnert et al., 2015), and even less than 10% in the middle and western TP. Therefore, there are only slight differences between MODIS LST and GST, and even smaller in the thawing and freezing indices in our study area. In the revised version, we added two figures of the snow depth (Fig.7, edited after Che et al.(2008)) and vegetation types (Fig.8, edited after Wang et al.(2016)) to show the possible regions influenced by the snow cover and vegetation. The two figures were as follow and could be found in the revised manuscript (P.30-31).

In the revised version, we explained this in the *Section 4* (P.13 L.381-397).

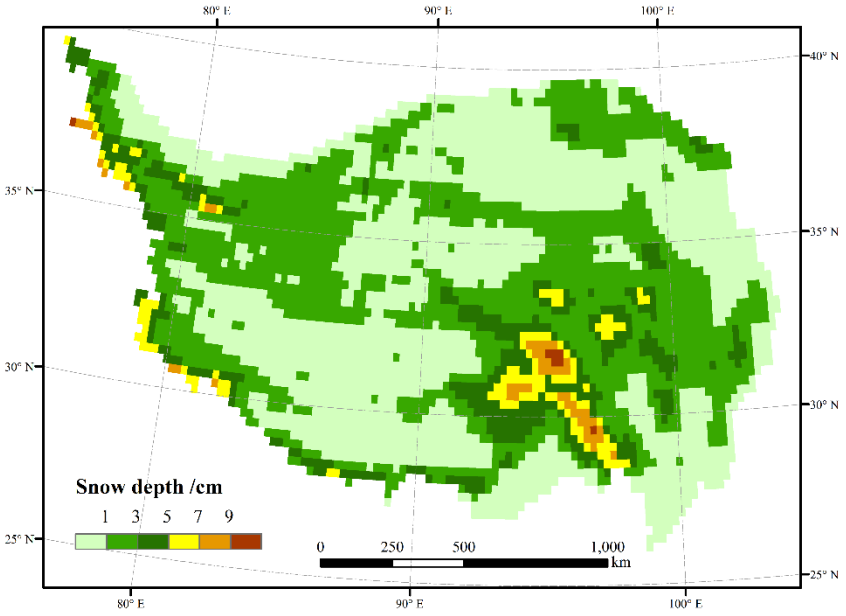

Figure 7. Annual average snow-depth distributions on the Tibetan Plateau from 1979 to 2014 (edited after Che et al.(2008))

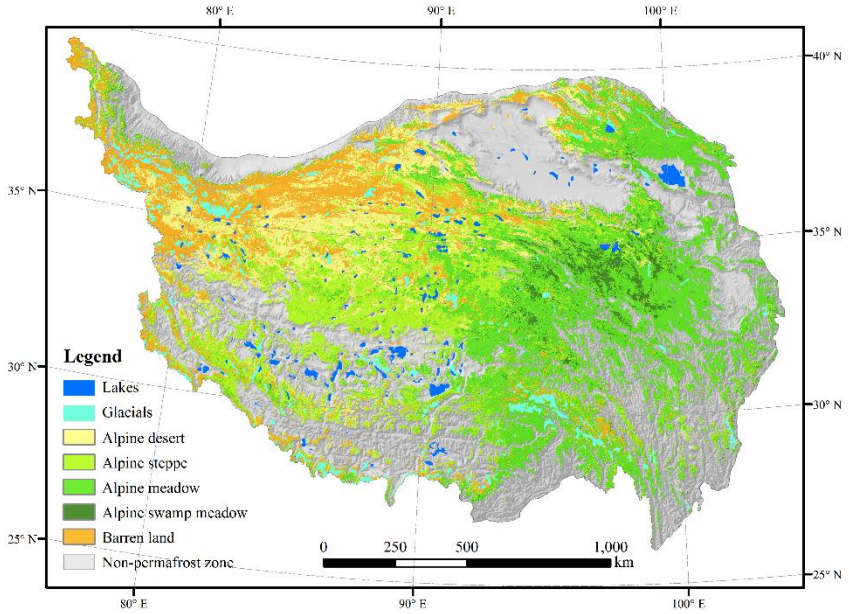

Figure 8. Vegetation types of the permafrost zone on the Tibetan Plateau (edited after Wang et al.(2016))

We are sorry about the inappropriate wording of "preferable". Actually, what we want to say is the remote sensing products are available data source besides the temperature interpolation and reanalysis datasets, especially for the remote areas with limited observations such as the Tibetan Plateau. As we discussed in the paper, the meteorological sites on the Tibetan Plateau are scarce and unevenly distributed (more in the Eastern TP and less in the Western TP; more in lower elevation and less in higher elevation), which lead to the high uncertainty of temperature interpolation in this region (Lin et al., 2002; Li et al., 2003). There is almost none meteorological sites in the permafrost region of the western TP, where permafrost most developed region, and this is why we trying MODIS LST products. In this study, all four observations of Terra and Aqua MODIS LST were employed to establish the multiple linear regression models of the daily mean GST estimation. The models validation in three permafrost sites showed that the determination (R^2), mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE) of 0.91 to 0.93, -0.21 to 1 ℃, 2.28 to 2.42 ℃, and 2.96 to 3.05 ℃, respectively (Zou et al., 2014). The uncertainties were mainly due to the several factors, including temperature differences caused by the time offset between half-hour interval of ground-based observation and satellite overpass time, and the mismatch of spatial scales between point and pixel observation. Although three sites, located at the continuous permafrost and underlie different vegetation types, seems few in validation and calibration, they will make the modified MODIS LST much be close to the real values.

In the revised version, we rewritten the earlier sentence with "preferable" as below: **And they were used as effective alternatives for LST, especially for in-situ observation limited regions, such as the TP (Zhang et al., 2004)**. Then, we added the evaluation of MODIS LST in the *Section 2.2.2* (P.6 L.189-191).

2. TTOP modelling output. The others provide a simple binary term for the presence

or absence of permafrost that is useful in the context of total are numbers but also means that huge amounts of information are unavailable. A map of TTOP temperatures could be useful in interpreting areas most susceptible to future change and also for the purposes of understanding permafrost thicknesses under a variety of environments. I would highly recommend the authors at least present one map showing the spatial distribution of TTOP temperatures.

Response:

Thanks for your excellent advice. We have change the binary map with the actual values derived from the TTOP model according to the permafrost distribution. In addition, the TTOP values were divided into six equal intervals so that the reviewers and potential readers can read and analyze conveniently.

The revised figure is as below, and could be found in the *P.25*.

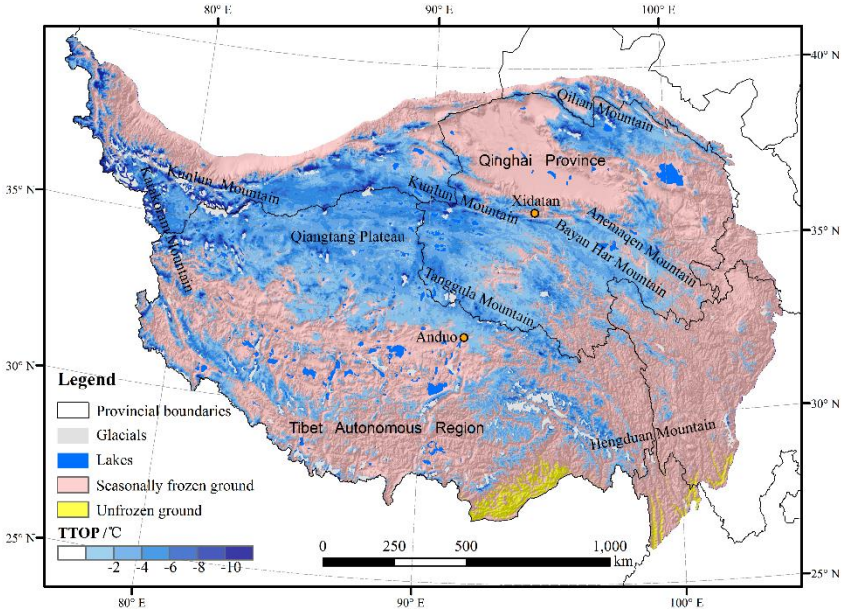

Figure 3. Spatial distribution of permafrost with the derived TTOP on the Tibetan Plateau

3. Uncertainties. Given the uncertainties that may be present in the LST products and in distributing rk across the landscape, it would seem important that some assessment of uncertainty is provided for the estimates of total permafrost area. It also may be a little optimistic to assume that all glacier area would correspond to permafrost area given the vast range of climates in the region. Such an assumption would require a very detailed assessment to rationalize – I'd prefer it be left out.

Response:

The uncertainty analysis was conducted in R statistical software (version 3.3.1, www.r-project.org) using the Percentile Method combined the uncertainties of MODIS LST and in distributing r_k across the soil types, and we use a 90% confidence interval to find the range of total permafrost areas. The results showed that the median permafrost area was 1.06×10^6 km^2, with 90% confidence interval of 0.97×10^6 km^2-1.15×10^6 km^2.

To avoid any confusions, the assumption that all glaciers area correspond to permafrost area has been left out in the revised version.

4. Non-equilibrium permafrost. The authors should consider the results of Riseborough (2007) when evaluating their TTOP model output and particularly in the context of non-equilibrium permafrost. Is the region warming and if so would this be impacting the distribution of permafrost as measured from this equilibrium model? One of the challenges in using a MODIS derived product is that the relatively short period of coverage makes it more challenging to model in hindcast.

Response:

It is really a good question. That is very interesting paper that we have read it seriously. In fact, with changing climate, short-term energy imbalances between the active layer and permafrost result in transient departures from the equilibrium condition. The TTOP model has an error in the top-of-permafrost temperature obtained with the equilibrium model that is higher where permafrost temperature is close to 0 °C. Permafrost on the TP is out of equilibrium under global climate warming, and there exists a long response time of permafrost bodies to atmospheric conditions. Any map based on a contemporary forcing likely underestimates permafrost extent. In the view of the solution of permafrost identify, the boundary of permafrost is the most sensitive region to the climate change and has close relation with the contemporary climate. Therefore, the essential of modern permafrost mapping is how to improve the accuracy of surface forcing and the soil parameters to identify the boundary. This study aims to improve the surface forcing with MODIS LST although relatively short period of coverage. The TTOP modeling in this study based on remote sensing LST and current soil parameters shows a high accuracy in the validation. However, the results may cannot capture thawing permafrost bodies, and more works still were needed to be done.

In the revised version, we discussed this issue in the *Section 4* (P.14 L.436-447).

Minor points:

L16: Remove “mostly”

Response:

Removed accordingly.

L27-28: Identifying ‘thawing regions’ seems unclear to me.

Response:

The “thawing regions” should be seasonally frozen ground, we have removed the statement of “thawing regions” in the sentence. To avoid any confusions, all the “thawing region” was instead of “seasonally frozen ground” in the revised manuscript. Thanks for pointing out.

L41-42: Urgent is perhaps a bit strong of a word here, as is ‘situation’.

Response:

The sentence "**Therefore, understanding the current permafrost situation on TP has become particularly urgent**" is a repetitive statement of the earlier sentence in the manuscript, which has removed and we have revised the earlier sentence as "**Moreover, an accurate contemporary permafrost distribution map is of significant importance for serve as a standard to estimate permafrost degradation and as a basis for further quantitative research.**" (L.40-41).

L46: "there is great variation" -> "there is considerable variation"

Response:

Revised accordingly (L.45). Thanks.

L49-50: This sentence should be re-written to be clearer. At present, it makes no sense.

Response:

It is a repetitive sentence and has been removed.

L51-52: What is the difference between a topographic map and a base map?

Response:

There is no difference between a topographic map and a base map, the sentence has revised as "**In 1980s and 90s, permafrost maps were compiled by different scientists, and the permafrost boundaries were plot on topographic maps by hands with conventional cartographic techniques**" (L.49-50).

L54: "On the" -> "On"

Response:

Revised accordingly. Thanks.

L55-56: This statement is not true. GIS techniques were used before 2000…

Response:

The sentence has revised as "**After 2000, GIS software began to be applied to the permafrost mapping on the TP**" (L.53-54).

L58: What does "stability of elevation" mean?

Response:

The "stability of elevation" means that elevation changes little or even remain constant for a long period of time. To avoid any confusion, the sentence has removed.

L74-75: I do not agree with this sentence. Temperature and reanalysis data have a higher

temporal resolution than MODIS and can be interpolated more accurately. In my experience, MODIS LST products in the Subarctic and Arctic are not suitable alone for characterizing spatial variations in temperature.

Response:

We agree the reviewer's comments about the issue of the applicability of MODIS LST. Actually, what we want to say is the remote sensing products are other available data source besides the temperature interpolation and reanalysis datasets, this is very important data especially for the remote areas with limited observations such as the Tibetan Plateau.

We have changed the sentence as "**And they were used as effective alternatives for LST, especially for in-situ observation limited regions, such as the TP (Zhang et al., 2004).**" (L.72-73).

L80: I agree. The authors should provide examples of this validation.

Response:

The sentence make no sense here, we have removed it and added some examples of MODIS LST validation in *L.164-169* and the validation in this study in *L.189-191*.

L87: Remove "plenty of"

Response:

Removed accordingly.

L89: Remove "perfect"

Response:

Removed accordingly.

L95: Remove this sentence

Response:

Removed accordingly.

L96: Remove "combined"

Response:

Removed accordingly.

L113: What is "drilling method". The grammar seems a bit off.

Response:

The "drilling method" has change to "borehole drilling" (L.110).

L136-137: The grammar in this sentence should be revised.

Response:

The sentence was re-written as: **The lower limit of permafrost (LLP) was determined based on the linear regression relationship between MAGT and elevation of boreholes, and the elevation where MAGT equals to 0 ℃ was regarded as the LLP (Li et al., 2012; Zhang et al., 2012; Chen et al., 2016)** (L.130-132).

L157: "mostly widely" -> "most widely"

Response:

Revised accordingly (L.152).

L174: "massive missing values" -> "many missing values"

Response:

The "massive missing values" has revised to "numerous missing values" (L.174).

L175: "Harmonic ANalysis Time" -> "Harmonic Analysis Time"

Response:

Revised accordingly (L.175).

L176-177: Remove sentence or combine with earlier sentence

Response:

The sentence has combined with the earlier sentence (L.175-178).

L197: What is "stability of the data"?

Response:

The "stability of the data" has removed to avoid the confusion.

L197: I prefer FDD and TDD or sFDD and sTDD to DDF and DDT.

Response:

The DDF and DDT has changed with FDD and TDD in the revised version.

L199: Amend to: "Soil thermal characteristics were modeled according to parameters measured from soil types encountered in the field".

Response:

Revised accordingly (L.201). Thanks.

L232: We do not need a sentence to tell us that an abbreviation was used.

Response:

The sentence has removed.

L259-260: Amend: “increases with increasing” and “decreases…decreases”.

Response:

Revised to “**The permafrost continuity decreases linearly as the elevation decreases and the ground temperature increases with increasing distance from the central region.**” (L.261-262).

L264: This sentence could be shortened with the use of brackets.

Response:

The sentence has been shortened with use of brackets as “**Some unfrozen ground exists in the southeast margin of the TP, whose area is approximately 0.03×10^6 km^2 (account for 1% of the total TP area)**” (L.266-267).

L280: Boreholes are not “convincing evidence” of permafrost rather they can determine if permafrost exists or not. This sentence should be revised.

Response:

The sentence has revised as “**The boreholes can determine whether permafrost exists or not**” (L.269).

L311: “…correct…correct” – please revise.

Response:

The sentence has revised as “**Although the correct pixels were few, the locations in the eastern part were just at the geographic boundary of permafrost**” (L.304-305).

L329: “overcomes this shortcoming” – That is not necessarily proven in this study.

Response:

The statement of “overcomes this shortcoming” is inappropriate, we have removed it in the sentence.

L360: “lower distance difference” – Please clarify.

Response:

The “lower distance difference” means the widths of seasonally frozen ground along the highway transect identified from TP-2016 have smaller difference with the investigation results than that of both TP-1996 and TP-2006. We have revised the

"lower distance difference" to "**smaller width difference**" to keep the agreement with other sentences.

L389-392: This sentence is confusing – please revise.

Response:

We have re-written the sentences as "**The dataset used in the earliest maps (compiled in 1980s and 90s) including air temperature, field data, aerial photographs, satellite images and many relevant maps (Tong and Li, 1983; Shi and Mi, 1988; Li and Cheng, 1996).**" (L.398-399)

L399: "are unevenly" -> "unevenly"

Response:

Revised accordingly.

L400: What is poor representativeness?

Response:

The "poor representativeness" means the monitoring sites is very few in the permafrost region of TP that the extrapolated air temperature may not reflect the actual climate condition of permafrost region. The sentence has revised as below: **In addition, high uncertainty exists in the air temperature interpolation because of the scarcity, unevenly distributed (more in the Eastern TP and less in the Western TP; more in lower elevation and less in higher elevation; very few in permafrost region) monitoring sites, resulting in the low accuracy of extrapolated air temperature of the TP (Lin et al., 2002; Li et al., 2003), especially for the permafrost region** (L.404-407).

L404: "the most accurate" – Remove this sentence.

Response:

The sentence has removed.

L409: Poor sentence grammar – Please revise.

Response:

The sentence has removed. And, the reference *Gruber.(2012)* was cited in the *Introduction* according to the other reviewer's suggestion (L.61-64).

L416: "reflects" -> "reflect"

Response:

The "reflects" has changed to "represent" (L.417).

L418: “high representativeness” – what does this mean?

Response:

The “high representativeness” means the temperature observed by automatic weather stations in typical permafrost region can represent the actual climate condition. In view of the wording “representativeness” may not a common word, we have revised the sentence as below: **In addition, the MODIS LST data was calibrated by the ground-based LST observations obtained from automatic weather stations in typical permafrost regions (Zou et al., 2014), which is corresponding to actual climate condition of permafrost region** (L.418-420).

L419: The case has not been proven for this statement.

Response:

We have revised the sentence as below: **In addition, the MODIS LST data was calibrated by the ground-based LST observations obtained from automatic weather stations in typical permafrost regions (Zou et al., 2014), which is corresponding to actual climate condition of permafrost region**(L.418-420).

L424: Difficult cannot be “large”

Response:

The sentence was revised as: **In the earliest maps, only some observed data from the field sites along Qinghai–Xizang Highway were used for map evaluation (Tong and Li, 1983; Shi and Mi, 1988; Li and Cheng, 1996)** (423-424).

L437: I do not believe that this method could be used elsewhere. Most permafrost regions receive snow therefore negating or reducing its potential utility.

Response:

The statement of “which could be used for other places” has removed.

L440: Misjudgements is not the correct term here.

L445: Please revise the grammar in this sentence.

L446: Please revise the grammar in this sentence.

Response:

The sentences of *L440, L445, L446* were re-written in the revised version.

L454: “In compliance” is not used correctly.

Response:

The “In compliance with” has revised to “**From the validation with**” (L.453).

L462-463: I do not believe this study has adequately demonstrated this. Please remove.

Response:

The sentence has removed.

References:

Che, T., Xin, L., Jin, R., Armstrong, R., and Zhang, T.: Snow depth derived from passive microwave remote-sensing data in China, Ann. Glaciol., 49(1), 145-154, 2008.

Coll, C., Caselles, V., Galve, J. M., Valor, E., Niclòs, R., Sánchez, J. M., and Rivas, R.: Ground measurements for the validation of land surface temperatures derived from AATSR and MODIS data, Remote. Sens. Environ., 97, 288-300, 2005.

Huang, X., Deng, J., Wang, W., Feng, Q., and Liang, T.: Impact of climate and elevation on snow cover using integrated remote sensing snow products in Tibetan Plateau, Remote. Sens. Environ., 190, 274-288, 2017.

Langer, M., Westermann, S., and Boike, J.: Spatial and temporal variations of summer surface temperatures of wet polygonal tundra in Siberia - implications for MODIS LST based permafrost monitoring, Remote. Sens. Environ. 114, 2059-2069, 2010.

Lehnert, L., Meyer, H., Wang, Y., Miehe, G., Thies, B., Reudenbach, C., and Bendix, J.: Retrieval of grassland plant coverage on the Tibetan Plateau based on a multi-scale, multi-sensor and multi-method approach, Remote. Sens. Environ. 164, 197-207, 2015.

Li, W., Zhao, L., Wu, X., Wang, S., Sheng, Y., Ping, C., Zhao, Y., Fang, H., and Shi, W.: Soil distribution modeling using inductive learning in the eastern part of permafrost regions in Qinghai-Xizang (Tibetan) Plateau, Catena., 126, 98-104, 2015a.

Li, W., Zhao, L., Wu, X., Zhao, Y., Fang, H., and Shi, W.: Distribution of soils and landform relationships in the permafrost regions of Qinghai-Xizang (Tibetan) Plateau, Chin. Sci. Bull., 60, 2216-2226, 2015b.

Pu, Z., Xu, L., and Salomonson, V. V.: MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau, Geophys. Res. Lett., 34, L06706, 2007.

Qin, D., Liu, S., and Li, P.: Snow cover distribution, variability, and response to climate change in western China, J. Climate, 19(9), 1820-1833, 2006.

Riseborough, D.: The effect of transient conditions on an equilibrium permafrost-climate model, Permafr. Perigl. Proc., 18, 21-32, 2007.

Romanovsky, V., Smith, S., Christiansen, H.: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: a synthesis, Permafr. Perigl. Proc., 21(2), 106-116, 2010.

Smith, S. L., Burgess, M. M., Riseborough, D., and Mark Nixon, F.: Recent trends from Canadian permafrost thermal monitoring network sites, Permafr. Perigl. Proc., 16(1), 19-30, 2005.

Wan, Z.: New refinements and validation of the MODIS land-surface temperature/emissivity products, Remote. Sens. Environ., 112, 59-74, 2008.

Wan, Z., Li, Z.: Radiance-based validation of the V5 MODIS land-surface temperature product, Int. J. Remote. Sens., 29, 5373-5395, 2008.

Wan, Z., Zhang, Y., Zhang, Y., and Li, Z.: Validation of the land-surface temperature products retrieved from Moderate Resolution Imaging Spectroradiometer data, Remote. Sens. Environ., 83, 163-180, 2002.

Wan, Z., Zhang, Y., Zhang, Y., and Li, Z.: Quality assessment and validation of the global land surface temperature, Int. J. Remote. Sens., 25, 261-274, 2004.

Wang, Z., Wang, Q., Zhao, L., Wu, X., Yue, G., Zou, D., Nan, Z., Liu, G., Pang, Q., Fang, H., Wu, T., Shi, J., Jiao, K., Zhao, Y., and Zhang, L.: Mapping the vegetation distribution of the permafrost zone on the Qinghai-Tibet Plateau. J. Mt. Sci., 13(6), 1035-1046, 2016.

Westermann, S., Langer, M., and Boike, J.: Spatial and temporal variations of summer surface temperatures of high-arctic tundra on Svalbard - Implications for MODIS LST based permafrost monitoring, Remote. Sens. Environ., 115(3), 908-922, 2011.

Wu, Q., and Liu, Y.: Ground temperature monitoring and its recent change in Qinghai-Tibet Plateau, Cold. Reg. Sci. Technol., 38, 85-92, 2004.

Wu, Q., Zhang, T.: Recent permafrost warming on the Qinghai-Tibetan Plateau, J. Geophys. Res., 113, D13, 2008.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Rev. Geophys., 43(4), 2005.

Zhao, L., Wu, Q., Marchenko, S. S., and Sharkhuu, N.: Thermal state of permafrost and active layer in Central Asia during the international polar year, Permafr. Perigl. Proc., 21, 198-207, 2010.

Zou, D., Zhao, L., Wu, T., Wu, X., Pang, Q., and Wang, Z.: Modeling ground surface temperature by means of remote sensing data in high-altitude areas: test in the central Tibetan Plateau with application of moderate-resolution imaging spectroradiometer Terra/Aqua land surface temperature and ground-based infrared radiometer, J. Appl. Remote. Sens., 8, 083516, 2014.