Authors reply to the comments by Anonymous Reviewer #2 of the manuscript gmd-2018-15

“PIC v1.2: Comprehensive R package for permafrost indices computing with daily weather observations and atmospheric forcing over the Qinghai–Tibet Plateau”

by Lihui Luo et al.

We thank Anonymous Reviewer #2 for the valuable feedback, which helped to improve the manuscript. Please find below the Reviewer comments in black, Author responses in green, and Changes to the manuscript in blue.

Response to reviewer comment 2:
Overall problems English is problematic. Before resubmission, ask a native English speaker with good geoscience background to help edit the manuscript when all technical details are taken care of.

Thanks for your insightful comments. In revising the paper, we have carefully considered your comments and suggestions. We agree with your comments on some details and the latest progress of permafrost modeling. To address these concerns, we make the following modifications to the manuscript: (1) Reorganized the manuscript structure; (2) Added the preparation of datasets and parameters, and comparative analysis between simulations and observations; (3) Modified inappropriate expression; (4) Highlighted the importance of the transparency and repeatability in permafrost modeling, especially for the Qinghai-Tibet Plateau; (5) Improved the flow of the manuscript language (Figure R1). We tried our best to address each of your points in detail. We feel the revision represents an improvement and hope you do also. For more details, please see our replies below.
Figure R1. Editorial Certificate.

Specific issues: Title: OK Abstract: OK

1. Introduction P2, Lines 7-8, winter snow cover in some of those areas is supposed to one of the thickest in the world.

Thanks for pointing this out.
We have updated the sentence as follows:

“Permafrost occurs mostly in high latitudes and altitudes with long, cold winters and thick winter snow, e.g., the Arctic, Antarctica, Alaska, the Alps, Northern Russia, Northern Canada, Northern Mongolia, and the Qinghai-Tibet Plateau (QTP) (Riseborough et al., 2008; Yi et al., 2014; Zhang et al., 2008)”

P2, Lines 14-16, sentence needs elaboration. The distribution and changes of permafrost with climate is necessary for infrastructure development, ecological and environmental assessments, and climate system modeling. The distribution of permafrost under influences of climate change is... Notes: the epidemic issue here in the paper is rambunctious listing of references in the text. It should follow the GMD format, or at least the earlier, the first principle. Such as, Lines 10-11, 15-16, and others. Change them all and make the list more reasonable.

Thanks for pointing this out. We check the reference format.
We have updated the sentence as follows:

“Understanding the distribution and changes of permafrost under the influence of climate change is necessary for infrastructure development, ecological and environmental assessment, and climate system modelling (Luo et al., 2017; Luo et al., 2012; Zhang et al., 2014)”

P3, Lines 3-5, please cite original references, who proposed the classification of permafrost on the basis of MAGT in Chin and on the QTP? Additionally, it is on the MAGT, rather than on the size of the MAGT. What is the size of the MAGT?

We add a reference. MAGT is often found at the depth from 10 m to 16 m over the QTP (Wu and Zhang, 2010), here we take the value of 15 meters. Usually, size connotes physical dimensions while magnitude connotes either a numerical measure of any sort of amount or metaphorical size. Our use of the word “size” is wrong. So we changed the “size” to “range”.

“Thereafter, the type and distribution of frozen soil can be classified in a variety of manners depending on the range and magnitude of these indices.”

Page 3, Paragraph 15, The land surface temperature significantly differs the near-surface air temperatures and ground surface temperatures, particularly for the simulation of the thermal regime of ground. This is significant when taking into account of different driving input of the modeling. Please refer to Difference between near-surface air, land surface and ground surface temperatures and their influences on the frozen
ground on the Qinghai-Tibet Plateau (Geoderma, Luo et al., 2018);

Thanks for pointing this out. We agree with your comments on the difference of three temperature values, input data with different temperatures will cause the difference of simulation. The Land Surface Temperature (LST) is the radiative skin temperature of the land surface, as measured in the direction of the remote sensor. LST is a mixture of vegetation and bare soil temperatures. The ground surface temperature (GST) is the soil temperature at 0–5 cm. The near-surface air temperature \((T_a)\) was measured at a screen-height of 1.5–2 m.

In the PIC v 1.1 package, we use near-surface air temperature and ground surface temperature at 0 cm, which came from weather stations and GLDAS gridded meteorological datasets. In the future we will use spatial data of land/ground surface temperature as a input data of PIC package, and we will consider the simulation difference between LST and GST.

Page 3, Line 20, please change “is a problem” to “problematic”;

We rewrote the sentence.

“The transparency and repeatability of data, parameters, model codes, computational processes, simulation output, visualization, and statistical analysis is a fundamental principle of scientific research in Earth system modelling. At present, there is a lack of open source software, shared data and parameters for permafrost modelling in the QTP.”

Page 5, Line 20, “MAGT is the soil temperature in (Wu and Zhang, 2010).” This sentence is incomplete.

Thanks for pointing this out. For a clearer description of MAGT, we rewrote the sentence as follows:

“MAGT is defined as the soil temperature at the depth of zero annual temperature change. \(T_{z,t}\) is the ground temperature at any time \(t\) and depth \(z\) below a ground surface. MAGT is often found at the depths from 10 m to 16 m over the QTP (Wu and Zhang, 2010). Here, we take the \(z\) value of 15 meters.”

Please also note the supplement to this comment: https://www.geosci-model-dev-discuss.net/gmd-2018-15/gmd-2018-15-RC2-supplement.pdf

We moved the reviewer’s comments here from the manuscript edits.

Page 2, Line 3, consecutive

This has been added, thank you.

Page 2, Line 7, permafrost occurs also in Alps where there is a considerable snow cover during the winter.

This has been added, thank you.

Page 2, Line 9, Need to check if for the inside cite, the journal request that multiple authors to be arranged
alphabetically and not by year.

Thanks. We check the reference format for the inside cite.

Page 2, Line 10, There are some other opinions in a recent paper. At least is adequate to cite them. Ran et al. 2018: Climate warming over the past half century has led to thermal degradation of permafrost on the Qinghai–Tibet Plateau. In: The Cryosphere, 12, 595–608

Thanks. Many recent articles have pointed out that the Qinghai-Tibet Plateau has warmed more than 0.25 degrees every ten years. We updated the sentence, and added a recent reference.

“The temperature in the QTP has increased by more than 0.25 °C per decade over the past 50 years (Li et al., 2010; Ran et al., 2018; Shen et al., 2015; Yao et al., 2007).”

Page 4, Line 5, I don't think this paragraph is necessary. This is a classical research article which structure is well known and is already organised based on it. Also is indicated to finish the introduction part with the purpose, for a easier article reading.

We deleted this paragraph.

Page 5, Line 5, These indices are indeed very well explained.

We have added more descriptions to these permafrost indices in section “Permafrost modeling”. We have updated the sentence as follows:

“DDTa and DDTs are the sums of mean daily air and ground surface above temperatures 0 °C (Celsius degree-days), respectively. DDFa and DDFs are the sums of mean daily air and ground surface temperatures below 0°C (Celsius degree-days), respectively.”

“Local variations in vegetation, topography, and snow cover may result in several differences between MAGST and MAAT.”

“MAGT is defined as the soil temperature at the depth of zero annual temperature change. Tz,t is the ground temperature at any time t and depth z below a ground surface. MAGT is often found at depths from 10 m to 16 m over the QTP (Wu and Zhang, 2010), Here, we take the z value of 15 metres.”

“The seasonal thawing/freezing n factor (nt/nf) relates thawing and freezing degree-days (DDTa/DDTs/DDFa/DDFs) in seasonal air temperature to ground surface temperatures.”

“TTOP indicates average temperatures at the top of the permafrost. The active layer is defined as the layer of ground subject to annual thawing and freezing underlain by permafrost.”


This has been corrected, thank you.

Page 9, Line 3, It could be written also "Results" as a chapter name here. Or joined.
As a Development and technical manuscript of “Geoscientific Model Development”, we reorganize the manuscript structure, and changed the title to "Implementation".

Page 10, Line 7-8, That’s great, because is processing automatically the outliers.

Thanks.

Page 13, Line 2-3, Can this be explained?

The simulated TTOP and ALT that uses the Stefan and Smith functions have higher TTOP and ALT than the Kudryavtsev function. The difference between them were also shown in other areas (Uxa, 2017; Wilhelm et al., 2015).

Figure 1, Missing scale bar.
Maybe a bit more info on the map (r.g. main roads and rivers, key cities), and the dots for the weather stations can be smaller if it will be too crowded with the additional info.

Thanks for pointing this out. We added the scale, and also add lake, glacier (the Second Glacier Inventory Dataset of China, v1.0), the legend of elevation map, and two major cities in the Qinghai-Tibet Plateau.

![Figure 1: Map of the data location over the QTP.](image)

Table 2, Typing error: too much space.

This has been corrected, thank you.

Table 2, It could be a better matching of left columns with right columns in this part for a easier reading.

We adjusted the arrangement of the columns.
Table 2, column

This has been corrected, thank you.

Table 3, It could be a note under the table to mention the abbreviations or to indicate that the abbreviations are specified in text.

We have added the sentence in the table caption as follows:

“Intercept: y-intercept; Slope: slope of regression line; R: Pearson's correlation coefficient, R2: coefficient of determination; RMSE: root mean squared error; NRMSE: normalized RMSE; SD_S: the standard deviation of TTOP using the Stefan function; SD_K: the standard deviation of TTOP using the Kudryavtsev function; MEF: modelling efficiency; NAE: normalized average error; VR: variance ratio; PBIAS: percent bias; NSE: Nash-Sutcliffe efficiency; RSR: RMSE-observations standard deviation ratio; and D: index of agreement.”

References:
Ran, Y., Li, X., and Cheng, G.: Climate warming over the past half century has led to thermal degradation of permafrost on the Qinghai-Tibet Plateau, Cryosphere, 12, 595-608, 2018.

Zhang, Y., Olthof, I., Fraser, R., and Wolfe, S. A.: A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections, Cryosphere, 8, 2253-2253, 2014.
**PIC v1.2: Comprehensive R package for permafrost indices computing with daily weather observations and atmospheric forcing over the Qinghai–Tibet Plateau**

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**Abstract.** An R package `PIC` v1.2 R package was developed, which integrates meteorological observations, remote sensing datagrids, meteorological datasets, soil databases, and field measurements to compute the factors or indices of permafrost and seasonal frozen soil. At present, 16 temperature/depth-related indices are integrated into the `PIC` v1.2 R package to estimate the possible change trends of frozen soil in the Qinghai–Tibet Plateau (QTP). These indices include the mean annual air temperature, (MAAT), mean annual ground surface temperature, (MAGST), mean annual ground temperature, (MAGT), seasonal thawing/freezing n factor (nₜ/nₕ), thawing/freezing degree-days (DDTₜ/DDTₕ), temperature at the top of the permafrost, (TTOP), active layer thickness (ALT), and maximum seasonal freeze depth. The `PIC` package v1.2 supports two computational modes, namely, the stations and region calculations that enable statistical analysis and intuitive visualization of the time series and spatial simulations. Over 52 weather stations and a central region of the QTP were prepared and simulated to evaluate the temporal-spatial trends of permafrost with the climate. More than 10 statistical methods and a sequential Mann-Kendall trend test were adopted to evaluate these indices in stations, and a sequential Mann-Kendall trend test and spatial trend...
Spatial methods were adopted to determine the spatial trends. Multiple visual manners were used to display the temporal and spatial variabilities of the stations and region. The data sets of 52 weather stations and a central region of QTP were prepared and simulated to evaluate the temporal–spatial change trends of permafrost with the climate. Simulation results show extensive permafrost degradation in the QTP, and the temporal—spatial trends of the permafrost conditions in the QTP were consistent with those of previous studies. The transparency and repeatability of the PIC v1.2 package will serve engineering applications and its data can be used and extended to assess the impact of climate change on permafrost.

1 Introduction

Permafrost, which is soil, rock, or sediment with temperatures that have remained at or below 0 °C for at least two consecutive years, is a key component of the cryosphere. The upper layer in permafrost regions is called the active layer, which undergoes seasonal freezing and thawing. Below this layer lies permafrost, the upper surface of which is called the upper limit of permafrost or the permafrost table. Changes in permafrost can affect water and heat exchanges, the carbon budget, and natural hazards with the climate change. Permafrost occurs mostly in high latitudes and altitudes with long, cold winters and thick winter snow cover, e.g., the Arctic, Antarctica, Alaska, the Alps, Northern Russia, Northern Canada, Northern Mongolia, and the Qinghai–Tibet Plateau (QTP) (Riseborough et al., 2008; Yi et al., 2014b, 2014c; Zhang et al., 2008a). Over half of the QTP land is underlain by permafrost (Ran et al., 2012) (Ran et al., 2012). The temperature in the QTP has increased by more than 0.25 °C per decade over the past 50 years (Li et al., 2010; Shen et al., 2015; Yao et al., 2007). Climate-induced warming of the near-surface atmospheric layer and a corresponding increase in ground temperatures will lead to substantial changes in the water and energy balance of regions underlain by permafrost (Hilbich et al., 2008). Such an increase in the temperature of the QTP can warm the ground through energy exchange at the surface and result in significant permafrost degradation. Understanding the distribution and changes of permafrost with the influence of climate change is necessary for infrastructure development, ecological and...
environmental assessments (Luo et al., 2017; Luo et al., 2012; Zhang et al., 2014).

Given the possibility of future climate warming, an evaluation of the magnitude of changes in the ground thermal regime has become desirable to assess the possible eco-environmental response and the impact on the QTP infrastructure. Permafrost modeling maximizes quantitative methods, such as analytical, numerical, or empirical methods, to predict the thermal condition of the ground in environments where permafrost may be present (Harris et al., 2009; Lewkowicz and Bonnaventure, 2008; Riseborough, 2011; Riseborough et al., 2008; Yi et al., 2014a, 2014b; Zhang et al., 2008b). At present, dozens of different factors or indices are used to evaluate the characteristics and dynamics of permafrost presence or absence (Riseborough, 2011; Riseborough et al., 2008), including the freezing/thawing index, mean annual air temperature (MAAT), mean annual ground temperature (MAGT), mean annual ground surface temperature (MAGST), temperature at the top of permafrost (TTOP), and the active layer thickness (ALT), among others. Thereafter, the type and distribution of frozen soil can be classified in a variety of manners depending on the index size and magnitude of these indices. For example, frozen soil can be divided into highly stable, stable, substable, transitional, unstable, and extremely unstable permafrost, as well as seasonal frozen soil that depends on the size of MAGT (Chen et al., 2012; Ran et al., 2012). These indices can be used to evaluate and predict the temporal and spatial variation in the thermal response of permafrost to the changing climatic conditions and properties of Earth’s surface and subsurface in one, two, or three dimensions (Juliussen and Humlum, 2007; Nelson et al., 1997; Riseborough et al., 2008; Wu et al., 2010; Zhang et al., 2005). Accordingly, successfully summarizing and categorizing a variety of frozen-soil indices requires permafrost modeling that concerns analytical, numerical, and empirical methodologies to compute the past and present condition of permafrost conditions. The Stefan solution (Nelson et al., 1997), Kudryavtsev’s approach (Kudryavtsev et al., 1977), the TTOP model (Smith and Riseborough, 1996), and the Geophysical Institute Permafrost Lab model (Romanovsky and Osterkamp, 1997; Sazonova and Romanovsky, 2003) are several important developments for permafrost modeling in recent years. Permafrost is a subsurface feature that is difficult to directly
observe and map. These methods integrate the effects of air and ground temperatures, topography, vegetation, and soil properties to map permafrost spatially and explicitly (Gisnås et al., 2013; Jafarov et al., 2012; Zhang et al., 2014). Weather observation data, including air and soil temperatures with different depths, are the main inputs for single-point simulation, whereas the spatial and temporal resolution of the atmospheric forcing dataset is the main input data of permafrost spatial modelling. These permafrost indices consist mainly of temperature-related and depth-related indices. The temperature-related indices depict the status of air or land surface temperature in frozen-soil environments, whereas the depth-related indices reveal the status of the active layer. Preparing atmospheric forcing data sets, snow depth and density, vegetation types, and soil classes are generally required for multi-dimensional simulation, which came across data sets from multi-source data fusion, particularly remote sensing and ground observation data is generally required for multi-dimensional permafrost simulation.

The current transparency and repeatability of data, parameters, model codes, computational processes, simulation output, visualization, and statistical analysis is a fundamental principle of scientific research in Earth system modelling. At present, there is a lack of open source software on shared data and parameters for permafrost modelling over modelling in the QTP which is a problem. Although many scientists in China have field data and models on hand, the integration of data and models into a new open source model can facilitate the deepening of the discussion and unfolding of permafrost research on the QTP. Given the current condition of permafrost modelling in the QTP, a comprehensive R package of permafrost indices computing (PIC v1.2, doi: 10.5281/zenodo.1237428) was developed to compute permafrost and seasonal frozen-soil indices (Luo, 2018). The goal is to determine the solutions to maintain or build the engineers in a manner that provides guidance for the future of highway and high-speed railway design and construction in the QTP, as well as further understand the effects of climate change on the permafrost dynamics of QTP. Therefore, the proposed software integrates meteorological observations, remote sensing data, gridded meteorological datasets, soil databases, field measurements, and permafrost modelling.
2 Package description

2.1 Overview

PIC v1.2 was developed in the R language and environment for statistical computing v. 3.3.3 and is distributed as open source software under the GNU-GPL 3.0 License (R Core Team, 2017). Therefore, the PIC v1.2 code can be modified as required to meet the needs of every user. The source code can be downloaded from the GitHub repository (https://github.com/iffylaw/PIC). The R package PIC v1.2 provides all the necessary functionality to perform the calculation, statistics, and drawing of permafrost indices with over 38 functions based on the user’s specific requirements (see Figure 2). The following packages are required in setting up PIC v1.2 (type library(PIC)): ggplot2 (Wickham et al., 2009), ggmap (Kahle and Wickham, 2013), RNNetCDF (Michna and Woods, 2013), and animation (Xie, 2013). These packages are automatically added to the R users’ library during installation. A data set that contains the daily weather observations, parameters, and information (i.e., from 1951 to 2010) of 52 weather stations in the QTP was bundled into this package. However, the regional data with the NetCDF format was placed in the GitHub repository. The data set variables excluded in the calculation can also be used as reference or provide support to further develop PIC. These variables include wind speed, precipitation, evaporation, humidity, and soil temperature at different depths. PIC v1.2 was primarily designed to compute indices of permafrost and seasonal frozen soil from observations and forcing data. Therefore, the current stable version of the program (v 1.1) includes functionalities that cover temperature-related indices (i.e., MAAT, MAGST, and TTOP) and depth-related indices (i.e., ALT and FD) that are commonly used in permafrost research. It is possible to evaluate the changes in frozen soil better by combining multiple indices for overall analysis.

PIC v1.2 supports two computational modes: the station and regional calculations that enable statistical analysis and visual displays of the time series and spatial simulations. The regional calculation adopts GIS approaches to compute each spatial grid. PIC v1.2 was initially developed to address the immediate need for a reliable and easy-to-use program for estimating temporal-spatial changes in frozen OTP soil. Thus, the workflow is comprised of deliberately simplified steps throughout the entire process. Once PIC v1.2 is installed, the workflow of the weather observations is considerably straightforward: (1) an
index of a weather station for one year or multiple years is calculated, (2) an index of 52 weather stations from 1951 to 2010 is calculated, and (3) an index of all stations or permafrost stations from 1951 to 2010 is drawn through a curve and spatial visualization. Step (1) is an optional step. The forcing data workflow has only two steps: (1) a total of 4 indices from 1980 to 2010 are calculated, including MAAT, $D_{DDT}$, $D_{DF}$, and ALT and (2) the spatial statistics and visualization of these 4 indices are drawn.

The remainder of this paper is organized as follows. Section 2 describes the prepared data sets, methodology of permafrost modeling, and statistical methods for stations and region. Section 3 presents a detailed description of the functions provided by PIC and the workflow. Section 4 demonstrates the application of the proposed software for the stations and region. Section 5 discusses several benefits and limitations of PIC. Lastly, Section 6 presents the conclusions.

2 Data and Methods

3.1 Data and parameters

**Daily weather observations.** Meteorological data were obtained from the China Meteorological Administration (CMA, http://www.cma.gov.cn/), particularly from permanent meteorological stations across QTP. A total of 52 weather stations with daily meteorological records (i.e., from 1951 to 2010) were selected, including the daily mean, maximum (max) and minimum (min) air temperatures, wind speed, observed and corrected precipitation, evaporation, air humidity, atmospheric pressure, sunshine duration, daily mean, max and min ground surface temperatures, and soil temperature with different depths (i.e., 5, 10, 15, 20, 40, 50, 80, 160, and 320 cm). These data have been corrected under specification for surface meteorological observation and quality control of CMA.

**Atmospheric forcing data set.** The QT Engineering Corridor (QTEC), which is located at the center of QTP, was selected in preparing the atmospheric forcing data. Global Land Data Assimilation System (GLDAS, https://ldas.gsfc.nasa.gov) and the weather station data of the surrounding QTEC were merged to produce a new data set for 1980 to 2010 with a daily 0.1° temporal–spatial resolution (Rui and Beaudoing, 2011).
Parameters. The parameters for the ground conditions were prepared based on vegetation and soil classification (Bicheron et al., 2008; Nachtergaele et al., 2009), field observations, and topographic maps. The parameter data have two data sets: one for weather stations and another for the QTEC region. Table 1 and Figure 1 show the detailed information of the data and parameters.

2.2 Permafrost modeling

The PIC package v1.2 enables the calculation of the thawing/freezing degree-days for air and ground surface (DDT$_a$/DDT$_g$/DDT$_f$/DDF), MAAT, MAGST, MAGT, the seasonal thawing/freezing $n$ factor ($n/n$), thawing/freezing degree-days of air and ground surface (DDT$_a$/DDT$_g$/DDT$_f$/DDF), TTOP, ALT, and the maximum seasonal freeze depth (FD).

These The permafrost and seasonal frozen--soil indices that employing the following functions are illustrated. Table 1 describes most of them.

$A_s$ is the annual temperature amplitude at the ground surface, where $T_{max}$ and $T_{min}$ are the annual maximal and minimal temperatures, respectively. at the ground surface, $A_s$ can be calculated as follows:

$$A_s = T_{max} - T_{min} \quad (1)$$

$L$ is the volumetric latent heat of fusion, $\rho$ is the dry density of soil, and $W$ is the water content of the soil in percentages.

$$L = \frac{80 \times \rho \times W}{100} \quad (2)$$

$DDT_a$ and $DDT_g$ are the thawing degree-days sums of the mean daily air and ground surface above temperatures 0 °C (Celsius degree-days), respectively. $DDT_a$ and $DDF_a$ are the freezing degree-days sums of the mean daily air and ground surface temperatures below 0 °C (Celsius degree-days), respectively. Degree-days are usually used to describe the air and ground surface temperature intensity, where $T_a$ and $T_g$ are the air and ground temperatures, respectively, and $n$ is the number of days in a year (Juliussen and Humlum, 2007, Juliussen and Humlum, 2007).

$$DDT_a = \sum_{1}^{n} T_a, \quad T_a > 0 \quad (3)$$

$$DDF_a = \sum_{1}^{n} T_a, \quad T_a < 0 \quad (4)$$
\[ DDT = \sum^n_{i=1} T_{a_i} T_z > 0 \] \hspace{1cm} (5)
\[ DDF = \sum^n_{i=1} T_{a_i} T_z < 0 \] \hspace{1cm} (6)

\( P \) is assigned a value of 365 days. Local variations in vegetation, topography, and snow cover may result in several differences between MAGST and MAAT. MAAT and MAGST can be computed as follows:

\[ \text{MAAT} = \frac{DDT - DDF}{P} \] \hspace{1cm} (7)
\[ \text{MAGST} = \frac{DDT - DDF}{P} \] \hspace{1cm} (8)

MAGST is defined as the soil temperature in (Wu and Zhang, 2010) at the depth of zero annual temperature change. \( T_z \) is the ground temperature at any time \( t \) and depth \( z \) below a ground surface. MAGST is often found at depths from 10 m to 16 m over the QTP (Wu and Zhang, 2010). Here, we take the \( z \) value of 15 metres. MAGST can be computed (Juliussen and Humlum, 2007; Riseborough et al., 2008) as follows:

\[ T_{z,t} = T_a + A_z \times e^{-\frac{z^2}{2/P_t}} \times \sin \left( \frac{2 \pi t}{P} - z \times \sqrt{\pi / \alpha P} \right) \] \hspace{1cm} (9)
\[ \text{MAGST} = T_{z,t} \text{ at } z = 15 \text{ and } t = 86400 \]. \hspace{1cm} (10)

The seasonal thawing/freezing factor (\( n/n_t \)) relates thawing and freezing degree-days (\( DDT/DFDT/DFDF/DFDF \)) in seasonal air temperature to ground surface temperatures. \( n \) and \( n_t \) can be computed (Riseborough et al., 2008) as follows:

\[ n = \frac{DDT}{DDT_a} \] \hspace{1cm} (11)
\[ n_t = \frac{DDF}{DDF_a} \] \hspace{1cm} (12)

TTOP indicates average temperatures at the top of the permafrost. The active layer is defined as the layer of ground subject to annual thawing and freezing underlain by permafrost. ALT refers to the maximum thawing depth of the active layer. Two methods serve the same purpose when computing TTOP and ALT. The subscripts \( s \) and \( k \) stand for the Smith and Kudryavtsev functions (Kudryavtsev et al., 1977; Smith and Riseborough, 1996), respectively.

\[ \text{TTOP}_s = \frac{n_s x S_D T_{a_s} - n_s x S_D T_{s}}{S_D x P} \] \hspace{1cm} (13)
The maximum thawing depth or ALT uses the Stefan and Kudryavtsev functions (Kudryavtsev et al., 1977; Riseborough et al., 2008), where $L$ is the latent heat of fusion of ice ($3.34 \times 10^5$ J/kg).

\[ TTOP_K = \frac{0.5 \times MAST \times (A_t + f_j) + A_t \times \frac{f_j - f_j}{\pi} \times \frac{MAST}{A_t} \times \arcsin \left( \frac{MAST}{A_t} \right) \sqrt{1 - \frac{n^2}{A_t^2}}}{A_t} \] (14)

\[ \lambda^* = \begin{cases} A_t, & \text{if numerator } < 0 \\ A_t, & \text{if numerator } > 0 \end{cases} \] (15)

\[ A_z = \frac{A_t - T_z}{A_t + T_z - 2x \times CT} - \frac{L}{2x \times CT} \] (17)

\[ Z_c = \frac{2 \times (A_t - T_z) \times \sqrt{(f_j + f_i) \times P_{in} \times C_y}}{2x \times A_t \times C_T + L} \] (18)

\[ ALT_K = \frac{2 \times (A_t - TTOP_K) \times \sqrt{(f_j + f_i) \times P_{in} \times C_y}}{2x \times A_t \times C_T} + \frac{(f_j + f_i) \times P_{in} \times C_y}{2x \times A_t \times C_T + L} \] (19)

 Freeze_depth is the maximum seasonal freezing depth that uses the Stefan function, which can be computed as follows:

\[ \text{Freeze_depth}_x = \frac{2x_i \times DDF}{L \times \rho \times (W - W_0)} \] (20)

### 2.3 Statistical methods

Statistical analysis can facilitate the evaluation of the change trend and the overall modelling performance of the model simulation. In particular, each statistic has strengths and weaknesses; thus, we adopted over 10 statistical methods to evaluate these indices in station computing for time series data. The quantitative statistics include the slope, $y$-intercept, Pearson’s correlation coefficient ($R$), coefficient of determination ($R^2$), root mean square error (RMSE), standard deviation (SD), ratio of scatter (RS), normalized RMSE (NRMSE), Nash–Sutcliffe efficiency (NSE), RMSE-observations standard deviation ratio (RSR), percent bias (PBIAS), normalized average error (NAE), variance ratio (VR), and index of agreement ($D$) (Jafarov et al., 2012; Legates and McCabe, 1999). The sequential Mann-Kendall (MK) trend test was used to statistically
assess whether there was a shift in trends of the climate factors and permafrost indices (Fraile, 1993). The original MK trend test can be calculated as follows:

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(x_j - x_i) \cdot (i = 2, 3, \ldots, n) \]  
(21)

\[ \text{sign}(x_j - x_i) = \begin{cases} 
1 & \text{if } x_j - x_i > 0 \\
0 & \text{if } x_j - x_i = 0 \\
-1 & \text{if } x_j - x_i < 0 
\end{cases} \]  
(22)

Two sequential series \( u_i \) values can be calculated as follows:

\[ u_i = \frac{S - n \cdot \text{mean}}{\text{Var}(S)} \quad (i = 1, 2, 3, \ldots, n) \]  
(23)

The two series for the MK trend test, a progressive one and a backward one, were separated up. If they cross each other and diverge beyond a specific threshold value and exceed the confidence level of 95%, then there is a statistically significant trend shift point.

The spatial trend can also be calculated to evaluate regional computing for temporal-spatial data through the function below. The index represents one permafrost index, \( n \) represents the sequential years, and \( \text{index}_i \) is the index value in year \( i \). Taking ALT as an example, a positive trend means that ALT was increasing, thereby indicating that permafrost degradation has intensified; a negative value means that ALT was decreasing, thereby indicating that permafrost degradation has a certain inhibition; and a zero trend suggests a lack of change (Chen et al., 2014; Stow et al., 2003).

\[ \text{Trend} = \frac{n \cdot \sum_{i=1}^{n} i \cdot \text{index}_i - \left( \sum_{i=1}^{n} \text{index}_i \right)^2}{n \cdot \sum_{i=1}^{n} (i^2) \cdot (\sum_{i=1}^{n} i)^2} \]  
(24)
3 Package description

PIC was developed in the R Language and Environment for Statistical Computing v. 3.3.3 and is distributed as open source software under the GNU GPL 3.0 License. Therefore, the PIC code can be modified as required to meet the needs of every user. The source code can be downloaded at the GitHub repository (https://github.com/iffylaw/PIC). The R package PIC provides all the necessary functionality to perform the calculation, statistics, and drawing of permafrost indices with over 38 functions based on the user’s specific requirements (see Figure 2). The following packages are required in setting up the PIC (type library(PIC)): ggplot2 (Wickham et al., 2009), ggmap (Kahle and Wickham, 2013), RNetCDF (Michna and Woods, 2013; Zambrano-Bigiarini and Rojas, 2013), and animation (Xie, 2013). These packages are automatically added to the users’ R library during installation. A data set that contains the daily weather observations, parameters, and information (i.e., from 1951 to 2010) of 52 weather stations in QTP were bundled into this package. However, the region data with the NetCDF format was placed in the GitHub repository. The data set variables excluded in the calculation can be used as references or provide support to further develop PIC. These variables include wind speed, precipitation, evaporation, humidity, and soil temperature at different depths. PIC was primarily designed to compute indices of permafrost and seasonal frozen soil from observations and forcing data. Therefore, the current stable version of the program (v. 1.0) includes functionalities that cover temperature-related indices (i.e., parameters MAAT, MAGST, and TTOP) and depth-related indices (i.e., ALT and FD) that are commonly used in permafrost research.

3.1 Daily weather observations

Table 2 shows detailed information of the data and parameters. Meteorological data were obtained from the China Meteorological Administration (CMA, http://www.cma.gov.cn/), particularly from permanent meteorological stations across the QTP (Figure 1). A total of 52 weather stations with daily meteorological records (i.e., from 1951 to 2010) were selected, including the daily mean, maximum (max) and minimum (min) air temperatures, wind speed, observed and corrected precipitation, evaporation, air humidity, atmospheric pressure, sunshine duration, daily mean, max and min ground surface temperatures, and soil temperature at different depths (i.e., 5, 10, 15, 20, 40, 50, 80, 160, and 320 cm). The PIC package supports two computational modes: the station and region calculations that enable statistical analysis and visual displays on the time series and spatial simulations. The regional calculation adopts GIS approaches to compute each spatial grid. PIC was initially developed to address an immediate need for a reliable and easy to use program to estimate the temporal–spatial
changes in frozen soil in QTP. Thus, the workflow comprises deliberately simplified steps involved throughout the entire process. Once PIC is installed, the workflow of the weather observations is considerably straightforward: (1) an index of a weather station for one year or multiple years is calculated, (2) an index of 52 weather stations from 1951 to 2010 is calculated, and (3) an index of all stations or permafrost stations from 1951 to 2010 is drawn through curve and spatial visualization.

These data have been corrected under specifications for surface meteorological observation and CMA quality control. Daily weather observations are used as the input data for the PIC v1.2 station calculation.

3.2 Atmospheric forcing dataset

The Qinghai-Tibet Engineering Corridor (QTEC), located at the centre of the QTP, was selected in preparing the atmospheric forcing data. Global Land Data Assimilation System (GLDAS, https://ldas.gsfc.nasa.gov) and the weather station data of the surrounding QTEC were merged through spatial interpolation and offset correction to produce a new data set for 1980 to 2010 with a daily 0.1° temporal-spatial resolution. An atmospheric forcing dataset was used as the input data for the PIC v1.2 regional calculation.

3.3 Parameters

The parameters for the ground conditions were based on soil property data and field observations. The parameter data have two sets: one for weather stations and another for the QTEC region. The Harmonized World Soil Database (HWSD, version 1.21) provides information on soil parameters that are available for evaluating soil thermal conductivity with field observations and can be used as input parameters to the PIC v1.2 package (Bicheron et al., 2008; Nachtergaele et al., 2009). The thermal conductivity of ground in a thawed/frozen state, $\lambda_t$ and $\lambda_c$, can be computed through the joint parameterization scheme of the Johansen method (Johansen, 1977) and Luo parameterization (Luo et al., 2009):

\[
\lambda_{dry} = \frac{0.135x_p+64.7}{2700-0.947x_p} 
\]

\[
\lambda_s = -\lambda_q^{\alpha} \times \lambda_0^{1-\alpha} 
\]

\[
\lambda_{sat} = \lambda_\theta^{1-\theta_s} \times \lambda_\theta \theta_s 
\]

\[
S_r = \frac{\theta_r}{\theta_s} 
\]
\[
K_{et} = \frac{K_s \times S_r}{1 + (K_t - 1) \times S_r} \quad (29)
\]
\[
K_{ef} = \frac{K_f \times S_r}{1 + (K_f - 1) \times S_r} \quad (30)
\]
\[
\lambda_t = (\lambda_{sat} - \lambda_{dry})K_{et} + \lambda_{dry} \quad (31)
\]
\[
\lambda_f = (\lambda_{sat} - \lambda_{dry})K_{ef} + \lambda_{dry} \quad (32)
\]

where the soil thermal conductivity of dry soil \(\lambda_{dry}\) depends on dry bulk density \(\rho\), the thermal conductivity of soil solids \(\lambda_s\) varies with the gravel content \(q\), \(\lambda_q\) is the thermal conductivity of quartz (7.7 W m\(^{-1}\) K\(^{-1}\)), \(\lambda_o\) is the thermal conductivity of other minerals (2.0 W m\(^{-1}\) K\(^{-1}\)), and \(q\) is the gravel content in the soil. The saturated soil thermal conductivity \(\lambda_{sat}\) depends on the thermal conductivity of soil solids \(\lambda_s\), liquid water \(\lambda_w\) (0.594 W m\(^{-1}\) K\(^{-1}\)), and the soil saturated water content \(\theta_s\). The degree of saturation \(S_r\) is a function of the soil water content, \(\theta\), and soil saturated water content, \(\theta_s\). The Kersten numbers in the thawed/frozen state, \(K_{et}\) and \(K_{ef}\), are two functions of the degree of saturation \(S_r\), and \(K_t\) and \(K_f\) values in the thawed/frozen state, \(K_t\) and \(K_f\), \(\rho\), \(q\), and \(\theta\) come from the T_BULK_DENSITY, T_GRAVEL, and T_BS fields of the HWSD. \(K_t\) and \(K_f\) in different soil textures can be found in Table 3. Figure 3 shows these parameters over the QTP.

4 Implementation

Step (1) is an optional step. The workflow of the forcing data has only two steps: (1) a total of 4 indices from 1980 to 2010 are calculated, including MAAT, DDF_a, DDF_w, and ALT and (2) the spatial statistic and visualization of these 4 indices are drawn. Table 2 describes most of these functions.

4 Examples

Several examples of the PIC v1.2 use and application were presented here. This section highlights several significant features of the package in terms of specific functions, including station and regional calculation, statistics, and visualization. However, PIC v1.2 includes numerous illustrations from the literature and possible detailed analyses. PIC v1.2
has built-in station data. The data set comprises two tables (data frame), namely, QTP_ATM for daily weather observations and Station_Info for information and parameters in each station. Users can modify or adjust the parameters in the Station_Info and use the data and parameters. Additional examples can be referenced in the GitHub repository. (https://github.com/iffylaw/PIC/blob/master/Examples.R)

4.1 Station calculation

We can use different functions in the R console to perform the calculations based on the selected method. For example, if a user wants to obtain a MAAT value for a certain year of a station, he/she can enter the following command. TempName and data are optional in the MAAT function.

```
MAAT (Year = 1980, TempName = “Temperature”, data = QTP_ATM, SID = 52908)
```

Users can also obtain the MAAT values for a specified period of years in a station.

```
MAAT (Year = 1980:2010, TempName = “Temperature”, data = QTP_ATM, SID = 52908)
```

The “Year” option can be assigned to a number and sequence. The other temperature/depth-related indices can also use the two inputs for the “Year” option. A user can obtain the values of all stations for an index. The “VarName” option can be equal to the function name in the Com_Indices_QTP function. The results can also be saved to a CSV file with column/row names. The case of the input VarName is supported.

```
Com_Indices_QTP (VarName = “MAAT”)
```

Given that the freezing/thawing index can be divided into freezing/thawing degree-days of the air and ground surface, the VarName option should add “_air” or “_ground” at the ends of the Freezing_index and Thawing_index. However, the abbreviation can also be utilized as the option input. The “Thawing_index_air” and “ta” are the same.

```
Com_Indices_QTP (VarName = “Thawing_index_air”)
```
```
Com_Indices_QTP (VarName = “ta”) 
```

After the TTOP indices are computed, the stations that may have permafrost should be determined. The Exist_Permafrost
function can determine and map the stations where permafrost exists. The probability of permafrost occurrence and most likely permafrost conditions are determined from the computing results of the Exist_Permafrost function (see Figure 3).

\begin{align*}
\text{TTOP\_S\_QTP} & \leq \text{Com\_Indices\_QTP (VarName = “TTOP\_Smith”)} \\
\text{TTOP\_K\_QTP} & \leq \text{Com\_Indices\_QTP (VarName = “TTOP\_Kudryavtsev”)} \\
\end{align*}

Exist_Permafrost (plot = “yes”)  

The QTP measurements have constantly been difficult. The data set has several null and anomalous values, as well as leading to a few anomalous values in computing the indices. Accordingly, these outlier values should be processed. The Outlier_Process function seeks the outlier values and sets these values to null values thereafter, which is an option because abnormal values have been processed in the Com\_Indices\_QTP.

\begin{align*}
\text{Outlier\_Process (MAAT\_QTP[,1:stations])}
\end{align*}

4.2 Region calculation

A total of four indices, including MAAT, DDF, DDT, and ALT, can be computed with the atmospheric forcing data set in the PIC package v1.2. This package supports the NetCDF format data; thus, the package reads and writes a NetCDF file to support computing. The input NetCDF files require a few forcing and parameter data. After the calculations, a user can compute the spatial statistics and draw the index changes through a GIF animation (see Sections 4.3 and 4.4).

\begin{align*}
\text{Spatial\_Pic (NetCDFName = “PIC\_indices.nc”, StartYear = 1980, EndYear = 2010)}
\end{align*}

4.3 Statistics

The stat function contains all the statistical methods for station calculation. The PIC package v1.2 provides two statistical calculations to compute the statistical values of all stations using Com\_Stats\_QTP: (1) the indices that vary with the change in the year and (2) the comparison of the same two indices for different computational methods. Options ind1 and ind2 were used; however, ind2 can be disregarded when computing the statistical values between a single datum and years.
TTOP and ALT were calculated utilizing two different functions, so these two indices should be compared. For example, the two TTOP values for all QTP stations are compared. A user can assign ind1 and ind2 to compute the ALT statistical values between the Stefan and Kudryavtsev functions. Thereafter, the statistical values are saved to the CSV file when executing the Com_Stats_QTP function. Table 3 shows all the statistical values of the selected stations.

<table>
<thead>
<tr>
<th>Function</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Com_Stats_QTP (ind1 = MAAT_QTP)</td>
<td>TTOP and ALT were calculated utilizing two different functions, so these two indices should be compared. For example, the two TTOP values for all QTP stations are compared. A user can assign ind1 and ind2 to compute the ALT statistical values between the Stefan and Kudryavtsev functions. Thereafter, the statistical values are saved to the CSV file when executing the Com_Stats_QTP function. Table 3 shows all the statistical values of the selected stations.</td>
</tr>
<tr>
<td>Com_Stats_QTP (ind1 = TTOP_S_QTP, ind2 = TTOP_K_QTP)</td>
<td></td>
</tr>
<tr>
<td>Com_Stats_QTP (ind1 = ALT_S_QTP, ind2 = ALT_K_QTP)</td>
<td></td>
</tr>
</tbody>
</table>

A spatial trend can also be computed using the Spatial_Stat function after the regional calculation. The function simultaneously saves the spatial trend of the five indices into the NetCDF file. In addition, the function draws the animation of the spatial trend (see Section 4.4).

**4.4 Visualization**

Station visualization can be produced by Plot_TTOP_ALT and Plot_3M. The Plot_TTOP_ALT function plots two TTOP or two ALT indices in a figure for all stations or stations with permafrost. VarName has the “TTOP” and “ALT” options, whereas SID has the “permafrost” and “all” options. The Plot_3M function draws the MAAT, MAGST, and MAGT indices. The two functions plot only the stations where permafrost exists when SID = “permafrost.”

```r
Plot_TTOP_ALT (VarName = “TTOP”, SID = “permafrost”)
Plot_TTOP_ALT (VarName = “ALT”, SID = “permafrost”)
Plot_3M(SID = “permafrost”)
```

The other approach of “ggplot2” was adopted to visualize the region (see Figure 4).

```r
ggplot_Pic (Type = “TTOP”, SID = “permafrost”)
```

The indices that change over time can also be plotted through a GIF animation that uses Map_Pic (Figure 5).

```r
Plot_TTOP_ALT (VarName = “TTOP”, SID = “permafrost”)
Plot_TTOP_ALT (VarName = “ALT”, SID = “permafrost”)
Plot_3M(SID = “permafrost”)
```
The input and output of the regional calculation can be drawn using the Netcdf_Multiplot function (see Figure 6). the Netcdf_Animation function, which uses animation to display these values. The spatial trend can also be drawn in the Spatial_Stat apart from calculating the spatial statistics. This function draws all four indices when “VarName” has no input (see Figure 2).

Netcdf_Multiplot (NetCDFName = “PIC_indices.nc”, VarName = “ALT”)
Netcdf_Animation (NetCDFName = “PIC_indices.nc”, VarName = “ALT”)
Spatial_Stat (“PIC_indices.nc”)

5 Discussion
5.1 PIC performance

This study proposes permafrost modelling to compute the changes in the active layer and permafrost with the climate, which considers the station and regional modelling. over the QTP. We apply the two approaches to 52 weather stations and a central region of the QTP. The PIC v1.2 simulation results from using the 52 stations' Exist_Permafrost function show that permafrost was detected at 12 stations based on the 52 observation stations. For QTEC, the Figure 4. The permafrost areas began to shrink from the southern and northern parts to the central QTEC region. (Figure 7). The permafrost, whether in permafrost stations or QTEC, continued to thaw with decreasing ALT, low surface offset and thermal offset, and high MAAT, MAGST, MAGT, and TTOP for most areas of QTP.

The PIC package v1.2 computes and maps the temporal dynamics and spatial distribution of permafrost in the stations and region. The regional modelling underwent more challenges than the stations’ input data and parameters. The station calculation can estimate the long-term temporal trend of the permafrost dynamics, whereas the regional calculation can estimate the temporal–spatial trend. Climate change indicates a pronounced warming and permafrost degradation in QTP.
The simulation results show widespread permafrost degradation in QTP, and the temporal–spatial trends of the permafrost conditions in QTP were consistent with those in previous studies (Wu and Zhang, 2010; Wu et al., 2010). In addition, the simulated TTOP and ALT that uses the Stefan and Smith functions have higher TTOP and ALT than the Kudryavtsev function. Although the overall trend of TTOP and ALT are coincident, the two different computational methods can be combined to simulate their variations. Furthermore, 16 indices can be collectively employed for a comprehensive analysis. Moreover, the station and regional calculation can be integrated to evaluate the temporal–spatial evolution of permafrost in the QTP. In particular, the station modeling can be applied to validate the simulated results of the region. Moreover, the regional calculation can extend from QTEC to the entire QTP and even the other permafrost regions.

The “for” loop is discarded, whereas the “apply” functions are used extensively to significantly lower the computation time. The current regional calculation only takes approximately 11 s. Apart from the Kudryavtsev model that requires considerable computation time (i.e., approximately 5 min), the station calculation also exhibited an improved efficiency. Therefore, PIC v1.2 can be considered an efficient R package.

Climate change indicates a pronounced warming and permafrost degradation in the QTP with active layer deepening (Chen et al., 2013; Cheng and Wu, 2007b; Wu and Zhang, 2010; Wu et al., 2010), and both the simulation of stations and the region in PIC v1.2 also show widespread permafrost degradation (Figures 4-8). Meanwhile, as shown in Figures 7 & 8, the permafrost in the QTEC also continued to thaw, with the ALT growing. The QTEC is the most accessible area of the QTP. Most boreholes were drilled in the QTEC to monitor changes of permafrost conditions, and this monitoring data provides support for model performance evaluation. Meanwhile, ALT was widely used, so we adopted the permafrost index to estimate PIC v1.2 simulation performance. The simulated PIC v1.2 ALT and previous literature in the QTEC are compared in Table 5. The
increasing rate of ALT averaged 0.50-7.50 cm yr\(^{-1}\). The rate during the 1990s to 2010s was greater at more than 4.00 cm yr\(^{-1}\) than during 1980 to the 1990s, at approximately 2.00 cm yr\(^{-1}\). Though both the observed and the simulated ALT and its variation in different locations of the QTEC were still relatively large, the ALT trend in PIC v1.2 was close to the observations and simulation in the QTEC. In recent decades, the permafrost thaw rate has increased significantly. The majority of observed ALT and its trend along the QTH and QTR were greater than the simulated grid ALT of PIC v1.2, mainly because the observation sites are near these engineering facilities. These comparative analyses suggest that the temporal-spatial trends of permafrost conditions in the QTEC using PIC v1.2 were consistent with previous studies. More importantly, the difference between simulation results highlights the importance of transparency and reusability of models, data, parameters, simulation results and so on.

### 5.2 Advantages

Previous studies in the QTP (1) used one or two indices, such as MAAT and MAGST, to evaluate the permafrost changes (Yang et al., 2010); (2) presented a static permafrost distribution that constructed a regression analysis method through the relationship between MAGT and elevation, latitude, and slope-aspects that presented a static permafrost distribution (Lu et al., 2013; Nan, 2005; Yin et al., 2017); and (3) did not share the model data and codes; hence, other researchers could not validate their results and conduct further study based on previous research results (McNutt, 2014). Compared with the previous permafrost modeling on the QTP, the PIC package v1.2 is considerably open, easy, intuitive, and reproducible for integrating data and most of the temperature/depth-related indices. The PIC v1.2 function supports the computation of multiple indices and different time periods, and the encoding mode is reusable and universal. This package can also be easily adopted to intuitively display the changes in the active layer and permafrost, as well as assess the impact of climate change.

The PIC v1.2 workflow is extremely simple and requires only one or two steps to obtain the simulated results and visual images. All running examples, data and code can be obtained from the GitHub repository. However, the permafrost modeling integrates satellite remote sensing data, gridded meteorological dataset, soil database, weather and field observations, parameters, and multiple functions and models, and supports dynamic change of parameters, parameter...
changes such as vegetation and ground condition changes. Over 50 QTP weather stations of QTP were introduced, which and they can approximately partially resolve the spatial change directions of the permafrost area. The QTEC region is an example of spatial modeling, which classifies land cover and topographic features to determine the input spatial input parameters. Spatial modeling also uses the GLDAS satellite temporal-spatial data to provide spatially detailed information of the active layer and permafrost. The QTEC region is an example of spatial modeling, which classifies land cover and topographic features to determine the input spatial parameters. Spatial modeling also uses the GLDAS satellite temporal-spatial data to provide spatially detailed information of the active layer and permafrost.

The QTEC region is an example of spatial modeling, which classifies land cover and topographic features to determine the input spatial parameters. Spatial modeling also uses the GLDAS satellite temporal-spatial data to provide spatially detailed information of the active layer and permafrost. The QTEC region is an example of spatial modeling, which classifies land cover and topographic features to determine the input spatial parameters. Spatial modeling also uses the GLDAS satellite temporal-spatial data to provide spatially detailed information of the active layer and permafrost.

The QTEC region is an example of spatial modeling, which classifies land cover and topographic features to determine the input spatial parameters. Spatial modeling also uses the GLDAS satellite temporal-spatial data to provide spatially detailed information of the active layer and permafrost.

5.3 Limitations and uncertainties

PIC v1.2 was developed with numerous indices, as well as support station and regional simulation. The PIC package v1.2 can be used to estimate the frozen soil status and possible changes over the QTP by calculating permafrost indices. This package has many engineering applications and can be used to assess the impact of climate change on permafrost. Moreover, this package provides observational data and provides the ability of a comprehensive analysis through the ability for multiple indices. The probability of permafrost occurrence and the most likely permafrost conditions are determined by computing the 16 indices. Although PIC v1.2 quantitatively integrates most of these indices, it still has several limitations and uncertainties. First, the regional calculation is one-dimensional and assumes that each grid cell is uniform without the water–heat exchange. Second, the heterogeneity in ground conditions of the QTP also brings along uncertainties of parameter preparation. Third, soil moisture changes at different depths affects the thermal conductivity and thermal capacity of the soil (Shanley and Chalmers, 1999; Yi et al., 2007); thus, thus, the soil input parameters should be dynamically changed. Lastly, climate forcing has several uncertainties (Zhang et al., 2014; Zhang et al., 2014), including input air and ground temperatures (i.e., the quality of the ground temperature in the QTP
is currently unreliable; thus, the regional calculation supports fewer indices than the station calculation. These deficiencies can be significant for the permafrost dynamics with environmental evolution.

6. Conclusions

An R package PIC v1.2 that computes the temperature/depth-related permafrost indices with daily weather observations and atmospheric forcing has been developed. This package is open source software and can be easily used with input data and parameters, and that users can customize their own data and parameters. A total of 16 permafrost indices for stations and the region are currently developed, and datasets of 52 weather stations and a central region of the QTP were prepared. Permafrost modelling and data are integrated into the PIC v1.2 R package PIC to simulate the temporal-spatial trends of permafrost with the climate estimate and estimate the status of the active layer and permafrost in the QTP. The current functionalities also include time-series statistics, spatial statistics, and visualization. Multiple visual manners display the temporal and spatial variability of the stations and the region. The package produces high-quality graphics that illustrate the status of frozen soil and may be used for subsequent publication in scientific journals and reports. The data sets of the 52 weather stations and a central region of QTP were prepared and simulated to evaluate the temporal-spatial change trends of permafrost with the climate. The simulated PIC v1.2 results generally indicate that the temporal—spatial trends of permafrost conditions essentially agree with previously published studies. The transparency and repeatability of the PIC v1.2 package has many engineering applications and its data can be used to assess the impact of climate change on permafrost. Additional features may be implemented in future releases of PIC to broaden its application range. In the future, the observational data of the active layer will be integrated into the PIC data sets, and the output simulation results will be compared with the observation data. The PIC package env1.2 will also be used to predict the future state of permafrost by utilizing projected climate forcing and scenarios. Additional functions and models will be absorbed into PIC to improve the simulation performance and perform comparative analyses with other functions and models. Parallel computation will be added to the PIC package to improve the computation efficiency. The key impact that PIC v1.2 is expected to provide
the open community is an increase in consistency within, and comparability among, studies. Furthermore, we encourage contributions from other scientists and developers, including suggestions and assistance, to modify and improve the proposed PIC package v1.2.

Code availability

The PIC v1.2 code that supports the findings of this study is stored within the GitHub repository (https://github.com/iffylaw/PIC).

Data availability

The data are included in the Supplement files or GitHub repository.

Competing interests

The authors declare no competing financial interests.

Acknowledgements

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Figure 1: Map of the data location over the QTP.
Figure 2: Mind map of the R package PIC v1.2.

Table 1: Most important user functions in the R package PIC v1.2. The equation column of this table corresponds to the equation in Section 2.

<table>
<thead>
<tr>
<th>R function</th>
<th>Equation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature-related indices</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freezing index</td>
<td>(4, 6)</td>
<td>Freezing degree-days for air and ground</td>
<td>°Cday</td>
</tr>
<tr>
<td>Thawing index</td>
<td>(3, 5)</td>
<td>Thawing degree-days for air and ground</td>
<td>°Cday</td>
</tr>
<tr>
<td>MAAT</td>
<td>(7)</td>
<td>Mean annual air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>MAGST</td>
<td>(8)</td>
<td>Mean annual ground surface temperature (5 cm)</td>
<td>°C</td>
</tr>
<tr>
<td>MAGT</td>
<td>(10)</td>
<td>Mean annual ground temperature (at 15 m)</td>
<td>°C</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT (11)</td>
<td>Thawing n factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NF (12)</td>
<td>Freezing n factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Offset</td>
<td>The difference between the MAGST and MAAT °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Offset</td>
<td>The difference between the TTOP and MAGST °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetation Offset</td>
<td>The second term (Surface_Offset) is negative and represents the reduction in MAGST due to vegetation effects in summer (vegetation offset).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The first term (Surface_Offset) on the right-hand-side is positive and represents the elevation of MAGST over MAAT due to the insulating effect of winter snow cover (nival offset).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nival Offset</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTOP_Smith (13)</td>
<td>The temperature at the top of the permafrost using Smith &amp; Riseborough function °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTOP_Kudryavtsev (14)</td>
<td>The temperature at the top of the permafrost using Kudryavtsev function °C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Depth-related indices**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze_depth_Stefan (20)</td>
<td>Maximum freezing depth using Stefan function m</td>
</tr>
<tr>
<td>Thaw_depth_Stefan (16)</td>
<td>Active layer thickness using Stefan function m</td>
</tr>
<tr>
<td>ALT_Kudryavtsev (19)</td>
<td>Active layer thickness (ALT) or maximum thawing depth using Kudryavtsev function m</td>
</tr>
</tbody>
</table>

**Region**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial_Pic (3,4,7,16)</td>
<td>Spatial changes with MAAT, DDTₐ, DDFₐ and ALT m</td>
</tr>
</tbody>
</table>

**Toolkit**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Com_Indices_QTP</td>
<td>Computing all indices for all stations of the QTP</td>
</tr>
<tr>
<td>Outlier_Process</td>
<td>Process the abnormal value</td>
</tr>
<tr>
<td>VLH (2)</td>
<td>Computing volumetric latent heat of fusion J/m³</td>
</tr>
<tr>
<td>Convert_4_geplot</td>
<td>Convert the values of TTOP &amp; ALT to one column</td>
</tr>
<tr>
<td>Exist_Permafrost</td>
<td>To determine the stations where permafrost exist by TTOP values</td>
</tr>
</tbody>
</table>

**Statistic**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat (21,22,23)</td>
<td>Statistical functions with 10 more methods</td>
</tr>
<tr>
<td>Spatial_Stat (24)</td>
<td>Spatial statistical method, just for spatial trend</td>
</tr>
<tr>
<td>Com_stats_QTP</td>
<td>Computing the statistical values for one or both of these indices</td>
</tr>
</tbody>
</table>

**Visualization**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
</table>
Table 2: Input data and parameters.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Meaning</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Daily mean air temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>Tmax</td>
<td>Daily maximum air temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>Tmin</td>
<td>Daily Minimum air temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>GT</td>
<td>Daily mean ground temperature in 0 cm</td>
<td>ºC</td>
</tr>
<tr>
<td>GT_0_MAX</td>
<td>Daily maximum ground temperature at 0 cm</td>
<td>ºC</td>
</tr>
<tr>
<td>GT_0_MIN</td>
<td>Daily minimum ground temperature at 0 cm</td>
<td>ºC</td>
</tr>
<tr>
<td>temp</td>
<td>Spatial daily mean air temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>( \lambda_t )</td>
<td>Thermal conductivity of ground in thawed state</td>
<td>W/m ºC K</td>
</tr>
<tr>
<td>( \lambda_f )</td>
<td>Thermal conductivity of ground in frozen state</td>
<td>W/m ºC K</td>
</tr>
<tr>
<td>L</td>
<td>Latent heat of fusion</td>
<td>J/m³</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Dry bulk density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>W</td>
<td>Soil water content in thawed state</td>
<td>%</td>
</tr>
<tr>
<td>( W_u )</td>
<td>Soil unfrozen water content in frozen state</td>
<td>%</td>
</tr>
<tr>
<td>( P_{\infty} )</td>
<td>period of the temperature wave, adjusted for snow melt</td>
<td>s</td>
</tr>
<tr>
<td>( C_T )</td>
<td>Volumetric heat capacity during thawing</td>
<td>J/m³</td>
</tr>
</tbody>
</table>
Figure 1: Map of the data location over QTP.
Figure 2: Mind map of the R package PIC.

Table 2: Most important user functions in the R package PIC. The equation of this table corresponds to the equation in Section 2.2.

<p>| Table 3: Parameters of thermal conductivity in the thawed/frozen state. The UADS Code came from soil texture classification of United States Department of Agriculture (USDA). The Qinghai-Tibet Plateau does not have the 1 and 8 of soil classification codes. θ: soil water content; $K_t$: thermal conductivity of soil solid in thawed state; $K_f$: thermal conductivity of soil solid in frozen state. |</p>
<table>
<thead>
<tr>
<th>R function</th>
<th>USDA Code</th>
<th>Description and reference Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>Temperature-related indices</td>
<td>Freezing_index</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>clay(heavy)</td>
<td>0.17</td>
<td>1.90</td>
</tr>
<tr>
<td>1</td>
<td>0.17</td>
<td>1.90</td>
</tr>
<tr>
<td>2</td>
<td>silty clay</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>clay (light)</td>
<td>0.17</td>
</tr>
<tr>
<td>Freezing_indexA</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Thawing_indexB</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>freezing degree days for air and ground</td>
<td>silty clay loam</td>
</tr>
<tr>
<td>5</td>
<td>thawing degree days for air and ground clay loam</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>silt</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>MAAT</td>
<td>0.17</td>
</tr>
<tr>
<td>8</td>
<td>MAGST</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>MAGT</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>sandy clay loam</td>
<td>0.15</td>
</tr>
<tr>
<td>11</td>
<td>NF11</td>
<td>0.15</td>
</tr>
<tr>
<td>12</td>
<td>NF12</td>
<td>0.06</td>
</tr>
</tbody>
</table>
### Factor

| Surface_Offset | The difference between the MAGST and MAAT °C |
| Thermal_Offset | The difference between the TTOP and MAGST °C |
| Vegetation_Offset | The second term (Surface_Offset) is negative, and represents the reduction in MAGST due to vegetation effects in summer (vegetation offset). |
| Nival_Offset | The first term (Surface_Offset) on the right-hand side is positive, and represents the elevation of MAGST over MAAT due to the insulating effect of winter snow cover (nival offset). |

### TTOP

- **TTOP-Smith**: The temperature at the top of the permafrost using Smith & Riseborough function
  - $0.06 \pm 0.01$ (13)
  - $4.60 \pm 1.70$
- **TTOP-Kudryavtsev**: The temperature at the top of the permafrost using Kudryavtsev function
  - $-0.06 \pm 0.01$ (14)

### Depth-related indices

- **Freeze_depth_Stefan**: Maximum freezing depth using Stefan function
- **Thaw_depth_Stefan**: Active layer thickness using Stefan function
- **ALT_Kudryavtsev**: Active layer thickness (ALT) or maximum thawing depth using Kudryavtsev function

### Region

- **Spatial_Piec**: Spatial changes with MAAT, DDF, DDF, and ALT m (3, 4, 7, 16)

### Toolkit

- **Stat**: Statistic functions with more than 10 methods
- **VLH**: Computing volumetric latent heat of fusion J/m³ (2)
- **Convert_2_ggplot**: A function to determine which stations exists permafrost by TTOP values.
<table>
<thead>
<tr>
<th>Spatial_Stat</th>
<th>Spatial statistic method, just for spatial trend (24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Com_State_QTP</td>
<td>Computing the statistic values for one or both of these indices</td>
</tr>
<tr>
<td><strong>Visualization</strong></td>
<td></td>
</tr>
<tr>
<td>Plot_3M</td>
<td>Plot MAAT, MAGST, and MAGT for all stations or a station</td>
</tr>
<tr>
<td>Plot_TTOP_ALT</td>
<td>Plot TTOP and ALT for all stations or a station</td>
</tr>
<tr>
<td>ggplot_Pic</td>
<td>Plot multiple indices all stations or a station using ggplot2</td>
</tr>
<tr>
<td>Map_Pic</td>
<td>Plot multiple indices all stations or a station using ggmap</td>
</tr>
<tr>
<td>Netcdf_Multiplot</td>
<td>Region visualization of NetCDF with multiple plots</td>
</tr>
<tr>
<td>Netcdf_Animation</td>
<td>Region animation of NetCDF</td>
</tr>
</tbody>
</table>
Figure 3: Spatial parameters for PIC v1.2 over the Qinghai-Tibet Plateau. (a) soil texture classification based on HWSD data; (b) dry bulk density $\rho$; (c) saturated water content $\theta_s$; (d) thermal conductivity of dry soil $\lambda_{dry}$; (e) thermal conductivity of soil solids $\lambda_s$; (f) saturated soil thermal conductivity $\lambda_{sat}$; (g) thermal conductivity of ground in thawed state $\lambda_t$; (h) thermal conductivity of ground in frozen state $\lambda_f$. 
Figure 4: Permafrost occurrence map. Google Maps is as a base map that uses the Exist_Permafrost function. “Other” indicates the seasonal frozen soil.

Table 34: The statistical values of TTOP apply Com_Stats_QTP for the stations where permafrost exists. SD_S_intercept: \( y \)-intercept; Slope: slope of regression line; R: Pearson's correlation coefficient; \( R^2 \): coefficient of determination; RMSE: root mean squared error; NRMSE: normalized RMSE; SD_S: the standard deviation of TTOP that uses the Stefan function; whereas SD_K_intercept: the standard deviation of TTOP that uses the Kudryavtsev function; MEF: modelling efficiency; NAE: normalized average error; VR: variance ratio; PBIAS: percent bias; NSE: Nash-Sutcliffe efficiency; RSR: RMSE-observations standard deviation ratio; and D: index of agreement.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Tuole</th>
<th>Wudaoliang</th>
<th>Anduo</th>
<th>Maduo</th>
<th>Qingshuihe</th>
<th>Shiqu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.69</td>
<td>-0.4</td>
<td>-0.59</td>
<td>-0.9</td>
<td>-1.24</td>
<td>-1.47</td>
</tr>
<tr>
<td>Slope</td>
<td>1.11</td>
<td>1.16</td>
<td>1.2</td>
<td>1.19</td>
<td>0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>R</td>
<td>0.97</td>
<td>0.96</td>
<td>0.97</td>
<td>0.97</td>
<td>0.96</td>
<td>0.86</td>
</tr>
<tr>
<td>R²</td>
<td>0.94</td>
<td>0.92</td>
<td>0.93</td>
<td>0.94</td>
<td>0.92</td>
<td>0.75</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.83</td>
<td>0.86</td>
<td>0.83</td>
<td>1.24</td>
<td>1.06</td>
<td>1.5</td>
</tr>
<tr>
<td>NRMSE</td>
<td>-0.85</td>
<td>-0.34</td>
<td>-1.23</td>
<td>-0.78</td>
<td>-0.52</td>
<td>-3.17</td>
</tr>
<tr>
<td>SD_S</td>
<td>0.59</td>
<td>0.8</td>
<td>0.78</td>
<td>0.61</td>
<td>1</td>
<td>0.69</td>
</tr>
<tr>
<td>SD_K</td>
<td>0.6</td>
<td>0.66</td>
<td>0.78</td>
<td>0.66</td>
<td>0.6</td>
<td>0.69</td>
</tr>
<tr>
<td>MEF</td>
<td>-0.85</td>
<td>0.03</td>
<td>-0.06</td>
<td>-2.7</td>
<td>0.07</td>
<td>-3.09</td>
</tr>
<tr>
<td>NAE</td>
<td>0.89</td>
<td>0.39</td>
<td>1.38</td>
<td>0.86</td>
<td>0.65</td>
<td>3.35</td>
</tr>
<tr>
<td>VR</td>
<td>1.03</td>
<td>0.68</td>
<td>1</td>
<td>1.14</td>
<td>0.35</td>
<td>1</td>
</tr>
<tr>
<td>PBIAS</td>
<td>-76.13</td>
<td>-26.54</td>
<td>-108.59</td>
<td>-67.31</td>
<td>-41.42</td>
<td>-255.56</td>
</tr>
</tbody>
</table>

**Indices**

- **slope**: Slope
- **R**: Correlation coefficient
- **R²**: Coefficient of determination
- **RMSE**: Root mean squared error
- **NRMSE**: Normalized root mean squared error
- **SD_S**: Standard deviation of slope
- **SD_K**: Standard deviation of K
- **MEF**: Model efficiency factor
- **NAE**: Nash-Sutcliffe efficiency
- **VR**: Verification ratio
- **PBIAS**: Percent bias
- **MSE**: Mean squared error
- **RSR**: Relative standard reduction
- **D**: Coefficient of determination

The table above shows the performance metrics for different indices and scenarios, with columns indicating TTOP (Kudryavtsev) and TTOP (Smith & Ristoborough) for various sites such as Anduo, Bange, Gangcha, Matuo, Menyuan, Qinghuhe, Seda, Shiqu, Tule, Wuqiaoliang, Yenigou, and Zaduo. The figures illustrate the temporal trends of these indices over the years from 1950 to 2010.
Figure 45: TTOP that uses the Smith and Kudryavtsev functions.

Figure 56: Index changes over time for MAAT. These graphs are animated in GIF mode.
Figure 67: Regional visualization of ALT.
Figure 78: Spatial trend of MAAT, $DDT_a$, $DDFa$, and ALT.

Table 5. The active layer thickness (ALT) and its trend between the PIC v1.2 simulation and literature analysis in the Qinghai-
<table>
<thead>
<tr>
<th>Mean ALT (m)</th>
<th>ALT Scope (m)</th>
<th>ALT trend (cm yr⁻¹)</th>
<th>Period</th>
<th>Location</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.03</td>
<td>0.97-3.87</td>
<td>2.89</td>
<td>1980-2010</td>
<td>The whole QTEC</td>
<td>PIC v1.2</td>
</tr>
<tr>
<td>2.18</td>
<td>1.00-3.20</td>
<td>1.33</td>
<td>1981-2010</td>
<td>Near the Qinghai-Tibet highway along the QTEC</td>
<td>Li et al. (2012)</td>
</tr>
<tr>
<td>—</td>
<td>1.00-3.00</td>
<td>0.50-2.00; 3.00-5.00 (1990s-2001)</td>
<td>1980-2001</td>
<td>Simulation along the Qinghai-Tibet Highway/Railway</td>
<td>Oelke and Zhang (2007)</td>
</tr>
<tr>
<td>—</td>
<td>1.30-3.50</td>
<td>—</td>
<td>—</td>
<td>Near the Qinghai-Tibet highway along the QTEC</td>
<td>Pang et al. (2009)</td>
</tr>
<tr>
<td>—</td>
<td>2.00-2.60</td>
<td>2.14-7.14</td>
<td>1991-1997</td>
<td>1 site (35°43′N, 94°05′E) Near the Qinghai-Tibet highway along the QTEC</td>
<td>Cheng and Wu (2007a)</td>
</tr>
<tr>
<td>—</td>
<td>1.84-3.07</td>
<td>—</td>
<td>1990s</td>
<td>17 Monitoring sites near the Qinghai-Tibet Highway/Railway along the QTEC</td>
<td>Jin et al. (2008)</td>
</tr>
<tr>
<td>2.41</td>
<td>1.32-4.57</td>
<td>7.50</td>
<td>1995-2007</td>
<td>10 Monitoring sites Near the Qinghai-Tibet highway along the QTEC</td>
<td>Wu and Zhang (2010)</td>
</tr>
<tr>
<td>2.40</td>
<td>1.61-3.38</td>
<td>4.26</td>
<td>2002-2012</td>
<td>10 Monitoring sites (34°49′N, 92°55′E) along the QTEC</td>
<td>Wu et al. (2015)</td>
</tr>
</tbody>
</table>