

# The physical properties of coarse fragment soils and their effects on permafrost dynamics: A case study on the central Qinghai-Tibetan Plateau

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**Abstract.** Soils on the Qinghai-Tibetan Plateau (QTP) have distinct physical properties from agricultural soils due to weak weathering and strong erosion. These properties might affect permafrost dynamics. However, few studies have investigated both quantitatively. In this study, we selected a permafrost site on the central region of the QTP and excavated soil samples down, to 200 cm. We measured soil porosity, thermal conductivity, saturated hydraulic conductivity and matric potential in the laboratory. Finally, we ran a simulation model replacing default sand or loam parameters with different combinations of these measured parameters. Our results ~~from the soil profile~~ showed that coarse fragment soils (diameter >2 mm) were ~55% on average, soil porosity was less than  $0.3 \text{ m}^3 \text{ m}^{-3}$ , saturated

1 hydraulic conductivity ranged from 0.004-0.03 mm s<sup>-1</sup>, and saturated matric potential ranged  
2 from -14 to -604 mm. When default sand or loam parameters were substituted with these  
3 measured values, the model errors of soil temperature, soil liquid water content, active layer  
4 depth and permafrost lower boundary were reduced. The root mean squared errors of active  
5 layer depths simulated using measured parameters versus the default sand and loam  
6 parameters were about 0.28, 1.06, 1.83 m, respectively. Among these measured parameters,  
7 porosities played a dominant role in reducing model errors and were much smaller than for  
8 soil textures used in land surface models. We also demonstrated that soil water dynamic  
9 processes should be considered, rather than using static properties under frozen and unfrozen  
10 soil states as in most permafrost models. We conclude that it is necessary to consider the  
11 distinct physical properties of coarse-fragment soils and water dynamics on the QTP when  
12 simulating dynamics of permafrost. Thus it is important to develop methods for systematic  
13 measurement of physical properties of coarse fragment soils and to develop a related spatial  
14 dataset for porosity.

15 **Key words:** Terrestrial Ecosystem Model; Active layer; Sensitivity test; Soil temperature;  
16 Soil water content; Porosity; Coarse fragment soils

## 17 1 Introduction

18 Permafrost underlies 25% of Earth's surface. Degradation of permafrost has been reported  
19 extensively in Alaska, Siberia and the Qinghai-Tibetan Plateau (QTP; Boike et al., 2013;  
20 Jorgenson et al., 2006; Wu and Zhang, 2010). Permafrost thaw has global impacts by  
21 releasing large quantities of soil carbon previously preserved in a frozen state and enhancing  
22 concentrations of atmospheric greenhouse gases, which will promote further atmospheric  
23 warming and degradation of permafrost (Anisimov, 2007; McGuire et al., 2009). Permafrost  
24 dynamics also have local to regional impacts on ecosystems by altering soil thermal and  
25 hydrological regimes (Salmon et al., 2015; Wang et al., 2008; Wright et al., 2009; Ye et al.,  
26 2009; Yi et al., 2014a). In addition, degradation of permafrost affects infrastructure, such as  
27 QTP railways and roads (Wu et al., 2004) or the Trans-Alaska Pipeline System in Alaska  
28 (Nelson et al., 2001). Therefore, it is critical to develop mitigation and adaptation strategies in  
29 permafrost regions for ongoing climate change. Accurate projection of the degree of  
30 permafrost degradation is a prerequisite for developing these strategies.

31 Significant effort has been made to improve modeling accuracy and efficiency of

1 permafrost dynamics along two primary lines of inquiry. One is to create suitable freezing and  
2 thawing algorithms for different applications, including land surface models (Chen et al.,  
3 2015; Oleson et al., 2010; Wang et al., 2017), permafrost models (Goodrich, 1978; Langer et  
4 al., 2013; Qin et al., 2017), and other related models (Fox, 1992; Woo et al., 2004). The other  
5 line of inquiry is focused on schemes of soil physical properties (Chen et al., 2012; Zhang et  
6 al., 2011), which play a critical role in permafrost dynamics. For example, porosity  
7 determines the maximum amount of water that can be contained in a soil layer, thermal  
8 properties determine the heat conduction within soil layers, and hydraulic properties  
9 determine the exchange of soil water between soil layers. The soil water content also  
10 determines the large amount of latent heat lost or gained by freezing or thawing, respectively.  
11 On the QTP, soil is coarse due to weak weathering and strong erosion (Arocena et al., 2012).  
12 Soils with gravel content (particle diameter >2 mm) have been reported in several studies  
13 (Chen et al., 2017; Du et al., 2017; Qin et al., 2015; Wang et al., 2011; Wu et al., 2016; Yang  
14 et al., 2009). These soil properties are likely different from those used in current modeling  
15 studies (Wang et al., 2013). For example, soil properties in Community Land Model are  
16 calculated from fractions of sand, silt and clay based on measurements of agriculture soils  
17 (Oleson et al., 2010). However, physical properties of coarse-fragment soils on the QTP and  
18 their effects on permafrost dynamics are under studied (Pan et al., 2017).

19 In this case study we investigated the characteristics of soil physical properties at a site on  
20 the central QTP and their effects on permafrost dynamics. We first measured soil physical  
21 properties of excavated soil samples in a laboratory. We then conducted a sensitivity analysis  
22 with an ecosystem model by substituting the default soil physical properties with those that  
23 we measured. We aimed to emphasize the effects of coarse fragment content on soil physical  
24 properties and on permafrost dynamics, rather than develop general schemes of soil physical  
25 properties for using in modeling studies on the QTP.

## 26 **2 Methods**

### 27 **2.1 Site description**

28 The site (34°49'46.2" N, 92°55'56.58" E, 4,628m.a.s.l.) is located in the Beiluhe basin, in the  
29 continuous permafrost region of the central QTP (Figure 1a, Zou et al. 2017). Based on the  
30 map of Li et al. (2015), soils of this region belong to Gelisols and Inceptisols, which occupy  
31 34% and 28% of the total area of permafrost region of the QTP, respectively. Land surface  
32 types include alpine meadow, alpine steppe, barren surface and thermokarst lakes (Figure 1b;

1 Lin et al., 2011).

2 The site is on top of upland plain landforms, which are formed from fluvial and deluvial  
3 sediments. The surficial sediments are dominated by fine to gravelly sands and stones (Figure  
4 2; Yin et al., 2017). Soils at this site are Inceptisols (Dr. Wangping Li, Lanzhou University of  
5 Technology, personal communication) that are commonly underlain by mudstone. The plant  
6 community type is mainly alpine meadow which is dominated by monocotyledonous species,  
7 primarily Poaceae and Cyperaceae. The dominant species are *Kobresia pygmaea*,  
8 accompanied *Elymus nutans*, *Carex moorcroftii*, *Oxytropis pusilla*, *Tibetia himalaica*,  
9 *Leontopodium nanum*, and *Androsace tapete* (Figure 2c-e).

10 A weather station was set up in 2002 (Figure 2a) to measure air temperature and relative  
11 humidity (2.2m, HMP45C-L11-/L36, Campbell Scientific Inc.), solar radiation (MS-102,  
12 EKO, Japan), and precipitation (QMR102, Vaisala Company). Soil temperatures were  
13 measured at depths of 5, 10, 20, 40, 80, and 160 cm using a PT-100 (EKO, Japan); soil  
14 moistures were measured at depths of 20, 40, 80, and 160 cm using a CS616-L50 (EKO,  
15 Japan). A CR3000 data logger (Campbell Scientific Inc., USA) was used to store these data at  
16 30 minute intervals. These readings were averaged or summed (e.g. precipitation) into  
17 monthly values to drive and validate the model. Based on measurements, multi-year mean  
18 annual air temperature, precipitation, downward solar radiation and relative humidity were -  
19 3.61 °C, 365.7 mm, 206.3 W m<sup>-2</sup> and 51.1%, respectively (Figure 3). The multi-year mean  
20 summer (June to August) air temperature and precipitation were 5.27 °C and 248.3 mm,  
21 respectively. The multi-year mean winter (December to February) air temperature and  
22 precipitation were -12.44 °C and 5.3 mm, respectively. The multi-year mean annual, summer,  
23 and winter soil temperatures at 40 cm were 0.17, 6.65, and -7.15 °C, respectively. Those at 80  
24 cm were 0.11, 4.32, and -4.86 °C, respectively

25 A borehole was drilled in 2002, and thermistors made by the State Key Laboratory of  
26 Frozen Soil Engineering, Chinese Academy of Sciences were installed at 0.5 m intervals from  
27 0.5 to 10 m, at 2 m intervals from 12 to 30 m, at 4 m intervals from 34 to 50 m., and at 55 and  
28 60 m. Temperature accuracy of this type of thermistor is  $\pm 0.05$  °C (Wu et al., 2016). The  
29 temperatures were recorded on the 5th and 20th days of each month using CR3000 data  
30 logger (Campbell Scientific Inc., USA). Based on our measurements, active layer depth is  
31 ~3.3 m, depth of zero annual amplitude is ~6.2 m, and the lower boundary of permafrost is at  
32 a depth of ~20 m. The multi-year mean ground temperatures at 0.5, 6, and 60 m are about -  
33 0.52, -0.30, and 1.81 °C, respectively.

## 1 2.2 Soil sampling and measurement

2 Permafrost dynamics are affected by atmosphere, vegetation, and soil textures, therefore, we  
3 excavated soil close to the weather station and borehole (Figure 2a) down to 2 m (Figure 2b) in  
4 August 2014. We used cut rings (10 cm diameter, 6.37 cm height and 500 cm<sup>3</sup>) to take soil  
5 samples at depth ranges of 0-10, 10-20, 20-30, 40-50, 70-80, 110-120, 150-160, and 190-200  
6 cm. Three replicates were sampled from the top of each depth range and sealed for analysis in  
7 the laboratory. Above 120 cm in the soil pit, coarse soil material was small enough in the cut  
8 rings. Below 150 cm, the material is weathered mudstone, which could also be sampled with  
9 our cut rings. Based on the excavated soil pit and measured soil temperature, this site belongs to  
10 Inceptisols with suborder of Gelept (soil taxonomy, ST, Soil Survey Staff, 2014). The soil pit  
11 consists of A horizon (~20 cm), Bw horizon (~20-80 cm) and C material dominated by  
12 fractured bedrock.

13 We used the KD2 Pro (Decagon, US) to measure thermal conductivity of soil samples. The  
14 steps we took to determine soil properties for each sample were as follows: 1) the soil sample  
15 was dried in an oven and weighed (0.001g precision) to calculate bulk density; then 2) the soil  
16 sample was exposed to a constant temperature (20°C) for 24 h, a certain volume of water was  
17 injected into the soil samples, and KD2 Pro (Decagon, USA) was used to measure the thermal  
18 conductivity; next 3) the sample and the KD2 probe were put into a refrigerator at -15°C for 12  
19 h and thermal conductivity was measured again; 4) steps 2 and 3 were repeated at increasing  
20 levels of soil volumetric water content until soil samples were up to the point of saturation;  
21 finally, 5), the soil sample was immersed in water for 24 h and weighed to calculate porosity,  
22 and the saturated unfrozen and frozen thermal conductivity were then measured, accordingly.  
23 The bulk density ( $\rho_b$ , g cm<sup>-3</sup>), porosity ( $\phi_m$ , m<sup>3</sup> m<sup>-3</sup>) and volumetric water content ( $\theta_{liq}$ , m<sup>3</sup>  
24 m<sup>-3</sup>) were calculated with the following equations.

$$25 \quad \rho_b = \frac{m_{dry} - m_{cr}}{V_{cr}} \quad (1)$$

$$26 \quad \phi_m = \frac{m_{sat} - m_{dry}}{V_{cr}} / \rho_w \quad (2)$$

$$27 \quad \theta_{liq} = \frac{W_{m_{all}} - m_{dry}}{V_{cr}} / \rho_w \quad (3)$$

28 Where  $m_{dry}$ ,  $m_{sat}$ ,  $m_{all}$ ,  $m_{cr}$  are mass of oven dried sample, saturated sample, sample with some  
29 water with cut ring, and empty cut ring (g), respectively.  $V_{cr}$  is the volume of cut ring (cm<sup>3</sup>).

1  $\rho_w$  is the density of water ( $1 \text{ g cm}^{-3}$ ). We also calculated porosity from bulk density ( $\phi_c, \text{g m}^{-3}$ ):

$$3 \quad \phi_c = 1 - \frac{\rho_b}{\rho_p} \quad (4)$$

4 Where  $\rho_p$  is particle density ( $2.65 \text{ g cm}^{-3}$ ).

5 We used pressure membrane instruments (1500F1, Soilmoisture Equipment Corp, US) to  
6 measure the matric potential of soil samples (Azam et al., 2014; Wang et al., 2007), using both  
7 15 bar and 5 bar pressure chambers. Pressure values were set at 0, 10, 20, 40, 60, 80, 100, 150,  
8 200, 300, and 400 kpa. It usually took 3-4 days to finish one measurement at one pressure level.  
9 We used a soil permeability meter (TST-70, Nanjing T-Bota Sciotech Instruments & Equipment  
10 Co., Ltd. China) to measure saturated hydraulic conductivity of soil samples (Gwenzi et al.,  
11 2011). Finally, soil samples were sieved through a 2.0 mm mesh, and soil particle size  
12 distribution was determined with a laser diffraction analyzer (Malvern-2000, Worcestershire,  
13 UK).

### 14 **2.3 Model description**

15 To simulate soil temperatures, soil liquid water content, temperature in rock layers, active  
16 layer depth (ALD) and permafrost low boundary (PLB) dynamics we used a dynamic organic  
17 soil version of Terrestrial Ecosystem Model (DOS-TEM). Models from the TEM family  
18 simulate the carbon and nitrogen pools of vegetation and soil, and their fluxes among  
19 atmosphere, vegetation, and soil (McGuire et al., 1992). They have been widely used in  
20 studies of cold region ecosystems (e.g. McGuire et al., 2000; Yuan et al., 2012; Zhuang et al.,  
21 2004; 2010). The DOS-TEM consists of four modules, environmental, ecological, fire  
22 disturbance, and dynamic organic soil (Yi et al., 2010). The environmental module operates  
23 on a daily time interval using mean daily air temperature, surface solar radiation, precipitation,  
24 and vapor pressure, which are downscaled from monthly input data (Yi et al., 2009a). The  
25 module takes into account radiation and water fluxes among the atmosphere, canopy, snow  
26 pack, and soil.

### 1 2.3.1 Implementation of soil thermal processes

2 Earlier versions of TEM did not simulate soil temperature (McGuire et al., 1992). Zhuang et  
3 al. (2001) incorporated Goodrich (1978) permafrost model into TEM. Yi et al. (2009b)  
4 incorporated a two-directional Stefan algorithm to simulate soil freezing and thawing for  
5 complex soils with changes in soil organic and moisture content. Temperatures of all soil  
6 layers in the DOS-TEM are updated daily. Phase change is calculated first before heat  
7 conduction. A two-directional Stefan algorithm is used to predict the depths of freezing or  
8 thawing fronts within the soil (Woo et al., 2004). It first simulates the depth of the front in the  
9 soil column from the top downward, using soil surface temperature as the driving temperature.  
10 It then simulates the front from the bottom upward using the soil temperature at a specified  
11 depth beneath a front as the driving temperature (bottom-up forcing). The latent heat used for  
12 phase change is recorded for each soil layer. If a layer contains  $n$  freezing or thawing fronts,  
13 this layer is then explicitly divided into  $n+1$  soil layers. All soil layers are grouped into 3 parts:  
14 1) those above the uppermost freezing or thawing front; 2) those below the lowermost  
15 freezing or thawing front; and 3) those between the uppermost and lowermost fronts. Soil  
16 temperatures are then updated by solving finite difference equations of each part with latent  
17 heat from phase change as an energy source or sink (Yi et al., 2014a). Soil surface  
18 temperature, which is used as a boundary condition, is calculated using daily air maximum,  
19 air minimum, radiation, and leaf area index (Yi et al., 2013).

20 The version of the DOS-TEM in this study uses the Côté and Konrad (2005) scheme to  
21 calculate thermal conductivity (Yi et al., 2013; Pan et al., 2017), which is also been used by  
22 other studies on the QTP (e.g. Chen et al., 2012, Luo et al., 2009), and is as follows:

$$23 \lambda = \begin{cases} k_e \lambda_{sat} + (1 - k_e) \lambda_{dry} & s > 10^{-5} \\ \lambda_{dry} & s \leq 10^{-5} \end{cases} \quad (5)$$

24 where  $\lambda$ ,  $\lambda_{sat}$ ,  $\lambda_{dry}$  are soil thermal conductivity, saturated soil thermal conductivity, and dry  
25 soil thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ ), respectively, and  $k_e$  is the Kersten number (Côté and  
26 Konrad, 2005). Dry thermal conductivity varies with soil properties according to:

$$27 \lambda_{dry} = \chi 10^{-\eta \phi} \quad (6)$$

28 where  $\chi$  ( $\text{W m}^{-1} \text{K}^{-1}$ ) and  $\eta$  (no unit) are parameters accounting for particle shape effects,  
29 which are specified for gravel, fine mineral and organic soil (Côté and Konrad, 2005), and  $\phi$

1 is porosity. Saturated thermal conductivity varies with water content and phase state  
 2 according to:

$$3 \quad \lambda_{sat} = \begin{cases} \lambda_s^{1-\phi} \lambda_{liq}^{\phi} & T \leq T_f \\ \lambda_s^{1-\phi} \lambda_{ice}^{\phi} & T > T_f \end{cases} \quad (7)$$

4 where  $\lambda_{liq}$ ,  $\lambda_{ice}$ ,  $\lambda_s$  are thermal conductivities of liquid water, ice, and soil solid ( $\text{W m}^{-1} \text{K}^{-1}$ ),  
 5 which are all constant values.  $T$  is temperature of soil ( $^{\circ}\text{C}$ ) and  $T_f$  is a constant freezing point  
 6 temperature of soil ( $0^{\circ}\text{C}$ ). In DOS-TEM, freezing or thawing processes are assumed to  
 7 happen at  $T_f$ , which is consistent with what happens in most land surface models (e.g. Oleson  
 8 et al. 2010).

### 9 **2.3.2 Implementation of soil hydrological processes**

10 Surface runoff, infiltration, and water redistribution among soil layers are simulated in a  
 11 similar way as Community Land Model 4 (Oleson et al., 2010). Soil matric potential ( $\Psi$ )  
 12 determines the direction of water movement, and hydraulic conductivity describes the ease  
 13 with which water can move through the soil.

$$14 \quad \Psi = \Psi_{sat} \left( \frac{\theta_{liq}}{\phi} \right)^{-B} \quad (8)$$

15 where  $\Psi_{sat}$  is saturated soil matric potential ( $\text{mm H}_2\text{O}$ , hereafter  $\text{mm}$ ), and  $B$  is pore size  
 16 distribution parameter. The soil hydraulic conductivity ( $K$ ,  $\text{mm s}^{-1}$ ) is a function of the  
 17 saturated soil hydraulic conductivity ( $K_{sat}$ ) as follows:

$$18 \quad K = K_{sat} \left( \frac{\theta_{liq}}{\phi} \right)^{2B+3} \quad (9)$$

19 Several important features relating to permafrost have been considered in the DOS-TEM  
 20 (see Yi et al., 2014b), including runoff from a perched saturated zone or exchanges of water  
 21 between the soil and a water reservoir. Runoff from a perched saturated zone above  
 22 permafrost is implemented following Swenson et al. (2013):

$$23 \quad Q_{perch} = \alpha k_p (z_{frost} - z_{perched}) \sin\left(\frac{\Theta}{180} \pi\right)$$

24 (10)

25 where  $\alpha$  is an adjustable parameter ( $0.6 \text{ m}^{-1}$ ),  $K_p$  is the mean saturated hydraulic conductivity  
 26 within the perched saturated zone ( $\text{mm s}^{-1}$ ),  $z_{frost}$  and  $z_{perched}$  are the depths to the permafrost  
 27 table and the perched water table ( $\text{m}$ ), respectively, and  $\Theta$  is slope ( $^{\circ}$ ).



1 The DOS-TEM has been verified against the Neumann Equation for water, mineral and  
2 organic soil under an idealized condition (Yi et al., 2014b), and validated against field  
3 measurements for various locations in Alaska, the Arctic, and the QTP (Yi et al., 2009b, Yi et  
4 al., 2013, Yi et al., 2014a).

## 5 **2.4 Model inputs and initialization**

6 We used the monthly averaged air temperature, downward radiation, precipitation and  
7 humidity as input to drive the DOS-TEM. Leaf area index (LAI), leaf area per unit ground  
8 surface area, was specified to be  $0.6 \text{ m}^2 \text{ m}^{-2}$  in July and August,  $0.1 \text{ m}^2 \text{ m}^{-2}$  in April and  
9 October,  $0 \text{ m}^2 \text{ m}^{-2}$  between November and March, and interpolated linearly in other months. It  
10 is used in the DOS-TEM to calculate ground surface temperature in combination with other  
11 meteorological variables (Yi et al., 2013). Its value is unchanged within each month.

12 Soil temperature and moisture were initialized at  $-1 \text{ }^\circ\text{C}$  and saturation. The temperature  
13 gradient at the bottom of bedrock was set to be  $0.06 \text{ }^\circ\text{C cm}^{-1}$  based on borehole observations.  
14 Volumetric unfrozen liquid water in winter was set to be 0.1 based on observations. Multi-  
15 year (2003-2012) mean monthly driving data were used to spin up the model for 100 yr. In  
16 this way, suitable initial values of soil moisture, temperature and rock temperature of each  
17 layer are generated before driving DOS-TEM with monthly data over the period of 2003-2012.

## 18 **2.5 Sensitivity analyses**

19 The soil textures on the QTP mainly consist of loam, sand, and coarse fragment soils (Wu and  
20 Nan, 2016). We used a uniform sand or loam soil profile to represent coarse and fine soil  
21 textures, respectively. Sands are the coarsest texture considered in most ~~the~~ modeling studies  
22 (e.g. Oleson et al., 2010). Therefore, we used our measured parameters to substitute the  
23 parameters of sand and loam to investigate the effects of coarse-fragment soil parameters on  
24 permafrost dynamics. We first ran DOS-TEM using the default porosity, soil thermal  
25 conductivity (Equation 5), hydraulic conductivity (Equation 9), and matric potential schemes  
26 of these two default soil textures (Equation 8). The default parameters  $\phi$ ,  $\Psi_{\text{sat}}$ ,  $K_{\text{sat}}$  and B were  
27 calculated based on soil texture used in Community Land Model (Equations 8 and 9; Oleson  
28 et al., 2010). We then substituted the default values of  $\phi$ ,  $\Psi_{\text{sat}}$ ,  $K_{\text{sat}}$  and B based on our  
29 laboratory measurements and calibration. Parameters  $\Psi_{\text{sat}}$  and B were fitted with measured  
30 matric potential data using Isqcurvefit tools of Matlab. We did not calibrate soil thermal

1 conductivity to retrieve parameters of Equations 6 and 7. Instead, we interpolated measured  
2 thermal conductivities over a range of degrees of saturation (0 to 1), which was used as a  
3 lookup table by the DOS-TEM. Therefore, our sensitivity analyses considered a set of 4  
4 factors, i.e. porosity, matric potential ( $\Psi_{\text{sat}}$  and B), hydraulic conductivity ( $K_{\text{sat}}$  and B) and  
5 thermal conductivity. We also analyzed 3 different slopes (0, 5, and  $10^\circ$ ) and 3 different soil  
6 thicknesses (3.25, 4.25, and 5.25 m) above 56 m of bed rock. There were 11 soil layers with  
7 the top 9 layers being 0.05, 0.1, 0.1, 0.2, 0.2, 0.2, 0.3, 0.3, and 0.3 m thick. The thicknesses of  
8 the bottom 2 soil layers were 0.5 and 1 m, 0.5 and 2 m, and 1.5, and 2 m for the 3.25, 4.25,  
9 and 5.25 m cases, respectively. There were 6 rock layers with thicknesses of 2, 2, 4, 8, 16, and  
10 20 m. Since the site is on the top of upland plain landforms, we did not further test the effects  
11 of aspect ~~on radiation on ground surface~~. We instead considered the effects of slope on  
12 surface runoff. In summary, our sensitivity analyses with the DOS-TEM involved 288  
13 different combinations of parameter values.

14 We did not measure the heat capacity. The maximum and minimum heat capacities of  
15 mineral soil types considered in land surface model are  $2.355$  and  $2.136 \text{ MJ m}^{-3}$ , respectively,  
16 giving a relative difference less than 10%. Therefore, in this study, we did not make  
17 sensitivity tests using thermal diffusivity (the ratio between thermal conductivity and heat  
18 capacity).

## 19 **3 Results**

### 20 **3.1 Soil physical properties**

#### 21 **3.1.1 Soil porosity, particle size and bulk density**

22 Results from laboratory analysis of the soil samples are shown in Table 1 and 2. The mean  
23 mass ratio of the coarse soil fraction (particle size diameter  $> 2 \text{ mm}$ ) of different soil layers  
24 ranged from 0.38 to 0.65 with a mean of 0.55. According to the USDA classification system  
25 (clay ( $< 2 \mu\text{m}$ ), silt ( $2 - 50 \mu\text{m}$ , in this study  $2 - 63 \mu\text{m}$ ) and sand ( $50 \mu\text{m} - 2.0 \text{ mm}$ , in this  
26 study  $63 \mu\text{m} - 2.0 \text{ mm}$ )), the major soil texture of this site was loamy sand, with the exception  
27 of sandy loam at 20-30 cm depth. The default porosities of sand and loam were 37.3% and  
28 43.5%, respectively. The  $\phi_m$  of samples down to 2 m depth ranged from 21% to 30% with a  
29 mean of 27%, and the mean  $\rho_b$  ranged from  $1.61$  to  $1.86 \text{ g cm}^{-3}$  with a mean of  $1.74 \text{ g cm}^{-3}$ .

1 The  $\phi_c$  (Equation 4) ranged from 29.8% to 39.2%. No significant relationships were found  
2 among  $\phi_m$ ,  $\rho_b$ , and the coarse soil fraction ( $p > 0.05$ ).

### 3 **3.1.2 Thermal conductivity**

4 The results of the thermal conductivity determinations are shown in Table 3. The unfrozen  
5  $\lambda_{dry}$  of different soil layers ranged from 0.24 to 0.40  $W m^{-1} K^{-1}$  with a mean of 0.36  $W m^{-1} K^{-1}$ ,  
6 and the frozen  $\lambda_{dry}$  ranged from 0.25 to 0.41  $W m^{-1} K^{-1}$  with a mean of 0.35  $W m^{-1} K^{-1}$ . The  
7 difference of  $\lambda_{dry}$  between frozen and unfrozen states was small. The unfrozen  $\lambda_{sat}$  of different  
8 soil layers ranged from 2.15 to 2.74  $W m^{-1} K^{-1}$  with a mean of 2.48  $W m^{-1} K^{-1}$ . The frozen  $\lambda_{sat}$   
9 ranged from 3.06 to 3.72  $W m^{-1} K^{-1}$  with a mean of 3.33  $W m^{-1} K^{-1}$ . The difference of  $\lambda_{sat}$   
10 between frozen and unfrozen states was about 0.85  $W m^{-1} K^{-1}$ . There existed a threshold of  
11 soil saturation (i.e.  $\sim 0.28 m^3 m^{-3}$ ), below which frozen soil thermal conductivity was slightly  
12 smaller than unfrozen soil (Figure 4a).

13 Results from determining thermal conductivities using the Côté and Konrad (2005) scheme  
14 are shown in Figure 4b. The default frozen and unfrozen  $\lambda_{dry}$  for sand and loam were about  
15 0.42 and 0.24  $W m^{-1} K^{-1}$ , respectively. The frozen and unfrozen  $\lambda_{sat}$  of sand were 3.11 and  
16 1.90  $W m^{-1} K^{-1}$ , respectively. Those of loam were about 2.36 and 1.33  $W m^{-1} K^{-1}$ , respectively.  
17 Results from determining thermal conductivities using the Farouki (1986) scheme are shown  
18 in Figure 4c. The default frozen and unfrozen  $\lambda_{dry}$  for sand and loam were about 0.97 and 0.63  
19  $W m^{-1} K^{-1}$ , respectively. The frozen and unfrozen  $\lambda_{sat}$  of sand were 5.21 and 3.18  $W m^{-1} K^{-1}$ ,  
20 respectively. Those of loam were about 4.49 and 2.52  $W m^{-1} K^{-1}$ , respectively.

### 21 **3.1.3 Saturated hydraulic conductivity**

22 The mean  $K_{sat}$  of soil layers, shown in Table 4, ranged from 0.0036 to 0.0315  $mm s^{-1}$ . The  
23 maximum  $K_{sat}$  was about 8.7 times larger than the minimum. The  $K_{sat}$  tended to be larger with  
24 increasing proportion of coarse fragment in the soil samples (Figure 5a), and was about 0.03-  
25 0.06  $mm s^{-1}$  for some samples with coarse fragment greater than 70%. The default  $K_{sat}$  of sand  
26 and loam were 0.024 and 0.0042  $mm s^{-1}$ , respectively.

### 27 **3.1.4 Matric potential**

28 The correlation coefficients between calculated and fitted ~~matric potential~~, shown in Table 4,  
29 were all greater than 0.96. The mean absolute value of  $\Psi_{sat}$  of soil layers ranged from 14.47 to

1 603.7 mm, and those of B ranged from 1.89 to 5.22 (Table 4 and Figure 5b). The default  
2 absolute value of  $\Psi_{\text{sat}}$  of sand and loam were 47.29 and 207.34 mm, respectively, and the B  
3 values 3.39 and 5.77, respectively.

## 4 **3.2 Comparisons between simulations using default vs. measured parameters**

### 5 **3.2.1 Soil temperature**

6 The mean root mean squared errors (RMSEs) between monthly measured soil temperatures  
7 and model runs with measured parameters using different combination of soil thicknesses  
8 (3.25, 4.25, and 5.25 m) and slopes (0, 5, and 10°) were about 1.07 °C at 20 cm (Figure 6c).  
9 The mean RMSEs for all model runs with default sand and loam parameters were about 0.97  
10 and 1.18 °C, respectively. For other soil layers, the RMSEs of model runs with measured  
11 parameters were much smaller than those with default sand and loam parameters (Figures 6d-  
12 l). The simulated soil temperatures using default sand and loam parameters were all lower  
13 than measured ones in summer at 100 and 200 cm, and in winter at 400 cm. The RMSEs can  
14 be as large as 2.53 °C (Figure 6e).

15 The standard deviations of soil temperatures among different slopes and soil thicknesses  
16 using measured parameters were larger than those using the default parameters (Figure 6); and  
17 they increased from 0.40 °C at 100 cm to 0.61 °C at 200 cm (Figure 6f and i). The standard  
18 deviations using default loam parameters were smaller (<0.15 °C at all depths) than those  
19 using default sand parameters.

### 20 **3.2.2 Soil liquid water**

21 The mean RMSEs between monthly measured  $\theta_{\text{liq}}$  and model simulations with measured  
22 parameters ranged from 0.03 to 0.09, which were smaller than RMSEs for sand and loam  
23 parameters (Figure 7). The model simulations for loam parameters have larger RMSEs than  
24 those for sand parameters.  $\theta_{\text{liq}}$  was always overestimated in warm seasons at depths of 10, 40  
25 and 80 cm.  $\theta_{\text{liq}}$  was underestimated at a depth of 160 cm, where the simulated soil was  
26 frozen. All model simulations overestimated  $\theta_{\text{liq}}$  at 40 cm, where the maximum measured  $\theta_{\text{liq}}$   
27 were about 0.1 (Figure 7d-f).

28 The standard deviations of  $\theta_{\text{liq}}$  among different slopes and soil thicknesses using sand  
29 parameters were about 0.077, which were larger than those using measured parameters

1 (~0.062). The standard deviations of  $\theta_{liq}$  using loam parameters (<0.032) were less than  
2 those using measured parameters.

### 3 **3.2.3 Active layer depth (ALD)**

4 The mean RMSEs between measured ALDs (derived from linear interpolation of soil  
5 temperatures) and modelled ALDs (simulated explicitly) were about 1.06, 1.72, and 0.28 m  
6 for model runs with sand, loam, and measured parameters (Figure 8a). The mean standard  
7 deviations were about 0.088, 0.026, and 0.28 m. All simulations using sand and loam  
8 parameters underestimated ALDs. When  $\phi_m$  was replaced with  $\phi_c$ , the mean RMSEs and  
9 standard deviations were about 0.55 m and 0.12 m, respectively.

### 10 **3.2.4 Permafrost lower boundary (PLB)**

11 The mean RMSEs between measured PLBs (derived from linear interpolation of temperatures)  
12 and modelled PLBs (derived from linear interpolation of simulated bed rock temperatures)  
13 were about 10.25, 10.23, and 6.71 m for model runs with sand, loam, and measured  
14 parameters (Figure 8b). The mean standard deviations were about 1.89, 1.51, and 6.62 m. All  
15 simulations using sand and loam parameters overestimated PLBs. When  $\phi_m$  was replaced  
16 with  $\phi_c$ , the mean RMSEs and standard deviations were about 4.78 m and 2.82 m,  
17 respectively.

## 18 **3.3 Model sensitivity analyses**

19 Deep soil layers used in models are usually specified as being thick. For example, a 1 m thick  
20 soil layer was used in our simulations starting around 3 m soil depth. Soil temperatures at this  
21 depth are usually close to 0 °C. Therefore, the RMSEs of deep soil layers were small and did  
22 not facilitate evaluation of model sensitivities. In the following subsections, we used 20 and  
23 100 cm soil temperatures, ALDs and PLBs for sensitivity analysis.

### 24 **3.3.1 Effects of single parameter sensitivity analyses**

#### 25 **Porosity**

26 Replacing default sand or loam porosity with  $\phi_m$  changed mean RMSEs of soil temperatures  
27 (model runs with 3 different slopes and 3 different soil thicknesses at 2 different soil depths)

1 from 1.18 or 1.84 °C to 1.25 or 1.09 °C, respectively (Figure 9 and 10). Mean RMSEs of ALD  
2 were reduced from 1.06 or 1.72 m to 0.22 or 0.85 m, respectively. Mean RMSEs of PLB were  
3 changed from 10.26 or 10.24 m to 6.61 or 10.97 m. Mean RMSEs of  $\theta_{liq}$  were reduced from  
4 0.074 or 0.14 to 0.06 or 0.062 when  $\phi_m$  were used for replacing default sand or loam porosity,  
5 respectively (Figure 11 and 12).

### 6 **Thermal conductivity**

7 Replacing default sand or loam thermal conductivity with measured parameters reduced mean  
8 RMSEs of soil temperatures from 1.18 or 1.84°C to 1.02 or 1.15°C, respectively (Figure 9 and  
9 10). Mean RMSEs of ALD were reduced from 1.06 or 1.72 m to 0.56 or 1.04 m, respectively.  
10 Mean RMSEs of PLB were changed from 10.26 or 10.24 m to 4.18 or 1.27 m, respectively.  
11 Mean RMSEs of  $\theta_{liq}$  changed very slightly (Figure 11 and 12).

### 12 **Hydraulic conductivity and matric potential**

13 Replacing default sand or loam hydraulic conductivity with measured parameters had very  
14 small effects on mean RMSEs of soil temperatures and ALDs (Figure 9 and 10). The same  
15 was true for matric potential. When hydraulic conductivity of default sand or loam was  
16 substituted, mean RMSEs of PLB decreased or increased, respectively. However, when  
17 matric potential was substituted, mean RMSEs of PLBs increased or decreased, respectively.  
18 When hydraulic conductivity or matric potential parameters were substituted in default sand  
19 or loam parameters, mean RMSEs of  $\theta_{liq}$  changed slightly (Figure 11 and 12).

### 20 **3.3.2 Effects of combined parameters**

21 We compared model simulations with different combinations of measured parameters  
22 (porosity, thermal conductivity, hydraulic conductivity and matric potential) to those with one  
23 substituted measured parameter. We ranked those model runs with less RMSEs than the best  
24 of the model runs with one parameter substituted with a measurement-derived value (Table 5  
25 and 6). We didn't consider the 10 cm soil temperature, which were similar among all model  
26 runs.

27 For sand, model simulations with porosity and thermal conductivity or hydraulic  
28 conductivity substituted had 4 outcomes with lower RMSEs (Table 5 and Figures 9 and 11).  
29 Only 2 out of 7 outcomes had lower RMSEs with all 4 parameters substituted. Among all the

1 18 cases with RMSEs less than the individual "best" RMSE, porosity was included 18 times,  
2 and thermal conductivity and hydraulic conductivity were included 10 times.

3 For loam, model simulations with porosity and thermal conductivity substituted had 5  
4 outcomes with lower RMSEs (Table 6 and Figures 10 and 12). Among all the 27 cases with  
5 RMSEs less than the individual "best" RMSE, porosity was included 27 times, and thermal  
6 conductivity was included 16 times, and matric potential 14 times.

### 7 **3.3.3 Effects of slope and soil thickness**

8 Changes of slope alone had small effects on simulated soil temperatures and ALDs (Figures 9  
9 and 10). An increase of slope generally reduced RMSEs of  $\theta_{liq}$  (Figures 11 and 12). Model  
10 simulations with porosity substituted had smaller differences in  $\theta_{liq}$  RMSE between different  
11 cases of slopes. For example, the mean RMSEs of model simulations with slopes of  $0^\circ$  or  $5^\circ$   
12 and sand parameters substituted with  $\phi_m$  were 0.078 or 0.048, respectively. While those with  
13 porosity not substituted were 0.141 or 0.055, respectively. Similarly, the mean RMSEs of  
14 model simulations using default loam parameters with porosity substituted were 0.08 or 0.05  
15 for slope of  $0^\circ$  or  $5^\circ$ , respectively. The mean RMSEs were 0.18 or 0.1 with porosity not  
16 substituted, respectively. For a further increase of slope to  $10^\circ$ , changes of RMSEs of  $\theta_{liq}$  at  
17 depths of 10-160 cm were small.

18 Soil thickness had small effects on 20 and 100 cm soil temperatures and 10-160 cm  $\theta_{liq}$ ,  
19 and it had prominent effects on PLB for a few cases only with a slope of  $10^\circ$  (Figures 9 and  
20 10).

## 21 **4 Discussion**

### 22 **4.1 Characteristics of soil physical properties**

23 Although the effects of coarse fragment soils on permafrost dynamics have been considered  
24 in a few modelling studies, the thermal and hydraulic properties of coarse fragment soils were  
25 calculated without validation or calibration (Pan et al., 2017; Wu et al., 2018). To our  
26 knowledge, this is the first study measuring physical properties of coarse fragment soil  
27 samples from permafrost region of the QTP.

1 The weight fraction of coarse fragment (diameter > 2mm, including gravel) in the soil  
2 samples we analysed was greater than 55% on average. While the typical soil types  
3 considered in land surface models and other models usually have much smaller diameter. For  
4 comparison, the fractions of gravel considered in Pan et al. (2017) ranges from 5% to 33%  
5 and from 10% to 28% for the Madoi and Naqu sites, respectively. The Beiluhe site and the  
6 aforementioned sites are located in regions with Gelisols and Inceptisols, which occupy ~62%  
7 of the permafrost regions of the QTP (Li et al., 2015). It is possible that coarse fragment soils  
8 commonly exist on the QTP. The dataset of Wu and Nan (2016) indicated that gravel content  
9 widely exists on the middle and western part of the QTP. The saturated hydraulic conductivity  
10 and matric potential of soil samples measured in this study were more similar to sand than to  
11 loam (see Section 3.1). It is consistent with the study of Wang et al. (2013) that coarse soil  
12 material has poor water holding capability.

13 The measured thermal conductivities of saturated soil samples were relatively close to  
14 those estimated by the Côté and Konrad (2005) scheme. But they were much less than those  
15 estimated by the Farouki scheme (Figure 4). Several other studies also found that Farouki  
16 scheme overestimated soil thermal conductivity (Chen et al. 2012; Luo et al., 2009).

17 One important finding of this study is the relatively small value of porosity. The  $\phi_m$  ranged  
18 from 0.206 to 0.302, which is less than those of soil types considered in land surface models.  
19 For example, the porosities of mineral soil types considered in Community Land Model range  
20 from 0.37 to 0.48 (Oleson et al., 2010). Porosity determines the maximum water stored in a  
21 soil layer, and affects soil thermal conductivity, hydraulic conductivity and matric potential  
22 (Equation 6-9). It plays a more important role than other parameters in simulated soil thermal  
23 and hydrological dynamics (Table 5 and 6; Figure 9-12). It is noteworthy that it is easy and  
24 efficient to measure porosity.

## 25 **4.2 Effects of soil water on permafrost dynamics**

26 Soil water not only affects soil thermal properties (e.g. thermal conductivity and heat  
27 capacity), but also affects the amount of latent heat lost or gained, for freezing or thawing,  
28 respectively (Goodrich, 1978; Farouki, 1986). Soil water is determined by infiltration,  
29 evapotranspiration, water movement among soil layers, subsurface runoff and exchange with  
30 a water reservoir. Therefore, processes or parameters that affect soil water dynamics will also  
31 affect permafrost dynamics. This study quantitatively assessed the effects of soil water on



1 permafrost dynamics. For example, when default loam parameters with high porosity and low  
2 saturated hydraulic conductivity were used, soil layers were almost saturated (Figure 7). The  
3 simulated ALDs were about 1.58 m, which was less than half of measured ALDs (Figure 8a).  
4 When the slope was 0°, subsurface runoff didn't occur in the saturated zone above the bottom  
5 of the active layer. The simulated  $\theta_{liq}$  was generally higher in the active layer. However,  
6 when the slope was 5°, the simulated  $\theta_{liq}$  was less and the RMSE was smaller (Figure 11 and  
7 12). These patterns were especially obvious when both porosity and saturated hydraulic  
8 conductivity were large (Equation 10; Figure 11 and 12). Other studies have also emphasized  
9 the importance of subsurface runoff above the bottom of the active layer (Frey and  
10 McClelland, 2009; Walvoord and Striegl, 2007). The effects of soil water content on soil  
11 thermal dynamics increased with soil and rock depth (Figure 9 and 10). The biggest effects  
12 were on PLB, which became manifest during long-term spinup procedures.

13 Land surface models generally represent soil water dynamics (e.g. Chen et al., 2015;  
14 Oleson et al., 2010; Wang et al., 2017). However, the thermal processes in permafrost models  
15 usually use specified thermal properties, which were static during model simulations (Li et al.,  
16 2009; Nan et al., 2005; Qin et al., 2017; Zou et al., 2017). As shown in this study, variation of  
17 soil water content in coarse-fragment soils strongly affects thermal and hydrological  
18 properties, thus it is critical to simulate soil water dynamics to properly project permafrost  
19 dynamics in the future.

## 20 **4.3 Limitations and Outlook**

### 21 **4.3.1 Sampling and laboratory measurement**

22 We used cut rings with 10 cm diameter to sample soil and weathered mudstones. However, it  
23 is very likely that there could have been much bigger coarse fragment soils. Therefore, larger  
24 containers should be used to take samples for further laboratory analysis in the future.

25 During our laboratory work, we found two phenomena. First, we originally used the QL-  
26 30 thermophysical instrument (Anter Corporation, US) to measure thermal conductivity. It  
27 worked properly under unfrozen condition. However, when frozen, the surface of the soil  
28 sample was usually uneven due to frost heave, which reduces the contact between the QL-30  
29 plate and the soil sample surface. The measured frozen thermal conductivities were smaller  
30 than unfrozen thermal conductivity even for the case of saturation, which were definitely

1 wrong, thus we used the KD2 pro to determine thermal conductivities. The second  
2 phenomenon was that there seems to be a threshold of soil saturation, below which unfrozen  
3 soil thermal conductivity is greater than frozen soil thermal conductivity (Figure 4a). This  
4 pattern was somewhat exhibited in estimates of the Côté and Konrad (2005) scheme (Figure  
5 4b), but not in the estimates of the Farouki scheme (Figure 4c). More measurements using  
6 instruments with higher accuracy should be made in the future.

7 The measured porosities are generally smaller than those calculated from bulk density.  
8 We made additional model simulations using porosities calculated from bulk density in  
9 combination with other measured parameters. Our results showed that the RMSEs of ALD  
10 and PLB were 0.55 m and 4.78 m, respectively (Figures not shown), whereas those calculated  
11 using  $\phi_m$  were 0.28 m and 6.71 m, respectively. There is a variety of methods for measuring  
12 soil porosity (Stephens et al., 1998). The method used in this study is widely used for its  
13 simplicity (e.g. Chen et al., 2012), and only requires measuring weights of samples under  
14 saturation and dry conditions (Equation 2). Soil samples were immersed in water for 24 h to  
15 research saturation. It is possible that some air still remained in soil after 24 h immersion  
16 under atmospheric pressure, although most of our soil samples contained coarse fragments. It  
17 is ideal to immerse soil samples in water under a vacuum condition to draw air out of soil  
18 samples completely in future studies.

### 19 **4.3.2 Model simulation**

20 Although the DOS-TEM using measured parameters provided satisfactory results, there are  
21 some aspects requiring further improvement in the future. For example, the measured soil  
22 moistures at 40 cm depth were less than  $0.1 \text{ m}^3 \text{ m}^{-3}$ . However, the simulated soil moistures  
23 were always much greater (Figure 7f). There were also spikes in measured soil moistures at  
24 80 and 160 cm depths, which were not presented in the simulation (Figure 7 i and l). In the  
25 DOS-TEM, the unfrozen soil water content, or supercold water, was prescribed to be  $0.1 \text{ m}^3$   
26  $\text{m}^{-3}$ . When soil is freezing, if soil liquid water content is less than this value, no phase change  
27 will happen (Figure 7k). Therefore, model results would improve with the capability to  
28 simulate the dynamics of unfrozen soil water content (Romanovsky and Osterkamp, 2000).

29 The TEM family models use monthly atmospheric data as driving for both site and  
30 regional applications. In this study, 30 min and daily driving data are available. Although it is  
31 possible to lose fidelity after daily interpolations, we still decided to use monthly driving data

1 for the following reasons: 1) Zhuang et al. (2001) performed a test with daily and monthly  
2 driving datasets. The results showed that the RMSEs of ALD were about 3 cm; 2) we will  
3 apply the model over large regions where reliable daily datasets might not be available.

#### 4 **4.3.3 Regional applications**

5 Coarse fragment soils affect soil physical properties. For example, soil porosity and saturated  
6 hydraulic conductivity are determined by the fraction of gravel, diameter, and degree of  
7 mixture (Zhang et al., 2011). Thus soil texture plays an important role in permafrost dynamics  
8 (Figure 8). The dominant soil texture on the QTP from Wu and Nan (2016) are loam, sand,  
9 and gravel. The specification of loam in simulations results in estimates of ALD that are much  
10 smaller than measurements (Yi et al., 2014a). To properly simulate the distribution and  
11 dynamics of permafrost on the QTP under climate change scenarios, it is important to develop  
12 proper schemes of soil physical properties in relation to coarse fragment content (including  
13 gravel) and to develop regional datasets of soil texture for input.

14 Organic soil carbon content in mineral soil on the QTP affects soil porosity and thermal  
15 conductivity (Chen et al., 2012). However, in the site considered in this study, the amount of  
16 organic soil carbon in soil was small (Figure 2), and we did not explicitly consider the effects  
17 of organic soil carbon on soil properties. Alpine swamp meadow, alpine meadow, alpine  
18 steppe and alpine desert are the major vegetation types on the QTP (Wang et al., 2016; see  
19 also Figure 1b). Alpine swamp meadow and alpine meadow usually contain fine soil particles  
20 and high organic carbon density; while the other two types usually contain coarse soil particle  
21 and low organic carbon density (Qin et al., 2015). More laboratory work is needed to develop  
22 proper schemes for representing mixed soil with fine mineral, coarse fragment (including  
23 gravel), and organic carbon in permafrost models. It is the first priority to develop schemes  
24 that make use of porosity data sets, due to its importance and simplicity of measurement.

25 The development of a spatially explicit dataset of soil texture is also required for regional  
26 projections of permafrost changes on the QTP. Currently, a preliminary dataset considering  
27 gravel exists (Wu and Nan, 2016), though gravel soil has only been mentioned in a few papers  
28 on the QTP (Chen et al., 2015; Wang et al., 2011; Yang et al., 2009). One way to improve the  
29 regional dataset is to collect relevant data through extensive field campaigns (e.g. Li et al.,  
30 2015). Ground penetrating radar is a feasible tool to retrieve soil thickness above the coarse  
31 fragment soil layer (Han et al., 2016), and coarse fragment soils can be identified in aerial

1 photos taken with unmanned aerial vehicles (Chen et al., 2017; Yi 2017). In combination with  
2 ancillary datasets (e.g. geomorphology, topography, vegetation), it is possible to improve the  
3 accuracy of spatial datasets of soil texture on the QTP (Li et al., 2015; Wu et al., 2016).  
4 Another way is to retrieve soil physical properties using data assimilation technology, such as  
5 Yang et al. (2016) who assimilated porosity using a land surface model and microwave data.

## 6 **5 Conclusions**

7 In this study, we excavated soil samples from a permafrost site on the central QTP and  
8 measured soil physical properties in laboratory. Coarse fragments were common in the soil  
9 profile (up to 65% of soil mass) and porosity was much smaller than the typical soil types  
10 used in land surface models. We then performed sensitivity analysis of these parameters on  
11 soil thermal and hydrological processes within a terrestrial ecosystem model. When default  
12 sand or loam parameters were substituted with measured soil properties, the model errors of  
13 active layer depth were reduced by 74% or 84%, respectively. Those of permafrost low  
14 boundary were reduced 35% or 34%, respectively. Sensitivity analyses showed that porosity  
15 played a more important role in reducing model errors than other soil properties examined.  
16 Though it is unclear how representative this soil is in the QTP, it is clear that soil physical  
17 properties specific to the QTP should be used to properly project permafrost dynamics into  
18 the future.

19 *Acknowledgements.* We would like to thank Prof. Dave McGuire of University of Alaska  
20 Fairbanks for his careful editing; Dr. Yi Sun for vegetation classification; Dr. Xia Cui of  
21 Lanzhou University, Mr. Guangyue Liu for determining depth of zero annual amplitude and  
22 Mr. Yan Qin for measurements of soil particle size distribution; Prof. Chien-Lu Ping of  
23 University of Alaska and Dr. Wangping Li of Lanzhou University of Technology for helping  
24 on soil taxonomy; and the editor and two anonymous reviewers for valuable comments. This  
25 study was jointly supported through grants provided as part of the National Natural Science  
26 Foundation Commission (41422102, 41690142, and 41730751), and the independent grants  
27 from the State Key Laboratory of Cryosphere Sciences (SKLCS-ZZ-2018).

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4

1 **Table 1.** The mean (standard deviation in brackets) of measured soil bulk density ( $\rho_b$ , g cm<sup>-3</sup>),  
 2 ~~calculated~~ porosity from bulk density ( $\phi_c$ , m<sup>3</sup> m<sup>-3</sup>), measured porosity ( $\phi_m$ , m<sup>3</sup> m<sup>-3</sup>) of  
 3 different layers based on soil samples in this study.

4

Layer (cm)	$\rho_b$	$\phi_c$	$\phi_m$
0—10	1.74 (0.21)	34.4 (0.08)	28.4 (0.03)
10—20	1.81 (0.11)	31.8 (0.04)	27.7 (0.02)
20—30	1.86 (0.32)	29.7 (0.12)	30.2 (0.05)
40—50	1.61 (0.23)	39.4 (0.09)	29.6 (0.02)
70—80	1.62 (0.20)	38.8 (0.08)	20.6 (0.11)
110—120	1.75 (0.09)	33.9 (0.04)	27.7 (0.01)
150—160	1.70 (0.15)	36.0 (0.06)	26.3 (0.02)
190—200	1.81 (0.09)	31.6 (0.03)	27.1 (0.02)

5

1 **Table 2.** The particle size diameter fractions (for >2 mm this is the mass ratio between soil  
2 particles greater than 2 mm and total soil sample, while for the other fractions this is the ratio  
3 between mass of the soil in the size range and the mass of all particles < 2mm) and soil  
4 texture (based on USDA classification) of different layers based on soil samples in this study.  
5

Layer (cm)	2mm				Texture
	>2 mm	- 63 μ m	63-2 μ m	<2 μ m	
0—10	0.38 (0.07)	0.77 (0.07)	0.18 (0.04)	0.05 (0.02)	Loamy sand
10—20	0.52 (0.14)	0.72 (0.11)	0.20 (0.05)	0.07 (0.05)	Loamy sand
20—30	0.55 (0.17)	0.69 (0.09)	0.24 (0.08)	0.07 (0.01)	Sandy loam
40—50	0.55 (0.19)	0.70 (0.13)	0.26 (0.11)	0.04 (0.02)	Loamy sand
70—80	0.65 (0.16)	0.71 (0.09)	0.25 (0.07)	0.04 (0.02)	Loamy sand
110—120	0.63 (0.05)	0.79 (0.09)	0.19 (0.08)	0.03 (0.02)	Loamy sand
150—160	0.63 (0.09)	0.85 (0.04)	0.13 (0.03)	0.02 (0.01)	Loamy sand
190—200	0.50 (0.19)	0.71 (0.19)	0.24 (0.14)	0.05 (0.05)	Loamy sand

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1 **Table 3.** The mean (standard deviation in brackets) of the measured frozen and unfrozen dry  
 2 and saturated soil thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ ) of different soil layers.

3

Layer (cm)	Dry		Saturated	
	Unfrozen	Frozen	Unfrozen	Frozen
0-10	0.238 (0.09)	0.414 (0.09)	2.322 (0.17)	3.122 (0.48)
10~20	0.340 (0.04)	0.365 (0.23)	2.147 (0.47)	3.193 (0.55)
20-30	0.395 (0.07)	0.420 (0.11)	2.743 (0.38)	3.059 (0.29)
40-50	0.346 (0.00)	0.388 (0.14)	2.539 (0.30)	3.184 (0.33)
70-80	0.340 (0.03)	0.289 (0.12)	2.589 (0.16)	3.362 (0.38)
110-120	0.400 (0.06)	0.271 (0.07)	2.616 (0.11)	3.721 (0.05)
150-160	0.401 (0.01)	0.248 (0.07)	2.246 (0.19)	3.647 (0.48)
190-200	0.399 (0.26)	0.392 (0.14)	2.609 (0.12)	3.329 (0.19)

4

5

1 **Table 4.** The mean (standard deviation) of measured saturated hydraulic conductivity ( $K_{sat}$ ;  
 2 mm s<sup>-1</sup>) and fitted absolute value of saturated matric potential ( $\Psi_{sat}$ ; mm), fitted pore size  
 3 distribution parameter (B) and the correlation coefficients ( $R^2$ ) between calculated matric  
 4 potential using fitted equations and measured.

5

Layer (cm)	$K_{sat}$	Matric potential		
		$\Psi_{sat}$	B	$R^2$
0-10	0.0285 (0.0274)	49.14	4.03	0.991
10~20	0.0056 (0.0036)	70.66	4.49	0.996
20-30	0.0047 (0.0027)	27.02	5.22	0.994
40-50	0.0078 (0.0043)	143.4	3.59	0.994
70-80	0.0072 (0.0054)	179.6	3.22	0.993
110-120	0.0315 (0.0054)	603.7	1.89	0.969
150-160	0.0053 (0.0028)	49.17	2.97	0.993
190-200	0.0036 (0.0023)	14.47	4.565	0.989

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7

1 **Table 5.** Model performance when default sand parameters are substituted with combinations  
 2 of measured porosity (I), thermal conductivity (II), hydraulic conductivity (III) and matric  
 3 potential (IV).

	Best	I	II	III	IV	V	VI	VII	VIII	IX	X	All
	II	III	V	III	IV	III	II	II	III	III		
						V	III	IV	IV	IV		
100 cm ST	II											
ALD	I	1										
PLB	II	1	2									
10 cm SM	I	7	2	4			1	5	6			3
40 cm SM	I											
80 cm SM	I	7	1	4			2	6	5			3
160 cm CM	I	1										

4 **Note:** Best column shows the model simulations (individual parameter substitution) with the  
 5 smallest root mean squared error (RMSE) for 100 cm soil temperature (ST, °C), active layer  
 6 depth (ALD, m), permafrost low boundary (PLB, m), 10, 40, 80 and 160 cm soil liquid water  
 7 content (SM, -); Numbers indicate the combination of parameters that have smaller RMSE  
 8 than the best model run using individual parameter substitution. “All” indicates the  
 9 combination of all 4 parameters. The smallest number indicates the smallest RMSE.

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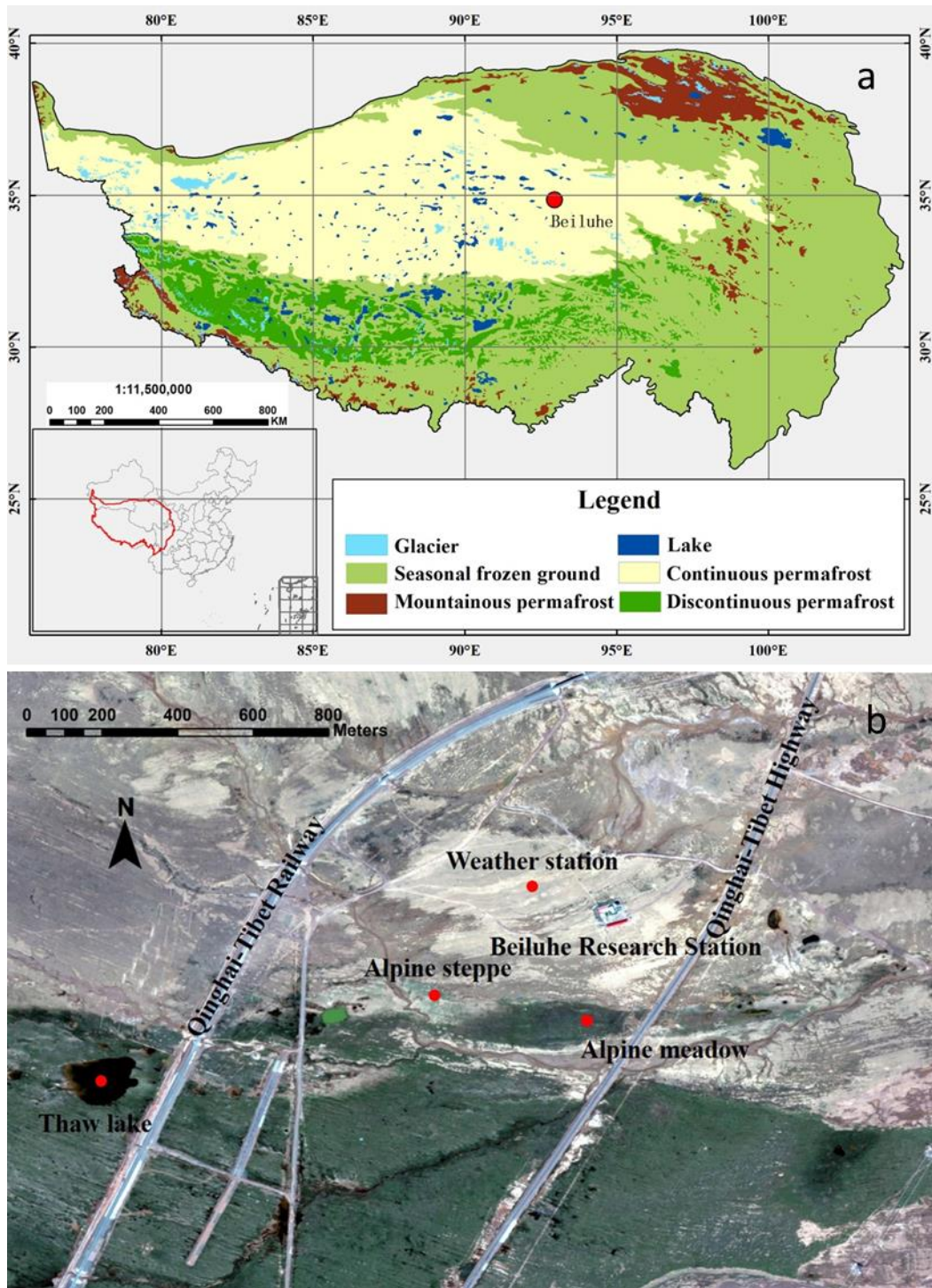
1 **Table 6** Model performance when default loam parameters are substituted with combinations  
 2 of measured porosity (I), thermal conductivity (II), hydraulic conductivity (III) and matric  
 3 potential (IV) .

4

	Best	I	I	I	II	II	I	I	I	I	II	All
		II	III	IV	III	IV	III	II	II	III	III	
							V	III	IV	IV	IV	
100 cm ST	I	1		2					3			
ALD	I	3	5					1	2	6		4
PLB	II											
10 cm SM	I	7	6	1				5	2	4		3
40 cm SM	I	5	7	1				6	3	4		2
80 cm SM	I											
160 cm SM	I	1	3					2				

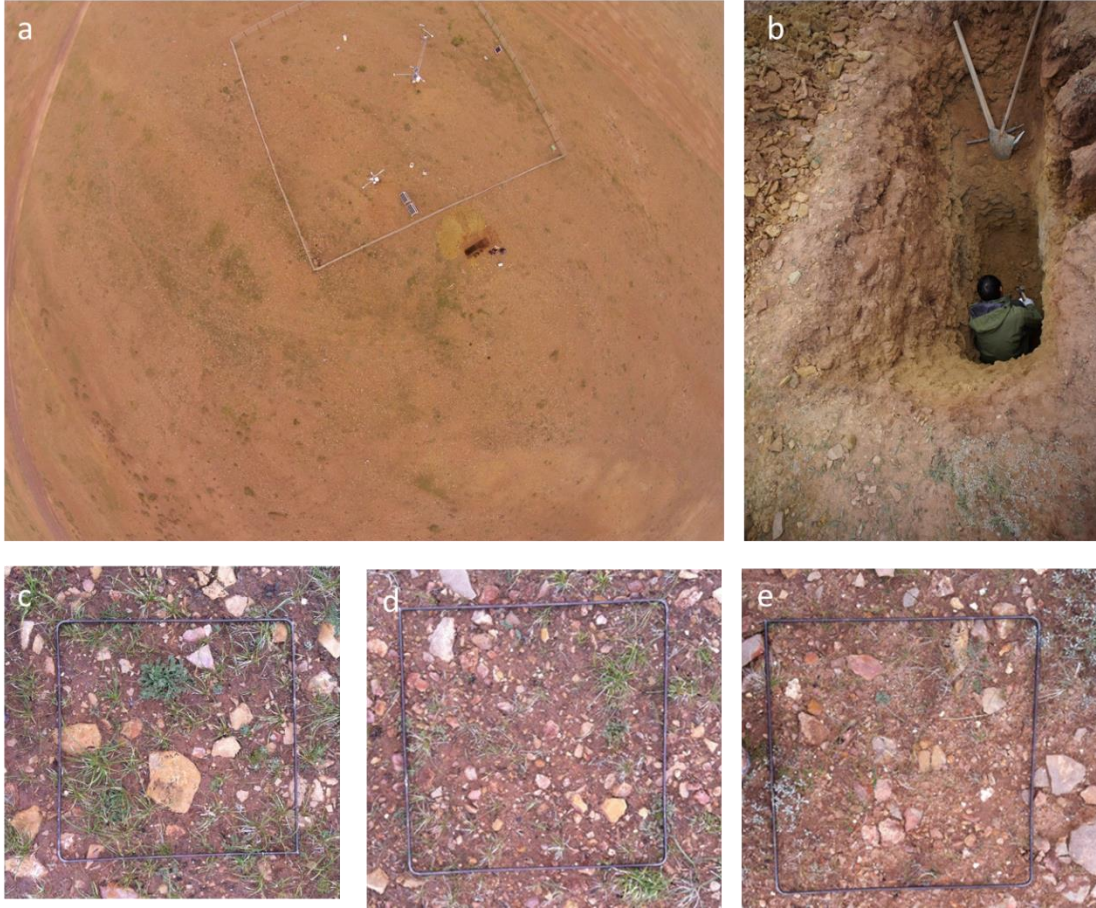
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 6 **Note:** Best column shows the model simulations (individual parameter substitution) with the  
 7 smallest root mean squared error (RMSE) for 100 cm soil temperature (ST, °C), active layer  
 8 depth (ALD, m), permafrost low boundary (PLB, m), 10, 40, 80 and 160 cm soil liquid water  
 9 content (SM, -); Numbers indicate the combination of parameters that have smaller RMSE  
 10 than the best model run using individual parameter substitution. “All” indicates the  
 11 combination of all 4 parameters. The smallest number indicates the smallest RMSE.

1 **Figure 1.** Locations of **a)** Beiluhe permafrost station on the Qinghai-Tibetan Plateau, and **b)**  
2 the weather station and the surrounding environment (Map data: Google, DigitalGlobe).



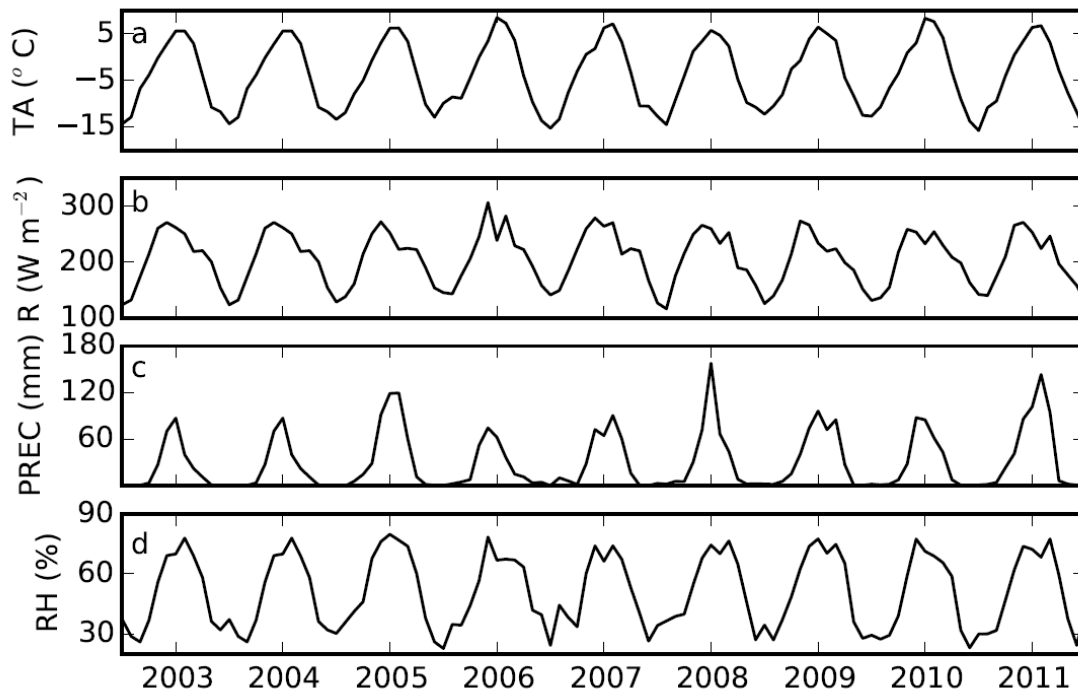
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1 **Figure 2.** Images of site conditions: **a)** the aerial view of the weather station and the  
2 excavated soil pit (the borehole is located in the lower left corner of white fence); **b)** the  
3 detailed view of the excavated soil pit; and **c)-e)** examples of vegetation, gravel and stones  
4 (iron frame is about 0.5 m×0.5 m).



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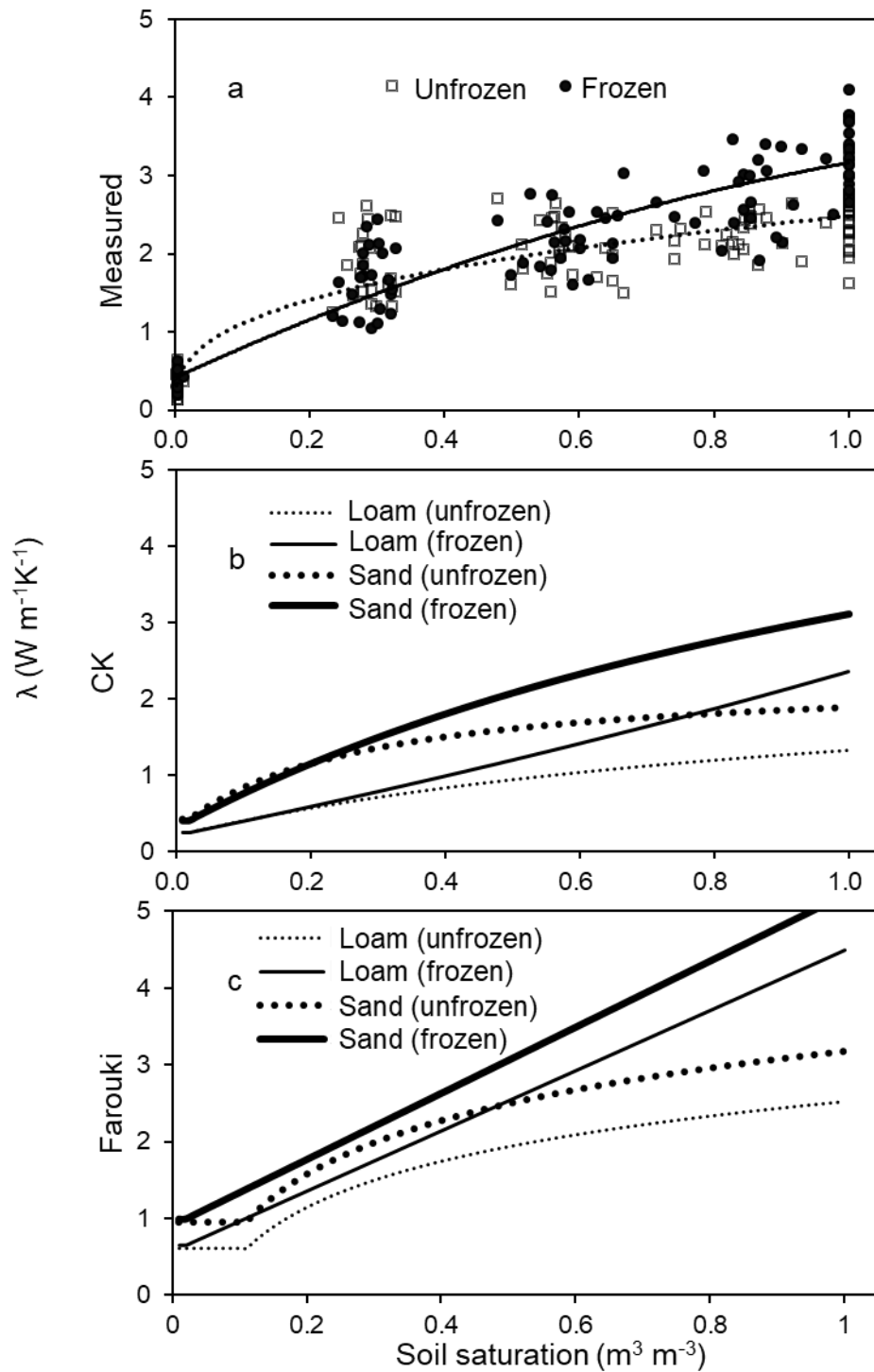
- 1 **Figure 3.** Time series of data measured at the Beiluhe weather station, Qinghai-Tibetan
- 2 Plateau, 2003 to 2011: **a)** air temperature (TA, °C); **b)** downward solar radiation (R, W m<sup>-2</sup>); **c)**
- 3 precipitation (PREC, mm); and **d)** relative humidity (RH, %).



4

1 **Figure 4.** The relationship between soil saturation (solid and dotted lines represent frozen and  
 2 unfrozen cases) and soil thermal conductivity ( $\lambda$ ,  $\text{W m}^{-1}\text{K}^{-1}$ ) from: **a)** measured values  
 3 (Measured; dots and empty diamonds represent measured frozen and unfrozen soil thermal  
 4 conductivities, respectively); **b)** using the Côté and Konrad (2005) scheme (CK); and **c)**  
 5 using the Farouki (1986) scheme (Farouki).

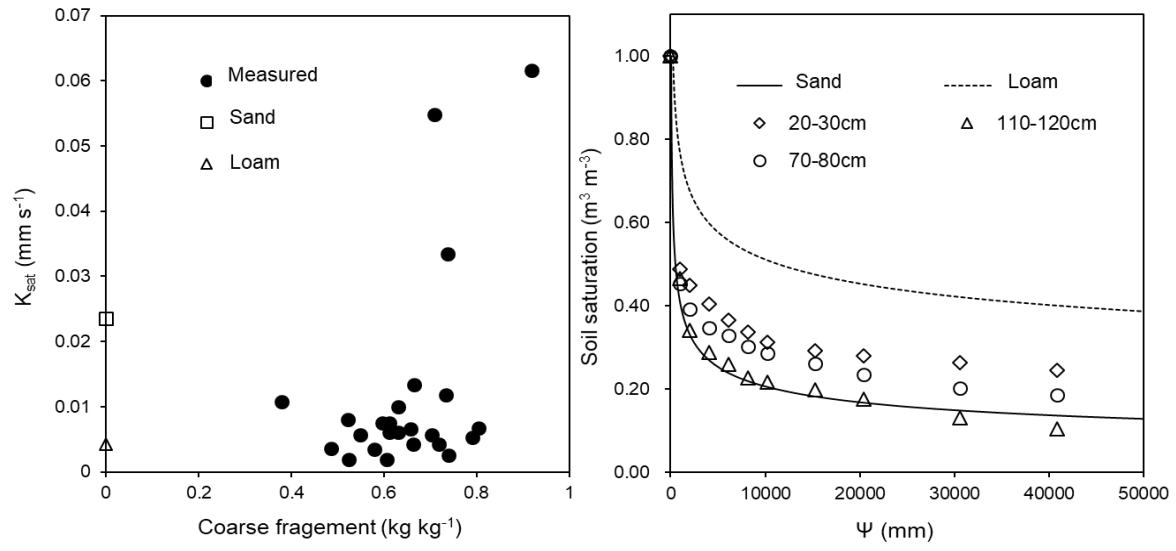
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1 **Figure 5.** The relations between: **a)** saturated hydraulic conductivity ( $K_{sat}$ ,  $\text{mm s}^{-1}$ ) and coarse  
 2 fragment fraction (Solid dots represent measured value; empty circle and empty triangle  
 3 represent the corresponding values of sand and loam used in Community Land Model,  
 4 respectively), and **b)** soil saturation ( $\text{m}^3 \text{m}^{-3}$ , lines) and absolute value of matric potential ( $\Psi$ ,  
 5  $\text{mm H}_2\text{O}$ ) at three representative depths (solid and dashed lines represent default values  
 6 (Oleson et al., 2010) of sand and loam, respectively).

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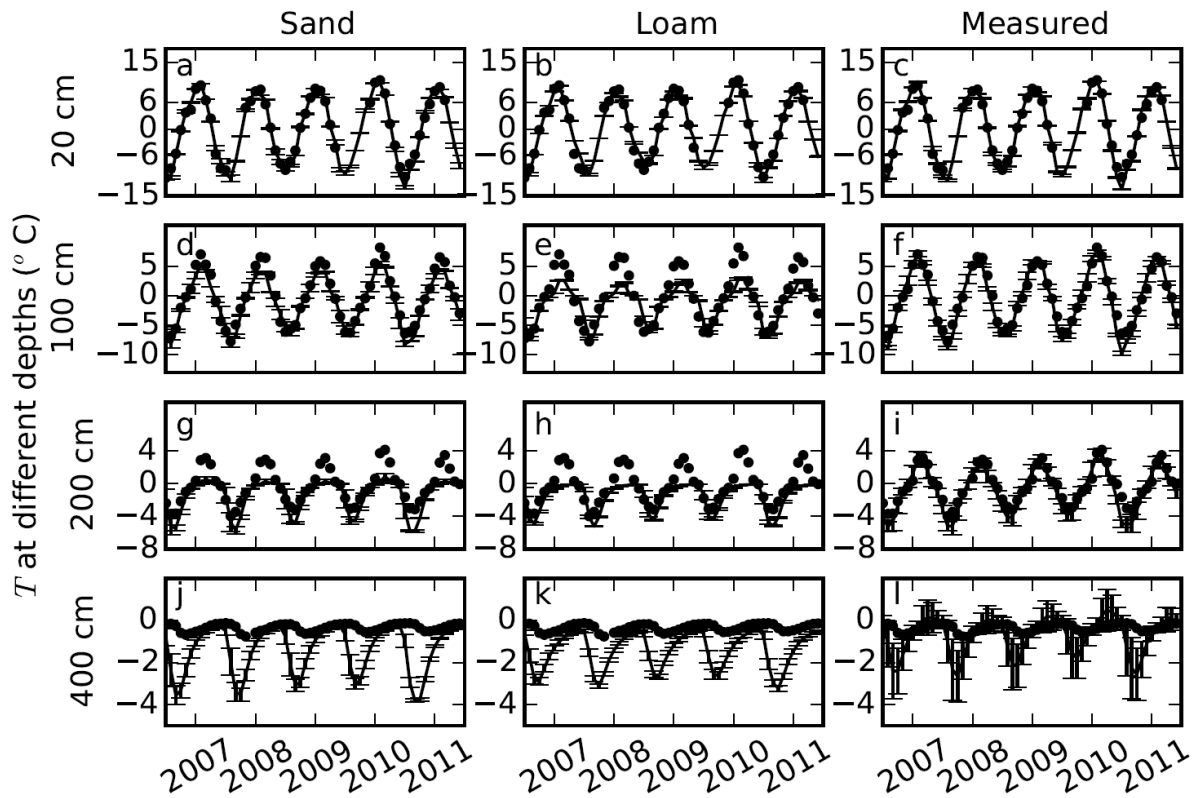


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1 **Figure 6.** Comparisons of soil temperatures ( $T$ , °C) simulated using default parameters for  
2 sand, loam, and our measured parameters (lines) with measured soil temperatures (dots) at 20,  
3 100, 200, and 400 cm depths. Error bars show the standard deviations calculated based on 9  
4 simulations with 3 different slopes and 3 different soil thicknesses (Measured porosities were  
5 used in the simulation).

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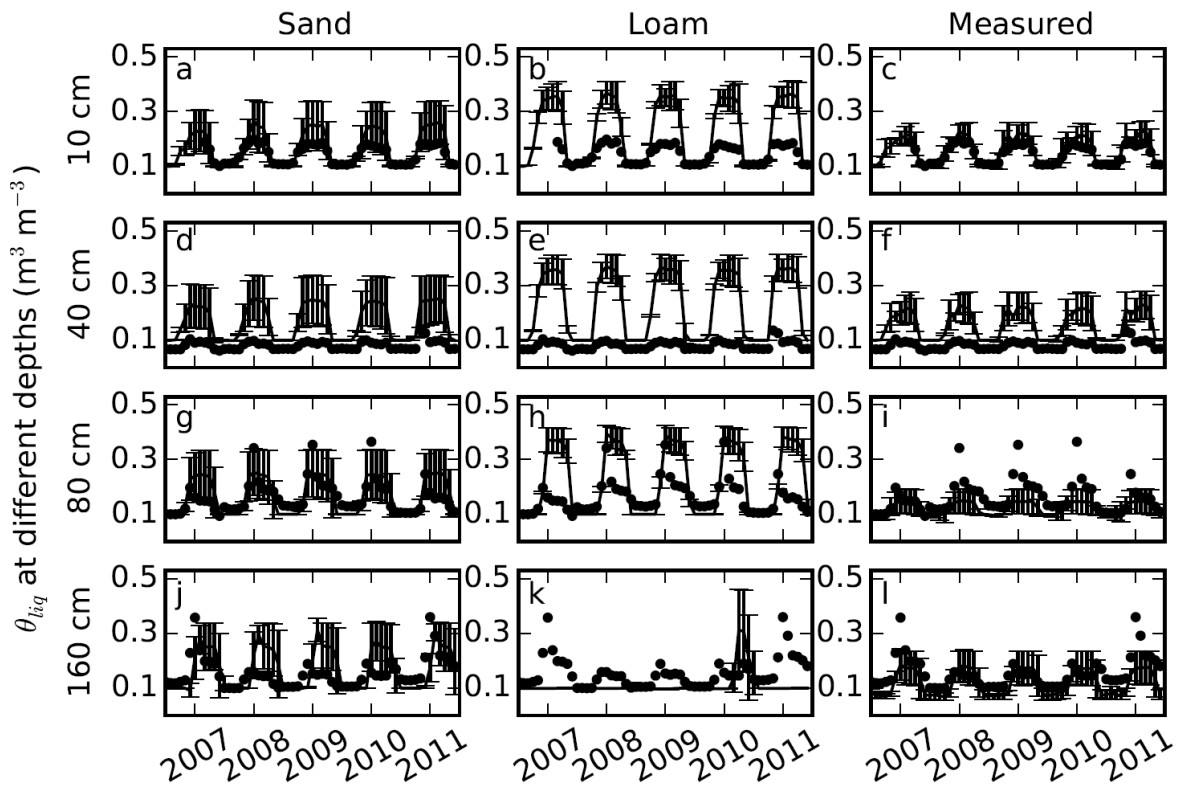


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1 **Figure 7.** Comparisons of soil volumetric liquid water content ( $\theta_{liq}, m^3 m^{-3}$ ) simulated using  
 2 default parameters sand, default loam, and measured parameters (lines) with measured soil  
 3 moistures (dots) at 10, 40, 80, and 160 cm depths. Error bars showed the standard deviation  
 4 calculated based on 9 simulations with 3 different slopes and 3 different soil thicknesses  
 5 (Measured porosities were used in the simulation).

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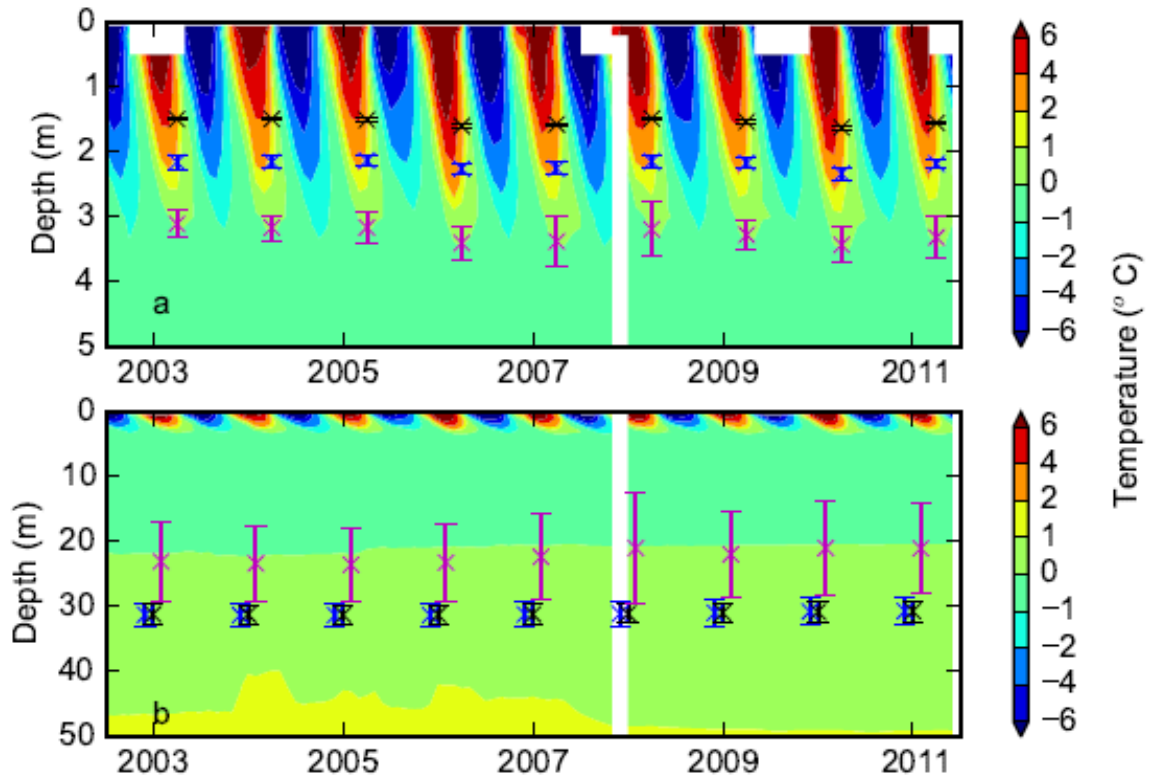


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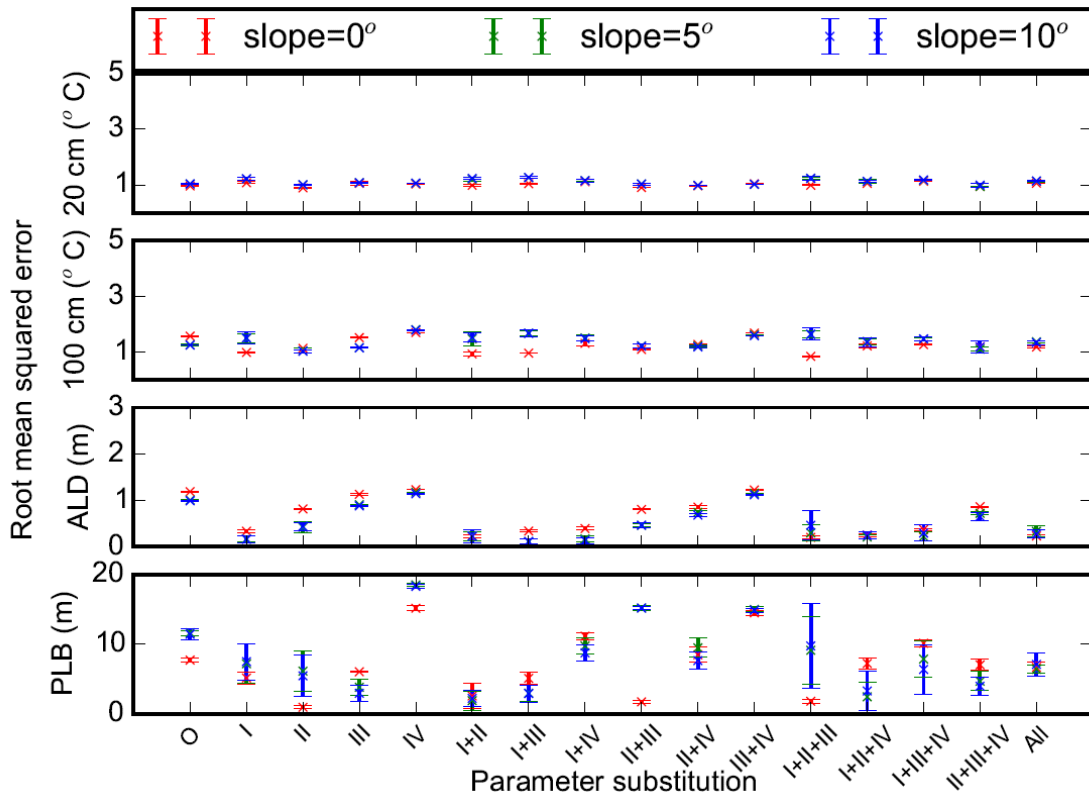


1 **Figure 8.** Contour plots showing **a)** soil temperature ( $^{\circ}\text{C}$ ) from borehole measurements down  
 2 to 5 m superimposed with simulated active layer depths over the period of 2003-2011; and **b)**  
 3 ground temperature down to 50 m superimposed with the simulated permafrost low boundary.  
 4 Black, blue and magenta represent simulations with loam, sand, and measured parameters,  
 5 respectively. Error bars show the standard deviation calculated based on 9 simulations with 3  
 6 different slopes and 3 different soil thicknesses (Measured porosities were used in the  
 7 simulation). White zones in the contour plots indicate missing borehole data.



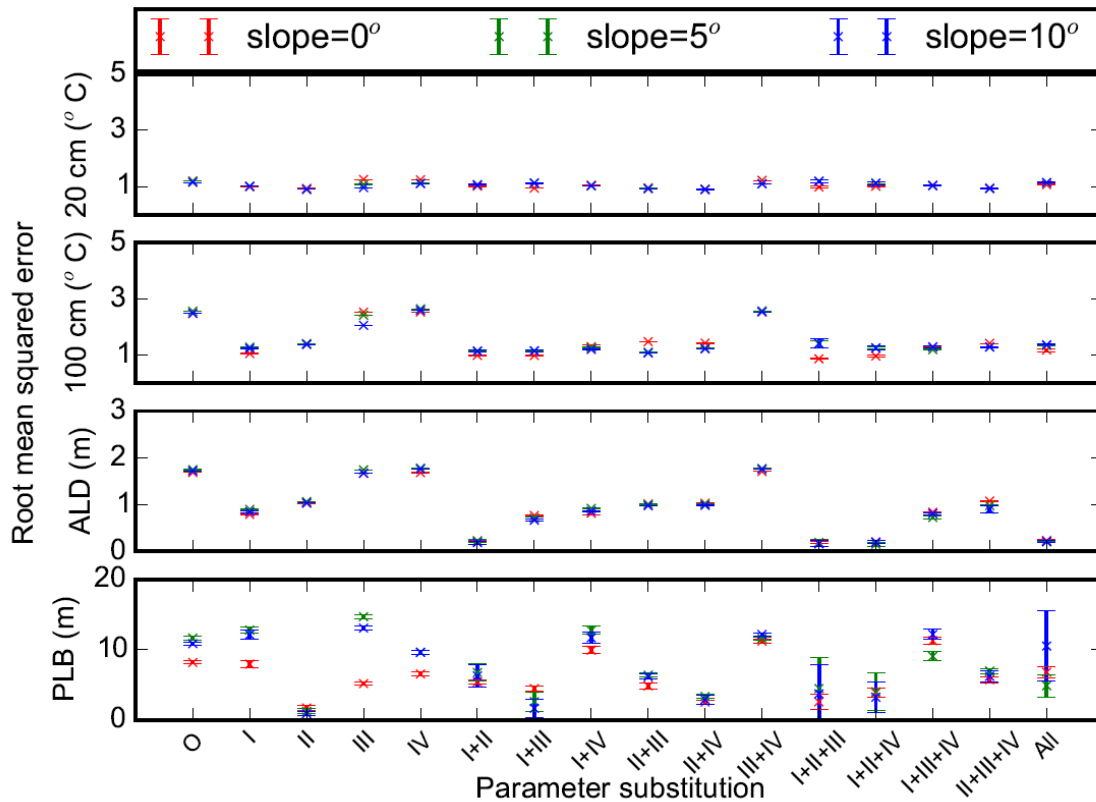
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1 **Figure 9.** Root mean squared errors between measurements and model simulations (with  
 2 different combinations of measured porosity (I), thermal conductivity (II), hydraulic  
 3 conductivity (III), and matric potential (IV) substituted for default sand parameters) for 20  
 4 and 100 cm soil temperatures ( $^{\circ}\text{C}$ ), active layer depth (ALD, m), and permafrost low  
 5 boundary (PLB, m). O and All represent model runs without substitution of default  
 6 parameters and with all 4 parameters substituted, respectively. Mean and standard deviation  
 7 of model simulations with 3 different soil thicknesses at each slope ( $0^{\circ}$ ,  $5^{\circ}$ , and  $10^{\circ}$ ) are shown.



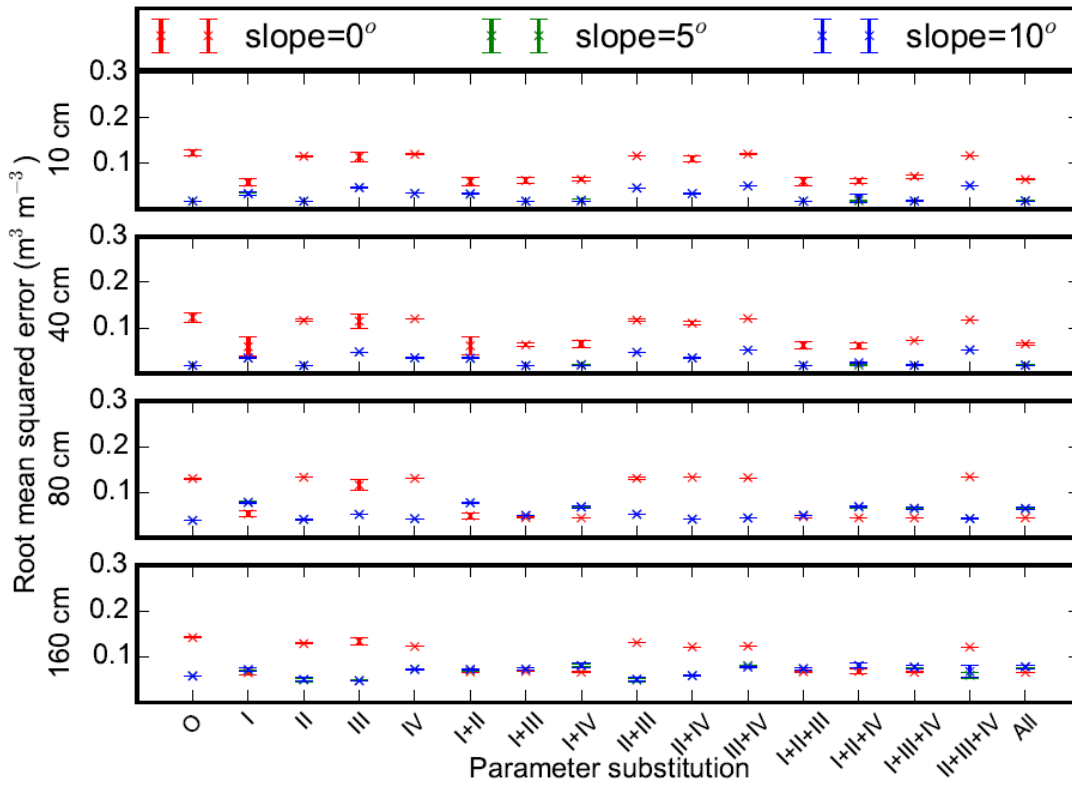
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1 **Figure 10.** Root mean squared errors between measurements and model simulations (with  
 2 different combinations of measured porosity (I), thermal conductivity (II), hydraulic  
 3 conductivity (III), and matric potential (IV) substituted for default loam parameters) for 20  
 4 and 100 cm soil temperatures ( $^{\circ}\text{C}$ ), active layer depth (ALD, m), and permafrost low  
 5 boundary (PLB, m). O and All represent model runs without substitution of default  
 6 parameters and with all 4 parameters substituted, respectively. Mean and standard deviation  
 7 of model simulations with 3 different soil thicknesses at each slope ( $0^{\circ}$ ,  $5^{\circ}$ , and  $10^{\circ}$ ) are shown.



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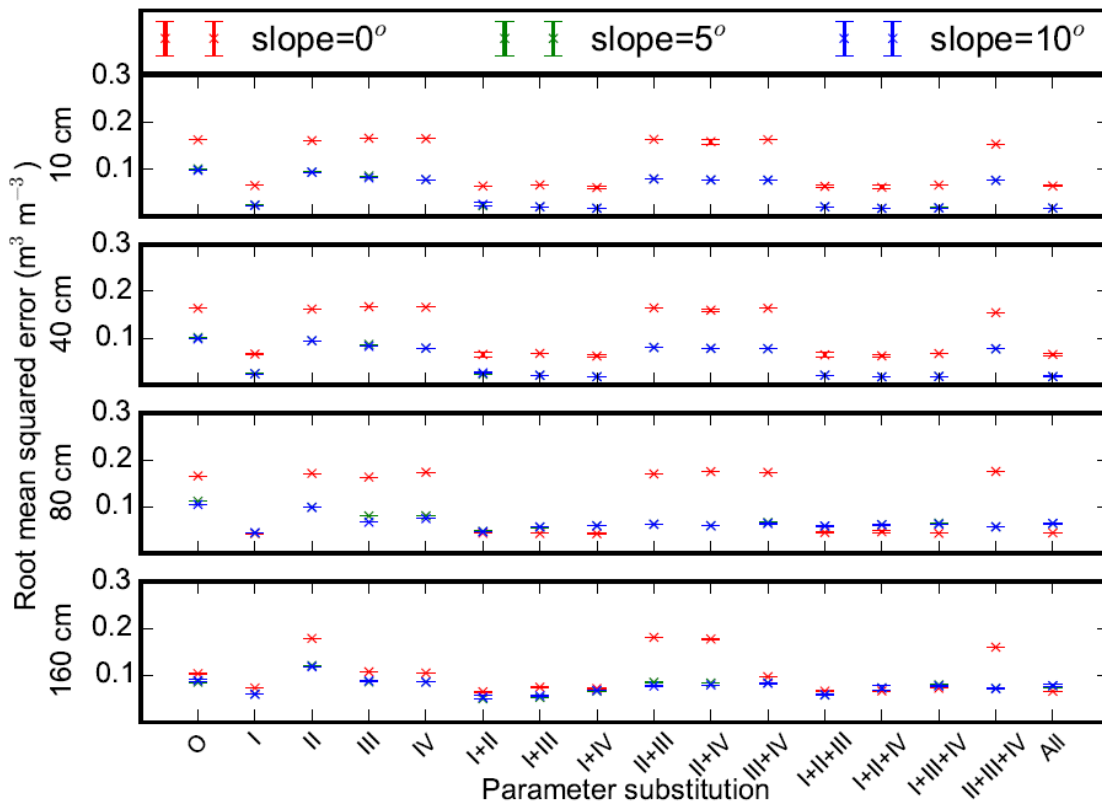
1 **Figure 11.** Root mean squared errors between measurements and model simulations (with  
 2 different combinations of measured porosity (I), thermal conductivity (II), hydraulic  
 3 conductivity (III), and matric potential (IV) substituted for default sand parameters) for 10 cm,  
 4 40 cm, 80 cm, and 160 cm soil volumetric liquid water content. O and All represent model  
 5 runs without substitution of default parameters and with all 4 parameters substituted,  
 6 respectively. Mean and standard deviation of model simulations with 3 different soil  
 7 thicknesses at each slope ( $0^\circ$ ,  $5^\circ$ , and  $10^\circ$ ) are shown.



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1 **Figure 12.** Root mean squared errors between measurements and model simulations (with  
 2 different combinations of measured porosity (I), thermal conductivity (II), hydraulic  
 3 conductivity (III), and matric potential (IV) substituted for default loam parameters) for 10 cm,  
 4 40 cm, 80 cm, and 160 cm soil volumetric liquid water content. O and All represent model  
 5 runs without substitution of default parameters and with all 4 parameters substituted,  
 6 respectively. Mean and standard deviation of model simulations with 3 different soil  
 7 thicknesses at each slope ( $0^\circ$ ,  $5^\circ$ , and  $10^\circ$ ) are shown.

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