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A generalized relationship between thermal conductivity and matric suction of soils

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ABSTRACT

The soil thermal conductivity (λ) and matric suction of soil water (*h*, the negative of matric potential) relationship has been widely used in land surface models for estimating soil temperature and heat flux following the McCumber and Pielke (1981, MP81) λ-*h* model. However, few datasets are available for evaluating the accuracy and feasibility of the MP81 λ-*h* model under various soil and moisture conditions. In this study, we developed a new λ-*h* model and compared its performance with that of the MP81 model using measurements on 18 soils with a wide range of textures, water contents and bulk densities. The heat pulse technique was used to measure λ, and the suction table, micro-tensiometers, pressure plate device, and the dew point potentiometer were applied to obtain soil water retention curves at the appropriate suction ranges. In the range of pF (the common logarithm of *h* in cm) ≤ 3, the λ-*h* relationships were highly nonlinear and varied strongly with soil texture and bulk density. In the dry range (i.e., pF > 3), there existed a universal λ-*h* relationship for all soil textures and bulk densities, and an exponential function was established to describe the relationship. Independent evaluations using λ-*h* data on five intact soil samples showed that the new model produced accurate λ data from pF values with root mean square errors (RMSE) with the range of 0.03–0.18 W m^{-1} K^{-1}. While, large errors (RMSEs within 0.17–0.36 W m^{-1} K^{-1}) were observed with λ estimates from the MP81 model.

1. Introduction

Soil thermal conductivity (λ) is an important physical property in land surface parameterization (Ek et al., 2003; Zheng et al., 2015). It is well known that soil λ depends on soil water content (θ), bulk density (ρ_b), texture, mineral composition, organic matter and temperature. Several λ models, such as de Vries (1963), Johansen (1975), Campbell (1985), Côté and Konrad (2005), and Lu et al. (2007), have been developed to describe the dependence of λ on soil texture, ρ_b and θ. These empirical and semi-empirical models, however, are sensitive to quartz fraction, which varies significantly across soils and largely affects the magnitude of λ values at a fixed θ (Lu et al., 2007; Lu et al., 2014). Soil mineralogy has a great impact on λ values, which have been extensively highlighted by many researchers (Wierenga et al., 1969; Bristow, 1998; Abu-Hamdeh and Reeder, 2000). According to the theory of percolation-based effective medium approximation, λ is also affected by both pore structure and geometrical characteristics of soil particles, as indicated by the non-universal relation between λ and degree of saturation (Ghanbarian and Daigle, 2016). Recently Likos (2014) estimated λ curves from bimodal water retention curves. This approach requires seven fitting parameters based on measured data. Considering the similarities between soil water retention curves (SWRC) and λ(θ) curves, Lu and Dong (2015) put forward an empirical λ(θ) model similar to the form of the van Genuchten (1980) water retention model. The model requires measurements of SWRCs in the entire θ range to get a λ(θ) curve. At present, no universal λ(θ) model is available for all soil types and conditions (Dong et al., 2015).

Rather than θ, λ may relate more closely to the energy state of soil water, which contains information of pore size and geometry. Al Nakshabandi and Kohnke (1965) first reported similar λ-matric suction (*h*, the negative of matric potential) relations among soils with different textures and ranges of ρ_b, i.e., 1.40–1.43 g cm^{-3} for a sand soil, 1.15–1.30 g cm^{-3} for a silt loam soil, and 0.89–1.00 g cm^{-3} for a clay soil. They pointed out that a general λ and *h* relationship existed that was independent of soil type and ρ_b, and it was possible to estimate λ from *h* by using such relations. Generally, soil matric suction controls

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the thickness of the soil water films and the size of the 'water bridges' between soil particles, which greatly influences soil heat flow and λ (Ewing and Horton, 2007). Using soil matric suction rather than θ enables more robust and transferable comparisons across different textured soils. Thereafter, McCumber and Pielke (1981) established a simple function by fitting the λ-h data from Al Nakshabandi and Kohnke (1965),

$$\begin{cases} \lambda = 418\exp[-(\mathrm{pF}+2.7)] & \mathrm{pF} \le 5.1 \\ \lambda = 0.1714 & \mathrm{pF} > 5.1 \end{cases} \quad (1)$$

where the unit of λ is W $m^{-1}K^{-1}$, and pF = $\log_{10}h$, where *h* is the matric suction expressed in centimeters. The form of Eq. (1) is slightly different from its original expression because the unit of λ is converted from cal s^{-1} cm^{-1} $°C^{-1}$ to W m^{-1} K^{-1}. Eq. (1) is hereafter referred to as the MP81 model.

The MP81 model has been applied widely used for estimating soil λ in the land surface models for simulating soil temperature and surface heat flux (Noilhan and Planton, 1989; Smirnova et al., 1997; Chen and Dudhia, 2001; Fernando et al., 2013; Massey et al., 2014). However, as pointed out by Peters-Lidard et al. (1998), the MP81 model tends to overestimate λ on wet soils and to underestimate λ on dry soils, leading to large errors in surface heat flux estimates. Béhaegel et al. (2007) demonstrated that the MP81 model gave unacceptable λ results (> 3 W m^{-1} K^{-1}) at high θ values. Chen and Dudhia (2001) used a maximum λ value of 1.9 W m^{-1} K^{-1} for soils of different textures because the MP81 model tended to overestimate λ on wet soils. McInnes (1981) determined the λ-*h* relation on five soils with some unreasonable *h* data points (*h* > 7) under dry conditions, and no knowledge of the measurement errors was given. Thus, despite the fact that the λ-*h* relationship has been widely used to simulate heat and water transport in soils, there is a general lack of λ-*h* data over the entire water range for various soil textural classes, and few studies have been performed to measure such relationships quantitatively (Campbell, 1988).

With the development of rapid and accurate methods available for measuring the energy state of soil water and thermal properties, e.g., the heat pulse method, the suction table and the dew point potentiometer, it is possible to obtain reliable λ-*h* data simultaneously in the complete saturation range, and to examine the relationship between λ and *h* using such datasets.

The objectives of this study are (1) to determine λ-*h* relation of various soil textures in the entire θ range, (2) to evaluate the MP81 model using the newly measured data, and (3) to develop a general model that describes the λ-*h* relationship across different soil textures.

2. Materials and methods

In this study, the λ-*h* relationship was examined on 18 soils. Table 1 lists the basic physical characteristics of the soil samples. The particle size distributions and soil organic matter contents were determined by using the pipette method (Gee and Or, 2002) and the Walkley–Black titration method (Nelson and Sommers, 1982), respectively. Three independent experiments were conducted to measure λ and *h* using the repacked soil cores (Experiment 1), intact and repacked soil samples during a continuous drying process (Experiment 2), and intact soil samples at various water contents (Experiment 3). The data from Experiments 1 and 2 were used to develop a new λ-*h* model, and the results from Experiment 3 were used for evaluating the new model.

2.1. Experiment 1: measurements on repacked soil samples

In this experiment, laboratory measurements of λ and *h* on repacked soil columns were conducted on Soils 1–9 (Table 1). The soil samples were air dried, ground, and sieved through a 2-mm screen, and then repacked into soil columns (50-mm inner diameter and 10-mm high) according to the desired ρ_b (Table 1). The pressure plate extractor method (Dane and Hopmans, 2002) was used to measure SWRC for the suction range ≤ 1500 kPa, and the dew point potentiometer (WP4-T, Decagon Devices, Pullman, WA) was used to determine SWRC in the suction range > 1500 kPa. Refer to Lu et al. (2008) for details of the SWRC measurements on repacked soil samples for the entire suction range. The pF scale is used for matric suction hereafter, since *h* values are of several orders of magnitude from saturation to oven-dryness.

To determine λ at the corresponding *h* values, we used the repacked soil columns of different θ, which was achieved by adding various amounts of water into the soil sample and mixing thoroughly. The moist soil was then packed into a column (50.2 mm inner diameter and 50.2 mm high) for soil thermal property measurement. A three-needle heat pulse probe was used for the heat pulse measurements (Ren et al., 1999). The sensor had three parallel needles with a spacing of 6 mm between adjacent needles. Each needle was 40 mm in length and 1.3 mm in diameter. During the heat pulse measurement, a certain amount of current was applied to the middle heater for 15 s to generate a heat pulse, and λ was calculated by using a nonlinear regression technique based on the temperature change versus time data in the two outer needles (Welch et al., 1996). Details on the heat pulse measurements were presented in Lu et al. (2007). After the heat pulse measurement, gravimetric θ and ρ_b data were determined by oven-drying the soil samples at 105 °C to constant weight. In both water potential measurements and heat pulse measurements, three repetitions were used.

2.2. Experiment 2: continuous measurements on repacked and intact soil samples

In Experiment 1, the λ-*h* data were obtained on repacked soil cores in a non-continuous way, and the data at large θ values were missing due to difficulties in repacking soil columns uniformly. To further evaluate the change of λ as a function of *h* in the range of pF < 2, we conducted the additional laboratory experiments where *h* was measured with a sandbox device (08.01 Sandbox, Eijkelkamp, Zeitz, Germany) and micro-tensiometers. For sandbox experiment (Soil C1), an intact soil core (50.2 mm inner diameter and 50.2 mm high) was collected from the 0- to 5-cm soil layer at the Experiment Farm of China Agricultural University, Beijing. The soil core was placed on the sandbox and slowly saturated with water (Fig. 1a). Then water was drained step by step by using a hanging water column system from complete saturation to suctions of 5, 10, 20, 40, 60, and 80 cm, respectively (Romano et al., 2002). After hydraulic equilibrium was achieved, a three-needle heat-pulse sensor was inserted vertically into the sample to determine λ. Three replicated measurements were conducted on the sample at each suction. Finally, the soil sample was oven-dried for measuring ρ_b.

Another experiment was conducted on two repacked soil columns (Soils C2 and C3), in which λ and *h* were monitored continuously from saturation under natural evaporation conditions using micro-tensiometers (Fig. 1b). Such method was also recommended by Drefke et al. (2017) for simultaneous measurements of λ and *h*. The height and diameter of the clear plexiglass column were 8 cm. The bottom of the column was covered with 1-cm thick quartz sand, and a filter paper was placed at the top of the quartz sand. The sieved soil samples were then packed at desired ρ_b (Table 1). A three-needle heat pulse sensor and a micro-tensiometer equipped with pressure transducers (Soil Measurement System, Tucson, AZ) were inserted to the soil column from pre-drilled holes (Fig. 1b). The micro-tensiometer had a measurement range of 0–100 kPa. The space between the sensors and plexiglass column was sealed with glue, and the soil samples were saturated using a Marriott bottle. The measurements were initiated when the soil columns were fully saturated and continued during the natural evaporation process. A datalogger (model CR23X, Campbell Scientific, Logan, UT) recorded the signals from the heat pulse sensor and pressure transducer hourly. The voltage signals from the pressure transducer changed linearly with