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# Determination of Desert Soil Apparent Thermal Diffusivity Using a Conduction-Convection Algorithm


## Abstract

Surface soil temperatures impact land-atmosphere interactions in desert environments. Soil apparent thermal diffusivity (*k*) is a crucial physical parameter affecting soil temperature. Previous studies using the conduction-convection algorithm reported *k* values of desert soils for only a few days. The main objective of this study is to determine the daily and monthly variations of desert *k* for a range of water contents over a 10 month period. The *k* values were estimated with a conduction-convection algorithm using soil temperature measured at the 0.00 m and 0.20 m depths from 1 January to 11 October 2011 at the Tazhong station in the Taklimakan desert of China. Generally, the daily values of *k* ranged from 1.46 × 10−7m2 s−1 to 5.88 × 10−7m2 s−1, and the 10 month average *k* value was 2.5(±0.8) × 10−7m2 s−1 for the 0.00 m to 0.20 m soil layer. The *k* values varied significantly with soil water content. The apparent convection parameter (*W*), which is the sum of the vertical gradient of *k* and apparent water flux density, was also determined. Comparison of the magnitudes of *W* and *k* gradients indicated that little water movement occurred during the dry months, some water infiltrated downward during the wet months, and some water moved upwards in response to evaporation following the wet months. These findings confirmed that the conduction-convection algorithm described the general pattern of soil water movement. The presented daily and monthly values of *k* can be used as soil parameters when modeling land-atmosphere interactions in the Taklimakan desert.


## Disciplines

Agriculture | Atmospheric Sciences | Desert Ecology | Soil Science

## Comments


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Zhiqiu Gao and Bing Tong contributed equally to the work and are co-first authors.

**Key Points:**
- Daily and monthly variations of *k* values for a desert soil were determined over a 10 month period with a conduction-convection model
- The conduction-convection model provided a clear soil apparent thermal diffusivity versus water content relationship for the desert soil
- The conduction-convection model described well the general pattern of soil water movement in the desert soil

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# Determination of Desert Soil Apparent Thermal Diffusivity Using a Conduction-Convection Algorithm

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**Abstract** Surface soil temperatures impact land-atmosphere interactions in desert environments. Soil apparent thermal diffusivity (*k*) is a crucial physical parameter affecting soil temperature. Previous studies using the conduction-convection algorithm reported *k* values of desert soils for only a few days. The main objective of this study is to determine the daily and monthly variations of desert *k* for a range of water contents over a 10 month period. The *k* values were estimated with a conduction-convection algorithm using soil temperature measured at the 0.00 m and 0.20 m depths from 1 January to 11 October 2011 at the Tazhong station in the Taklimakan desert of China. Generally, the daily values of *k* ranged from $1.46 \times 10^{-7} m^2 s^{-1}$ to $5.88 \times 10^{-7} m^2 s^{-1}$, and the 10 month average *k* value was $2.5(\pm 0.8) \times 10^{-7} m^2 s^{-1}$ for the 0.00 m to 0.20 m soil layer. The *k* values varied significantly with soil water content. The apparent convection parameter (*W*), which is the sum of the vertical gradient of *k* and apparent water flux density, was also determined. Comparison of the magnitudes of *W* and *k* gradients indicated that little water movement occurred during the dry months, some water infiltrated downward during the wet months, and some water moved upwards in response to evaporation following the wet months. These findings confirmed that the conduction-convection algorithm described the general pattern of soil water movement. The presented daily and monthly values of *k* can be used as soil parameters when modeling land-atmosphere interactions in the Taklimakan desert.

## 1. Introduction

Soil temperature plays an important role in regulating land surface processes, and it is used in land surface modeling, numerical weather forecasting, and climate prediction (Holmes et al., 2008). It is especially relevant for the soil surface. Accurate prediction of soil surface temperature requires a realistic understanding of the soil thermal properties, namely, volumetric heat capacity, thermal conductivity, and apparent thermal diffusivity. Soil volumetric heat capacity can be derived from soil components (Van Wijk & De Vries, 1963). Soil apparent thermal conductivity and thermal diffusivity are related by volumetric heat capacity; thus, only one needs to be determined. The soil apparent thermal diffusivity (*k*) is associated with transient processes of heat conduction and intraporous convection (Zhang & Osterkamp, 1995; Passerat de Silans et al., 1996). Several algorithms are available to calculate the apparent thermal diffusivity of field soil from observed temperature variations. Most of these methods are based on solutions of one-dimensional conduction heat transfer equations with constant diffusivity and soil upper boundary described by a sinusoidal function (Van Wijk & De Vries, 1963), by two harmonics (Nerpin & Chudnovskii, 1967; Seemann 1979), or by a Fourier series (Heusinkveld et al., 2004; Horton et al., 1983). Horton et al. (1983) examined six methods (the amplitude, phase, arctangent, logarithmic, numerical, and harmonic) to determine soil apparent thermal diffusivity and reported that the Harmonic method outperformed than the other methods.

Some methods of estimating soil apparent thermal diffusivity are based on the solution of the one-dimensional soil conduction-convection heat transfer equation. Gao et al. (2003) incorporated thermal conduction and convection and obtained an analytical solution of the soil heat transfer equation with constant soil apparent thermal diffusivity, and sinusoidal upper boundary temperature. They derived an expression for soil apparent thermal diffusivity (*k*). Gao et al. (2008) improved the algorithm by considering vertical heterogeneity in $k$. Based on the algorithm proposed by Gao et al. (2008), Hu et al. (2016) described the soil upper boundary condition by a Fourier series instead of a sinusoidal function. The mean soil apparent thermal diffusivity and water flux density were derived by using a genetic algorithm method. Wang et al. (2010) compared six algorithms (the amplitude, phase, arctangent, logarithmic, conduction-convection, and harmonic) to determine the soil $k$ at a site in the Loess Plateau of China and showed that the harmonic algorithm performed best, and the conduction-convection algorithm followed. Compared with the harmonic algorithm, the conduction-convection algorithm has a less accurate description of the upper boundary temperature, but by accounting for the vertical gradient of soil thermal diffusivity and the apparent water flux density, it includes more physics in the soil heat transfer process. Compared with the algorithm determination of $k$ proposed by Hu et al. (2016), the algorithm of $k$ proposed by Gao et al. (2008) is easier to calculate and has the specific mathematical expression for $k$.

Deserts occupy 40% of the total land area of Earth (Warner, 2004) and soil temperature is an important parameter that affects desert-atmosphere interactions (Jacobs et al., 1999, 2000), which have many important hydrological and climatic implications. Studies have shown that land-air interactions over the Taklimakan desert in China, one of the world's largest sandy deserts and the largest in Asia, affect not only the local and regional climate but also the monsoon circulation in China (Zhang & Huang, 2004). Most previous studies used traditional methods that only take into account thermal conduction to estimate soil thermal properties over deserts. Zhang and Huang (2004) calculated the soil $k$ as the ratio of thermal conductivity and volumetric heat capacity, which were determined by measured surface soil temperature and soil heat fluxes at two layers collected at a site over a typical arid region of the Dunhuang Gobi. Based on the method proposed by Zhang and Huang (2004), Wang et al. (2005) derived soil thermal parameters with data measured at a cold semidesert site on the western Tibetan Plateau, and Liu et al. (2011, 2012) estimated the soil thermal parameters with data measured at a desert site in the Taklimakan desert hinterland. Heusinkveld et al. (2004) estimated soil apparent thermal diffusivity from an iteration process by fitting the amplitude and phase of soil temperature at one depth, and then estimating soil temperature in a sandy desert belt situated in the northwest of Negev, Israel. Later, Gao et al. (2007) showed that the conduction-convection algorithm (Gao et al., 2003) gave more realistic soil temperature estimations than did the traditional algorithm using the same soil temperature data (1 day) from Heusinkveld et al. (2004).

Earlier studies have not used a conduction-convection model to determine temporal variations in desert soil apparent thermal diffusivity. To quantify the monthly values of soil apparent thermal diffusivity such as to meet the need of land surface models, in this paper, soil temperature data over a 10 month period collected in the Taklimakan desert hinterland were analyzed. A conduction-convection model was used. The apparent convection parameter ($W$), the sum of vertical gradient of soil apparent thermal diffusivity and apparent water flux density, was also determined.

## 2. Material and Methods

### 2.1. Material

The Taklimakan desert is the largest desert in China [Warner, 2004], and the world's second largest shifting sand desert, 85% of which consists of shifting and crescent-shaped sand dunes. The data used here were collected at the Taklimakan desert Atmosphere and Environment Observation Experiment Station located at Tazhong (hereinafter referred to as Tazhong station) from 1 January (day of year (DOY) 1) to 11 October (DOY 284) 2011. This site was located at 83.64°E, 38.98°N with an altitude of 1103 m. The ground surface was bare and relatively flat. The soil at the site was predominantly fine sand. The site had an arid climate zone with maximum and minimum air temperatures of 319 K and 240 K. The mean annual air temperature and precipitation were 285 K and 24 mm, respectively. The site had 2,690 h of sunshine and 263 frost-free days per year (averaged from 1996 to 2010).

Soil temperatures were measured at the 0.00 m, 0.10 m, 0.20 m, and 0.40 m depths by Temperature Probes, 109L (Campbell Scientific Inc.), with accuracy ±0.2 K. Soil volumetric water contents (VWC) were measured at the 0.025 m, 0.10 m, 0.20 m, and 0.40 m depths by Soil Moisture Sensors, CS616 (Campbell Scientific Inc.), with accuracy ±2.5% VWC. The soil temperature and moisture sensors were sampled each second, and each sensor output was averaged over 30 min time period and recorded. Standard micrometeorological measurements were also made at the site, including four radiation components, wind speed, wind direction, air temperature, relative humidity, air pressure, and precipitation. The precipitation was measured by rain gauge and the output was averaged over a 60 min time period and recorded.

### 2.2. Review of the Conduction-Convection Algorithm

Expanding the heat conduction equation presented by Van Wijk and De Vries (1963), Gao et al. (2003) presented the conduction and sensible convection heat transfer equation with an assumption that the soil apparent thermal diffusivity was vertically homogenous. But in reality $k$ could vary vertically in soil. Under such conditions, Gao et al. (2008) presented the following heat transfer equation,

$$\begin{aligned}\frac{\partial T}{\partial t} &= \frac{1}{C_g}\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) - \frac{Cw}{Cg}w\theta\frac{\partial T}{\partial z} = \frac{\lambda}{C_g}\frac{\partial^2 T}{\partial z^2} + \frac{1}{C_g}\frac{\partial\lambda}{\partial z}\frac{\partial T}{\partial z} - \frac{Cw}{Cg}w\theta\frac{\partial T}{\partial z} \\ &= k\frac{\partial^2 T}{\partial z^2} + \frac{\partial k}{\partial z}\frac{\partial T}{\partial z} - \frac{Cw}{Cg}w\theta\frac{\partial T}{\partial z},\end{aligned} \tag{1}$$

which can be reduced to the followed equation:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} + W\frac{\partial T}{\partial z}, \tag{2}$$

where $T$ (K) is soil temperature, $t$ (s) is the time, and $z$ (m) is the vertical coordinate positive downward; $k$ ($m^2\ s^{-1}$) is soil apparent thermal diffusivity and $k \equiv \lambda/C_g$, where $\lambda$ (W m$^{-1}$ K$^{-1}$) is the thermal conductivity and $C_g$ (J m$^{-3}$ K$^{-1}$) is the volumetric heat capacity of soil; $W = \partial k/\partial z - (C_w/C_g)w\theta$ (m s$^{-1}$) is the apparent convection parameter. $W$ consists of two parts: (1) $\partial k/\partial z$, the vertical gradient of soil apparent thermal diffusivity, and (2) $-(C_w/C_g)w\theta$, the apparent liquid water flux density, where $C_w$ (J m$^{-3}$ K$^{-1}$) is the volumetric heat capacity of water, $w$ (m s$^{-1}$) represents the apparent liquid water velocity (positive downward), and $\theta$ (m$^3$ m$^{-3}$) is the soil volumetric water content.

The solution to equation (2) for a sinusoid temperature boundary condition is (Gao et al., 2008)

$$T(z_2, t) = \overline{T_2} + A_1 \exp(-(z_2 - z_1)\alpha M)\sin(\omega t - \Phi_1 - (z_2 - z_1)\alpha N), \tag{3}$$

where $M = \frac{\alpha}{\omega}\left\{W + \frac{1}{\sqrt{2}}\left[W^2 + \left(W^4 + \frac{4\omega^4}{\alpha^4}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\right\}$ and $N = \sqrt{2}\frac{\omega}{\alpha}\left[W^2 + \left(W^4 + \frac{4\omega^4}{\alpha^4}\right)^{\frac{1}{2}}\right]^{-\frac{1}{2}}$, $d \equiv \sqrt{\omega/(2k)}$, where $d^{-1}$ is the damping depth of the diurnal temperature wave. Equation (3) suggests that the amplitude of the soil temperature wave decreases exponentially with depth and its phase increases linearly with depth. Gao et al. (2008) denoted $A_2 = A_1 \exp[-(z_2 - z_1)dM]$ and $\Phi_2 = \Phi_1 + (z_2 - z_1)dN$, where the definitions of $A_2$ and $\Phi_2$ are similar to those of $A_1$ and $\Phi_1$, except for the soil depth $z_2$. Assuming $z_1 < z_2$ (i.e., $A_1 > A_2$ and $\Phi_1 < \Phi_2$), Gao et al. (2008) derived the following equations:

$$k_{c-c} = -\frac{(z_1 - z_2)^2 \omega \ln(A_1/A_2)}{(\Phi_1 - \Phi_2)\left[(\Phi_1 - \Phi_2)^2 + \ln^2(A_1/A_2)\right]}, \tag{4}$$

$$W = \frac{\omega(z_1 - z_2)}{\Phi_1 - \Phi_2}\left[\frac{2\ln^2(A_1/A_2)}{(\Phi_1 - \Phi_2)^2 + \ln^2(A_1/A_2)} - 1\right]. \tag{5}$$

Equation (5) indicates that $W > 0$ ($W < 0$) when the absolute values of logarithm of the amplitude ratio of soil temperatures ($\ln(A_1/A_2)$) are larger (smaller) than those of the phase shift ($\Phi_2 - \Phi_1$). There is more detailed description about the relationship between $\ln(A_1/A_2)$ and ($\Phi_2 - \Phi_1$) to $k$ and $W$ in Gao et al. (2008) and Tong et al. (2017). Equation (4) implies that the soil apparent thermal diffusivity can be determined using amplitudes and phases of soil temperatures collected at two depths.

## 3. Results and Discussions

### 3.1. The Variations of Soil Temperature, Volumetric Water Content, and Precipitation

Figure 1a shows the soil temperature measured at the 0.00 m, 0.10 m, 0.20 m, and 0.40 m depths. It is clear that diurnal soil temperature amplitudes decreased with depth and were close to zero at the 0.40 m depth. The maximum (minimum) surface soil temperature during this 284 day period was 342.2 K (243.5 K) at 1400 (0730) local time (LT), recorded on DOY 205 (DOY 8). The soil temperatures were below the freezing point

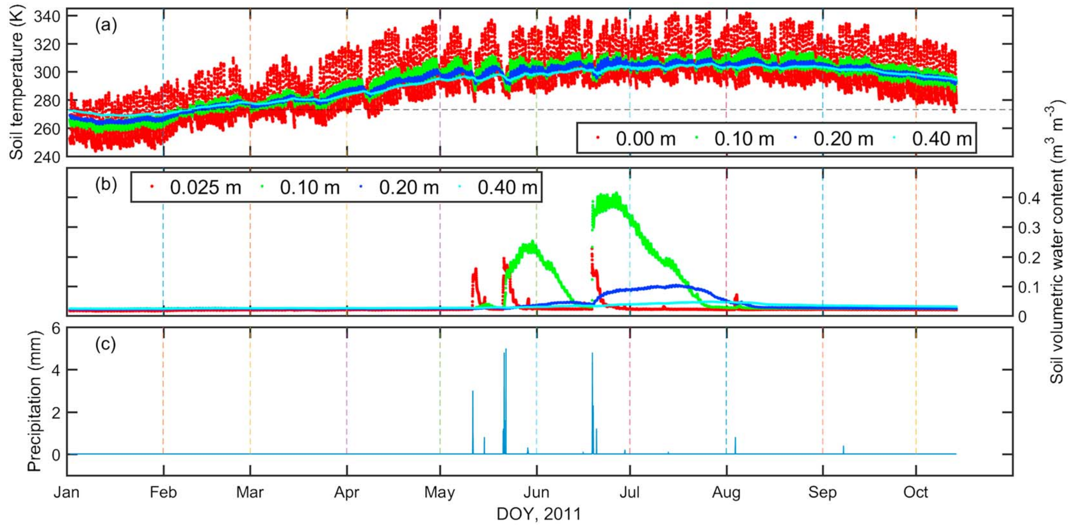


**Figure 1.** Temporal variations of (a) soil temperature (K) measured at the 0.00 m, 0.10 m, 0.20 m, and 0.40 m depths; (b) volumetric water content ($m^3\ m^{-3}$) measured at the 0.025 m, 0.10 m, 0.20 m, and 0.40 m depths; and (c) precipitation (mm) at the Tazhong station from DOY 1 to 284, 2011.

during January, except at the surface during some daytime. The temperature gradient between the surface and the 0.10 m depth reached 354 $\mathrm{K\,m^{-1}}$ at 1300 LT on DOY 102. Such a large vertical temperature gradient only occurs in a bare surface owing to the large daytime solar heating, which is the nature of the uncultivated Taklimakan desert. Figure 1b shows the temporal variations in the soil volumetric water content ($\theta$). The soil was dry with $\theta$ mostly ranging between 0.015 and 0.03 $\mathrm{m^3\,m^{-3}}$. The $\theta$ were approximately constant except after rainfall. The maximum $\theta$ value reached 0.40 $\mathrm{m^3\,m^{-3}}$ at the 0.10 m depth. The maximum $\theta$ value at the 0.025 m depth was usually smaller than that at the 0.10 m depth, probably due to soil water evaporation. Soil water contents at the deeper depths decreased after the rainfalls over a period of about 1 month.

The measured precipitation at the Tazhong station is shown in Figure 1c. Rain mainly occurred in May and June, and there were three major precipitation events. The maximum precipitation was close to 5 mm at 20 and 21 May and 17 June. It is apparent that both soil temperature and soil water content responded to precipitation.

### 3.2. The Variations of Soil Temperature Phases and Amplitudes

Soil temperature is controlled by multiple factors, such as the absorbed radiation energy, cloud cover, and soil physical processes (Gao et al., 2003). Here soil temperatures were analyzed in order to estimate the soil apparent thermal diffusivity ($k$) and the apparent convection parameter ($W$). We used the function, $T_i = \overline{T_i} + A_i \sin(\omega t - \Phi_i)\ (i = 1, 2)$, to best approximate soil temperatures collected at the 0.00 m and 0.20 m depths to obtain the soil phases and amplitudes and then calculated $k$ and $W$ using equations (4) and (5). Owing to the diminished diurnal variation in soil temperature at 0.40 m depth, the soil temperature at this depth was not analyzed.

The temporal variations of soil temperature phase $\Phi$ (rad) and amplitude $A$ (K) are shown in Figure 2. Generally, the soil temperature phases increased with the measured depth, namely, about 1.83 rad and 4.45 rad for the 0.00 m and 0.20 m depths, respectively. The soil temperature phases varied most sharply at the 0.00 m depth. At the 0.20 m depth, the soil temperature phases varied inversely with water content during the wet months (May, June, and July). For the soil temperature amplitudes, the magnitudes and the degree of fluctuations decreased with depth. The ranges of soil temperature amplitudes were mostly between 10 and 25 K, and 0.5 and 2 K for the 0.00 m and 0.20 m depths, respectively.

### 3.3. The Daily and Monthly Variations of Soil Apparent Thermal Diffusivity ($k$) and the Apparent Convection Parameter ($W$)

After determining the phases and amplitudes of soil temperature, the phase shift ($\Phi_2 - \Phi_1$) and logarithm of the amplitude ratio of soil temperatures ($\ln(A_1/A_2)$) for the 0.00 m to 0.20 m soil layer were obtained,

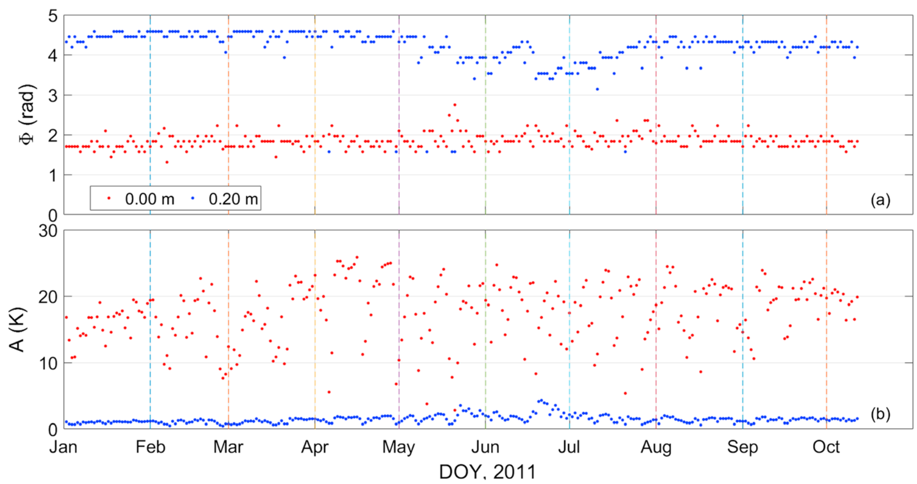


**Figure 2.** Temporal variations of (a) soil phase $\Phi$ (rad) and (b) amplitude $A$ (K) obtained by sinusoidal fitting temperature measured at the 0.00 m and 0.20 m depths at the Tazhong station from DOY 1 to 284, 2011.

and then $k$ and $W$ were determined with equations (4) and (5). To obtain the $k$ gradients, one part of $W$, the $k1$ and $k2$ for the 0.00 m to 0.10 m and 0.10 m to 0.20 m soil layers were also calculated with equation (4). The $k$ gradients $((k1-k2)/(0.05-0.15))$ represented the 0.05 m to 0.15 m soil layer, which were assumed approximately to represent the 0.00 m to 0.20 m soil layer. The $\theta$ for the 0.025 m to 0.20 m soil layer was determined by the arithmetic average of $\theta$ at the 0.025 m, 0.10 m, and 0.20 m depths. Figure 3 shows the daily variations of $(\Phi_2-\Phi_1)$, $\ln(A_1/A_2)$, $k$, $W$, and $\theta$ for the 0.00 m to 0.20 m soil layer.

The raining and heavy-cloudy days were deleted, and the number of days used for each month is presented in Table 1 and Figure 4. The $k$ and $W$ are based on the analytical solution of a one-dimensional conduction-convection heat transfer equation with the soil upper boundary described by a sinusoidal function. Rain and heavy clouds impact the variation patterns of soil surface temperature. Thus, during

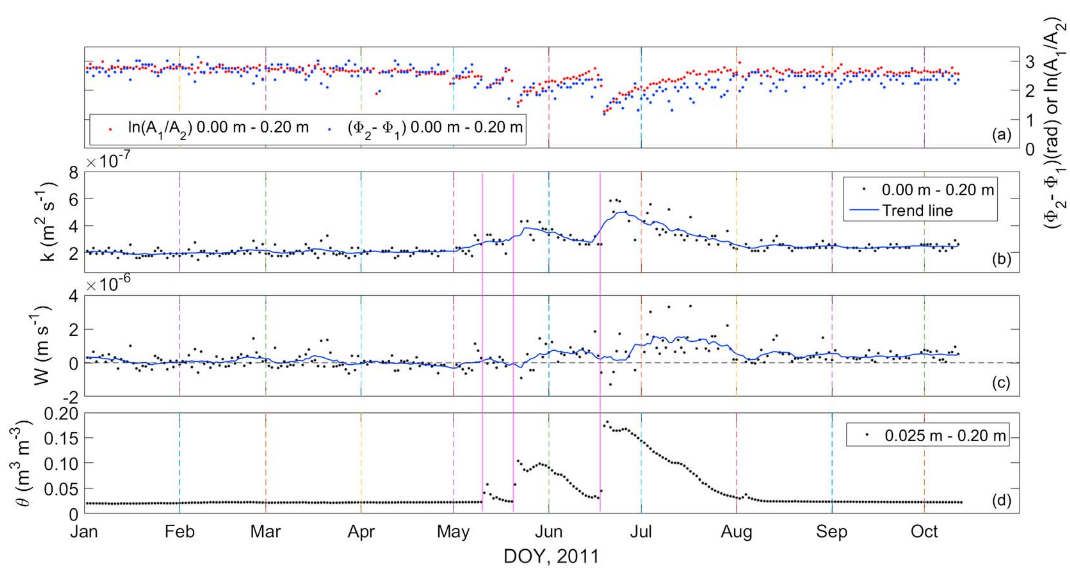


**Figure 3.** Temporal variations of (a) phase shift $(\Phi_2-\Phi_1)$ (rad) and logarithm of the amplitude ratio of soil temperatures $\ln(A_1/A_2)$, (b) soil apparent thermal diffusivity $k$ ($m^2\ s^{-1}$), (c) the apparent convection parameter $W$ ($m\ \ s^{-1}$) for the 0.00 m to 0.20 m soil layer, and (d) volumetric water content $\theta$ ($m^3\ \ m^{-3}$) for the 0.025 m to 0.20 m soil layer at the Tazhong station from DOY 1 to 284, 2011. The three pinks lines correspond to the times of three major precipitation events.

**Table 1**
*The Monthly Average and One Standard Deviation (SD) Values of Soil Apparent Thermal Diffusivity k ($m^2\ s^{-1}$) and the Apparent Convection Parameter W ($m\ s^{-1}$) for the 0.00 m to 0.20 m Soil Layer*

| Months | $k$ ($m^2\ s^{-1}$) Mean ± SD | $W$ ($m\ s^{-1}$) Mean ± SD | Days |
|---|---|---|---|
| Jan | 1.95 (± 0.25) × $10^{-7}$ | 0.86 (± 3.32) × $10^{-7}$ | 31 |
| Feb | 2.06 (± 0.30) × $10^{-7}$ | 1.66 (± 4.08) × $10^{-7}$ | 28 |
| Mar | 2.06 (± 0.38) × $10^{-7}$ | 0.91 (± 4.85) × $10^{-7}$ | 31 |
| Apr | 2.05 (± 0.19) × $10^{-7}$ | −0.68 (± 2.42) × $10^{-7}$ | 25 |
| May | 2.96 (± 0.76) × $10^{-7}$ | 1.01 (± 5.95) × $10^{-7}$ | 24 |
| Jun | 3.63 (± 1.17) × $10^{-7}$ | 4.56 (± 7.34) × $10^{-7}$ | 26 |
| Jul | 3.51 (± 0.86) × $10^{-7}$ | 12.76 (± 8.60) × $10^{-7}$ | 26 |
| Aug | 2.45 (± 0.28) × $10^{-7}$ | 4.32 (± 4.38) × $10^{-7}$ | 29 |
| Sep | 2.41 (± 0.16) × $10^{-7}$ | 3.93 (± 2.22) × $10^{-7}$ | 21 |
| Oct | 2.47 (± 0.24) × $10^{-7}$ | 4.92 (± 2.78) × $10^{-7}$ | 11 |
| Average | 2.52 (± 0.80) × $10^{-7}$ | 3.23 (± 6.25) × $10^{-7}$ | |
| Average (dry months) | 2.16 (± 0.33) × $10^{-7}$ | 1.92 (± 4.09) × $10^{-7}$ | |
| Average (wet months) | 3.36 (± 0.96) × $10^{-7}$ | 6.36 (± 8.91) × $10^{-7}$ | |

heavy-cloudy days and rainy days, the soil surface temperatures may not vary sinusoidally, so that the conduction-convection algorithm is not applicable on such days.

The values of $\theta$ were almost constant (about 0.020 and 0.025 $m^3\ m^{-3}$) during the dry months (January, February, March, April, August, September, and October) and showed two peaks during the wet months (Figure 3d).

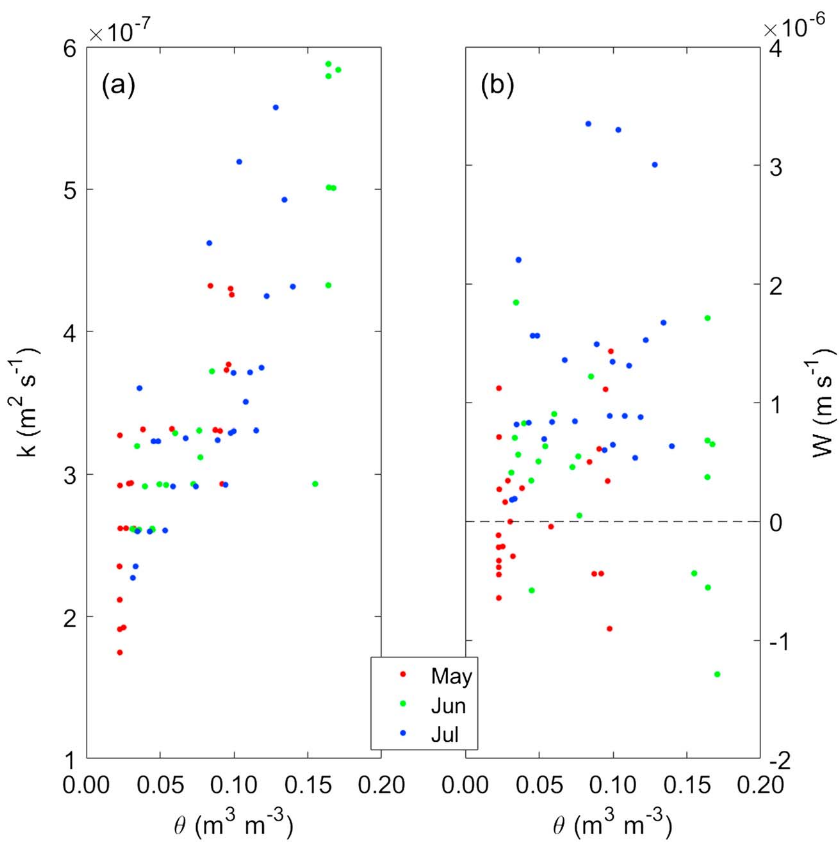


**Figure 4.** Variations of (a) soil apparent thermal diffusivity $k$ ($m^2\ s^{-1}$) and (b) the apparent convection parameter $W$ ($m\ s^{-1}$) against volumetric water content $\theta$ ($m^3\ m^{-3}$) for the 0.00 m to 0.20 m soil layer for May, June, and July 2011.

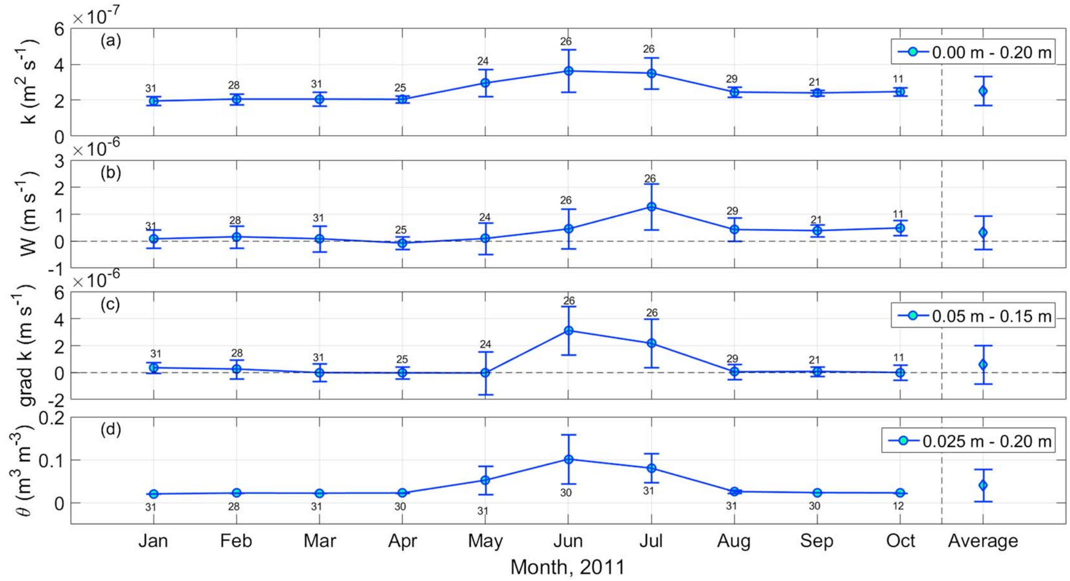


**Figure 5.** Monthly averaged and 10 month averaged values of (a) soil apparent thermal diffusivity $k$ ($m^2\ s^{-1}$), (b) the apparent convection parameter $W$ ($m\quad s^{-1}$), (c) the gradient of soil apparent thermal diffusivity ($m\quad s^{-1}$) for the 0.00 m to 0.20 m soil layer, and (d) volumetric water content $\theta$ ($m^3\ m^{-3}$) for the 0.025 m to 0.20 m soil layer from DOY 1 to 284, 2011.

As shown in Figure 3a, in general, the variation pattern of $(\Phi_2 - \Phi_1)$ and $\ln(A_1/A_2)$ was similar. The values of $(\Phi_2 - \Phi_1)$ and $\ln(A_1/A_2)$ were relatively stable during the dry months and varied sharply during the wet months. Their values were similar before June, and the $\ln(A_1/A_2)$ values were larger than $(\Phi_2 - \Phi_1)$ values after May.

The $k$ values varied with $\theta$. The values were relatively small during the dry months, and values increased, showing two peaks during the wet months. The ranges of $k$ values were from $1.46 \times 10^{-7} m^2\ s^{-1}$ (DOY 37) to $5.88 \times 10^{-7} m^2\ s^{-1}$ (DOY 173). It is obvious that the $k$ values increased sharply during the wetting process and decreased slightly during the drying process. The daily variation of $k$ and the daily variations of $(\Phi_2 - \Phi_1)$ and $\ln(A_1/A_2)$ were in the opposite direction during the wet months. Tong et al. (2017) derived the mathematical relationships between $k$ and $W$ with $(\Phi_2 - \Phi_1)$ and $\ln(A_1/A_2)$ and reported that the values of $k$ and $W$ depended on the relative magnitudes of $(\Phi_2 - \Phi_1)$ and $\ln(A_1/A_2)$.

Generally, similar to $k$, $W$ kept relatively stable during the dry months and varied sharply during the wet months. The daily values of $W$ fluctuated slightly near zero during the dry months, while they were mostly positive during and just following the wet months.

At the three major precipitation events during May to June, rainwater moved into soil, soil water content increased and resulted in $k$ values increasing sharply, and $W$ values tending to become negative. After the rainy days, as soil water evaporated and liquid water moved upward, soil water content decreased, resulting in $k$ values decreasing slightly, and $W$ values becoming positive.

Figure 4 presents the variations of $k$ and $W$ against $\theta$ for the 0.00 m to 0.20 m soil layer for the wet months. Generally, the results show that $k$ increased as $\theta$ increasing from 0.02 to 0.18 $m^3\ m^{-3}$. Most of the $W$ values were positive, but some values were negative on the days just after rainfall.

The monthly values of $k$ and $W$ were calculated by the arithmetic mean of daily values of $k$ and $W$ for each month. The monthly average and one standard deviation (SD) values of $k$, $W$, $k$ gradients, and $\theta$ are presented in Figure 5 and Table 1. The days used in each month exceeded 77.5% (24 days/31 days).

Generally, the SD of $k$ and $W$ were larger during the wet months. The monthly average values of $k$ increased with $\theta$, reached a peak value of 3.63 $(\pm 1.17) \times 10^{-7} m^2\ s^{-1}$ in June and then decreased as $\theta$ decreased. The average value of $k$ for the 10 month period was 2.52 $(\pm\ 0.80) \times 10^{-7} m^2\ s^{-1}$. The average value of $k$ for the dry months was 36% less than the $k$ value for the wet months (Table 1). The results indicated that the soil water content should be considered when selecting the proper value of desert soil apparent thermal diffusivity.

**Table 2**
*Comparison of Soil Apparent Thermal Diffusivity k ($m^2$ $s^{-1}$) Values From Previous Studies and the Present Study*

| Number | Thermal diffusivity $k$ ($m^2$ $s^{-1}$) | Soil type | Reference |
|---|---|---|---|
| 1 | $2.4 \times 10^{-7}$ | dry quartz sand | Stull (1988) |
| 2 | $2.3 \times 10^{-7}$ | dry sandy soil | Pielke (1984)/Garratt (1992) |
| 3 | $2.4 \times 10^{-7}$ | dry sandy soil | List (1966)/Oke (1987); Warner (2004) |
| 4 | $1.6 (\pm 0.5) \times 10^{-7}$, for 0.025 m<br>$2.5 (\pm 0.6) \times 10^{-7}$, for 0.075 m | sand (Gobi) | Zhang and Huang (2004) |
| 5 | $6.2 \times 10^{-7}$, for 0.00 m–0.015 m<br>$3.3 \times 10^{-7}$, for 0.015 m–0.034 m<br>$1.0 \times 10^{-7}$, for 0.034 m–0.050 m<br>$2.9 \times 10^{-7}$, for 0.050 m–0.100 m | sand (desert) | Gao et al. (2007) |
| 6 | $1.5 (\pm 0.1) \times 10^{-7}$, for 0.05 m | sand (desert) | Liu et al. (2011) |
| 7 | $2.5 (\pm 0.8) \times 10^{-7}$, for 0.00 m–0.20 m | sand (desert) | the present study |

The results of $W$ are shown in Figure 5b and Table 1. The monthly values of $W$ were approximately equal to zero during the dry months, and they were positive during and just following the wet months. The absolute monthly values of $W$ varied as soil water content varied. The peak value of 12.8 (±8.6) $\times$ $10^{-7}$m $s^{-1}$ occurred in July. The average value of $W$ for the 10 month period was $3.23(\pm 6.25) \times 10^{-7}$m $s^{-1}$.

To examine the trend of water movement, the monthly values of $k$ gradients were also calculated. The values were positive during the wet months, and they were close to zero during the dry months. Comparing Figures 5b and 5c, the values of $W$ and $k$ gradients were close to zero from January to April, and the apparent liquid water velocity ($w$) was approximately equal to zero based on $W = \partial k/\partial z - (C_w/C_g) w\theta$. The results indicated that during this period, little soil water movement occurred, which made physical sense for this dry period. During the wet months, the values of $W$ and $k$ gradients were positive, and $k$ gradients values were larger than $W$ values. Thus, the $w$ values were positive, which indicated that as a result of rainfall, some water infiltrated into the soil. After the wet months, $W$ values stayed positive while $k$ gradients values were approximately to zero; thus, $w$ values were negative. This result indicated that soil water moved upward in response to evaporation. These results indicated that the conduction-convection model was able to capture the pattern of water movement in this desert soil.

A few earlier studies have reported values of soil apparent thermal diffusivity ($k$) of dry soil, as shown in Table 2. The values of $k$ reported by Stull (1988), Pielke (1984), Garratt (1992), List (1966), Oke (1987), and Warner (2004) were obtained under laboratory conditions. Zhang and Huang (2004), Wang et al. (2005), and Liu et al. (2011) estimated $k$ based on a method developed by Zhang and Huang (2004). Gao et al. (2007) reported $k$ for a single day in the northwest part of the Negev desert in Israel. In the present study, the mean value was 2.5 (± 0.8) $\times$ $10^{-7}$$m^2$ $s^{-1}$ for the 0.00 m to 0.20 m soil layer. The $k$ values of the present study were similar to previous results obtained on laboratory samples. Soils used in those studies were sandy soils, and the water contents were very low. The differences in $k$ between the other studies and the present study are because the soil properties (e.g., soil texture, soil water content, porosity, and mineral component) were different. However, it should be noted that the differences in $k$ between Liu et al. (2011) and our results are probably caused by using different methods. Liu et al. (2011) calculated the soil apparent thermal diffusivity as the ratio of thermal conductivity and volumetric heat capacity, and the thermal conductivity was determined by measuring soil heat fluxes at two soil depths. Even with a well-calibrated soil heat flux sensor it is difficult to measure the soil heat flux accurately, because the soil heat and moisture fluxes are disturbed (Van Loon et al., 1998). Heat flux plates measure only sensible heat as it moves past the plate by means of the temperature gradient which exists across the plate. Latent heat which is hidden in the evaporative process is not detected (Gardner & Hanks, 1966). In the desert soil, due to small soil water contents, some water movement probably occurred in the form of water vapor. Actual soil heat flux would tend to be underestimated by heat flux plates, while soil temperature gradients would be correct. Thus, soil thermal conductivity was underestimated, and soil apparent thermal diffusivity determined as the ratio of thermal conductivity and volumetric heat capacity was also underestimated. This is a plausible explanation for the relatively small values of $k$ reported by Liu et al. (2011).

## 4. Conclusions

Soil apparent thermal diffusivities ($k$) were determined with the conduction-convection algorithm (Gao et al., 2008) using soil temperature measured at the Tazhong station in China in 2011. The $k$ values varied as the volumetric water content varied. Values were relatively small during the dry months, and values increased, showing two peaks during the wet months. The 10 month average value of $k$ was 2.5 ($\pm$ 0.8) $\times$ $10^{-7}$m$^2$ s$^{-1}$ for the 0.00 m to 0.20 m soil layer. The difference of average monthly values of $k$ between dry months and wet months was relatively large. The variable ($W$) that represents the sum of the vertical gradient of soil apparent thermal diffusivity and apparent liquid water flux was also obtained. The monthly average values of $W$ were approximately equal to zero at the dry months and were mostly positive during and just after the wet months. Based on the two parts of $W$, soil water movement patterns were analyzed, which indicated that the conductive-convective algorithm captured the overall pattern of soil water movement.

The soil apparent thermal diffusivity varied sharply with water content in this Taklimakan desert soil, so if soil apparent thermal diffusivity was used as an input parameter in land surface models, the soil water content must be considered. The daily and monthly variations of soil apparent thermal diffusivity for the 10 month period in this study could be used to select appropriate soil parameters when modeling the land-atmosphere interactions in the Taklimakan desert. Developing a method for determining the soil apparent thermal diffusivity while accounting explicitly for vapor transport in the upper soil profile is a topic for future research.

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