Evaluation of Soil Thermal Conductivity Schemes for Use in Land Surface Modeling

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Outline

1. Background and Objectives
2. Data and Method
3. Results
4. Conclusions and Discussions
Soil hydraulic and thermal properties is required for land surface modeling at various scales.

Soil heat transfer equation in land surface models (LSMs):

$$ C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] + S $$

Parameters to be determined:
- $C$ – bulk soil heat capacity
- $k$ – bulk soil thermal conductivity (STC)
Objectives 1

How to calculate soil thermal conductivity accurately in LSMs?

Easy to obtain

- Standard soil properties
  - Texture
  - Porosity
  - Soil minerals
  - Bulk density

Difficult to obtain

- Hydraulic parameters
  - Moisture retention
  - Hydraulic conductivity
- Thermal parameters
  - Heat capacity
  - Thermal conductivity
- Biogeochemical parameters
  - Soil carbon parameterization
  - Soil mineralization and decomposition parameterization

STC schemes: Theretical & Empirical models

Table 3 Selected mixing models and mathematical models for effective thermal conductivity of soils

| Models          | Equations                                                                 |
|-----------------|---------------------------------------------------------------------------|
| Series          | $k = \sum_{i=1}^{n} S_i k_i$                                              |
| Geometric mean  | $k = \frac{1}{S} \sum_{i=1}^{n} k_i$                                      |
| Quadratic       | $k = \left( \sum_{i=1}^{n} \phi_i \right)^2$                             |
| Effective       | $\phi = \sum_{i=1}^{n} \phi_i$                                           |
| Self-consistent| $k = \left( \sum_{i=1}^{n} k_i \phi_i \right)^{1/3}$                     |

Dong et al., 2015

Table 4 Selected empirical models for effective thermal conductivity of soils

| Models          | Parameters   | $S$ ($\phi$) | $n$ | $\gamma_{dry}$ | $k_s$, $k_d$, $k_{sat}$ | Others                                     |
|-----------------|--------------|--------------|-----|---------------|--------------------------|--------------------------------------------|
| Kersten (1949)  | $k_s = k_0 S$ | $\gamma_{dry}$ | $k_s$, $k_{sat}$ | $k_d = k_{sat}^{1-n}$ | $k_{dry}$ = $0.1359 \gamma_{dry}^{0.667} 294072 n$ | Silt-clay: $k_{eff} = 0.1442 \log \theta - 0.2 \cdot 10^{0.6243/\gamma_{dry}}$ |
| Johansen (1975) | $k_s = k_0 S$ | $\gamma_{dry}$ | $k_s$, $k_{sat}$ | $k_d = k_{sat}^{1-n}$ | $k_{dry}$ = $0.1359 \gamma_{dry}^{0.667} 294072 n$ | Sandy soil: $k_{eff} = 0.1442 \log \theta - 0.2 \cdot 10^{0.6243/\gamma_{dry}}$ |
| Côté and Konrad (2005) | $k_s = k_0 S$ | $\gamma_{dry}$ | $k_s$, $k_{sat}$ | $k_d = k_{sat}^{1-n}$ | $k_{dry}$ = $0.1359 \gamma_{dry}^{0.667} 294072 n$ | Course sand: $k_s = 0.7 \log S + 1.0$ |
| Lu et al. (2007) | $k_s = k_0 S$ | $\gamma_{dry}$ | $k_s$, $k_{sat}$ | $k_d = k_{sat}^{1-n}$ | $k_{dry}$ = $0.1359 \gamma_{dry}^{0.667} 294072 n$ | Fine soil: $k_s = \log S + 1.0$ |
| Chen (2008)     | $k_s = k_0 S$ | $\gamma_{dry}$ | $k_s$, $k_{sat}$ | $k_d = k_{sat}^{1-n}$ | $k_{dry}$ = $0.1359 \gamma_{dry}^{0.667} 294072 n$ | Sandy soil: $k_{eff} = 0.1442 \log \theta - 0.2 \cdot 10^{0.6243/\gamma_{dry}}$ |

Key parameters: $S$—degree of saturation, $S = \phi/(1 - \phi_s)$, $[-]$; $\theta$—volumetric water content, $\theta = (n \cdot S)$, $[-]$; $n$—porosity, $n = (1 - \phi_s)$, $[-]$; $\gamma_{dry}$—dry bulk density, $\gamma_{dry} = G_s(1 - n)$, $(kg/m^3)$; $k_s$—thermal conductivity of quartz, $(W/mK)$; $k_o$—thermal conductivity of organic materials, $(W/mK)$; $k_e$—Kersten number, $k_e = (k_{eff} - k_{sat})/(k_{sat} - k_{dry})$, $[-]$

Empirical parameters: $a, b, c$—fitted parameters for different materials

Dong et al., 2015
How to calculate soil thermal conductivity accurately in LSMs?

Comparisons of STC schemes in the literatures

| Authors                  | STC schemes to be compared                  | Best performed scheme                                      |
|--------------------------|---------------------------------------------|------------------------------------------------------------|
| Peters-Lidard et al., 1998 | McCumber and Pielke (1981) Johansen (1975)  | Johansen (1975)                                             |
| Barry-Macaulay et al. (2015) | Johansen (1975) Côté and Konrad (2005) Balland and Arp (2005) Lu et al. (2007)  | Côté and Konrad (2005)                                       |
| Zhang and Wang (2017)     | 13 typical STC models                       | Chen (2008), Haigh (2012), and Zhang et al. (2015) (especially for predicting sand thermal conductivity) |
| ...                      |                                             |                                                            |

Q: Which STC scheme should be used in LSMs, especially on global scale?

- Previous evaluations were mostly based on direct STC measurements under specific experimental conditions or on local soil samples. *(Local property dependent)*
- Previous evaluations were not based LSM applications.
How to include effects of more soil components?

| Material                      | Density (kg/m³) | Heat capacity (kJ/kg K) | Thermal conductivity (W/m K) | Thermal diffusivity (m²/s) × 10⁻⁷ |
|-------------------------------|-----------------|-------------------------|------------------------------|----------------------------------|
| Air (10 °C)                   | 1.25            | 1.000                   | 0.0026                       | 0.21                             |
| Water (25 °C)                 | 999.87          | 4.200                   | 0.56                         | 1.43                             |
| Water vapor (1 atm, 400 K)    | –               | 1.901                   | 0.016                        | 233.8                            |
| Ice (0 °C)                    | 917             | 2.040                   | 2.25                         | 12                               |
| Quartz                       | 2,660           | 0.733                   | 8.40                         | 43.08                            |
| Granite                      | 2,750           | 0.890                   | 1.70–4.00                    | ~ 12                             |
| Gypsum                       | 1,000           | 1.090                   | 0.51                         | 4.7                              |
| Limestone                    | 2,300           | 0.900                   | 1.26–1.33                    | ~ 5                              |
| Marble                       | 2,600           | 0.810                   | 2.80                         | 13                               |
| Mica                         | 2,883           | 0.880                   | 0.75                         | 2.956                            |
| Clay                         | 1,450           | 0.880                   | 1.28                         | 10                               |
| Sandstone                    | ~2,270          | 0.710                   | 1.60–2.10                    | 10–13                            |

*Source* Bejan and Kraus (2003)

Most STC schemes were derived from only mineral fractions of the soil (particle diameters <2 mm), while few have considered other effects, e.g. soil organic matter (SOM) and gravels (particle diameters >2 mm).
How to include effects of more soil components?

More global soil basic property datasets are developed, which contain more soil components, e.g. GSDE (Shangguan et al., 2014), Soilgrids (Hengl et al., 2017).

| Soil Property                     | Unit          | WISE | NCSS | ESDB | GSM | SLC | China | ASRIS | SOTWISE |
|-----------------------------------|---------------|------|------|------|-----|-----|-------|-------|---------|
| Total carbon                      | %             |      |      |      |     |     |       |       |         |
| Organic carbon                    | %             |      |      |      |     |     |       |       |         |
| Total nitrogen                    | %             |      |      |      |     |     |       |       |         |
| Total sulfur                      | %             |      |      |      |     |     |       |       |         |
| Calcium carbonate content         | %             |      |      |      |     |     |       |       |         |
| Gypsum content                    | %             |      |      |      |     |     |       |       |         |
| pH, measured in water             | none          |      |      |      |     |     |       |       |         |
| pH, measured in KCL solution     | none          |      |      |      |     |     |       |       |         |
| pH, measured in CaCl₂ solution   | none          |      |      |      |     |     |       |       |         |
| Electrical conductivity           | ds/m or mmho/cm |      |      |      |     |     |       |       |         |
| Exchangeable calcium              | cmol/kg       |      |      |      |     |     |       |       |         |
| Exchangeable magnesium            | cmol/kg       |      |      |      |     |     |       |       |         |
| Exchangeable sodium               | cmol/kg       |      |      |      |     |     |       |       |         |
| Exchangeable potassium            | cmol/kg       |      |      |      |     |     |       |       |         |
| Exchangeable aluminum             | cmol/kg       |      |      |      |     |     |       |       |         |
| Exchangeable acidity              | cmol/kg       |      |      |      |     |     |       |       |         |
| Cation exchange capacity          | cmol/kg       |      |      |      |     |     |       |       |         |
| Base saturation, expressed as % of CEC | %   |      |      |      |     |     |       |       |         |
| Sand content                      | %             |      |      |      |     |     |       |       |         |
| Silt content                      | %             |      |      |      |     |     |       |       |         |
| Clay content                      | %             |      |      |      |     |     |       |       |         |
| Gravel content                    | % in volume   |      |      |      |     |     |       |       |         |
| Bulk density                      | g/cm³         |      |      |      |     |     |       |       |         |

Summary: Choose a STC scheme which can make land surface models perform better; Include effects of more soil components (e.g. organic carbon and gravels) in the selected STC schemes.
1. Background and Objectives

2. Data and Method

3. Results

4. Conclusions and Discussions
STC schemes

Seven STC schemes are selected to be compared, with the consideration of effects of organic carbon and gravels.

- *Johansen* [1975]
- *Farouki* [1981]
- *Côté and Konrad* [2005]
- *Balland and Arp* [2005]
- *Lu et al.* [2007]
- *Tarnawski and Leong* [2012]
- *De Vries* [1963]

\[ k = (k_{sat} - k_{dry}) K_e + k_{dry} \]

Empirical schemes

Mechanistic schemes
STC schemes

Example: Johansen (1975) scheme

\[ k = \left( k_{sat} - k_{dry} \right) K_e + k_{dry} \]

\[ k_{dry} = f_{minerals} \frac{0.135 \rho_d + 0.0647}{2.7 - 0.947 \rho_d} + f_{om} k_{om\_dry} + f_{gravel} k_{gravel} \]

\[ k_{om\_dry} = 0.05 \quad k_{gravel} = 0.039n^{-2.2} \]

\[ k_{sat} = k_s^{1-n} k_{water} \]

\[ k_s^{1-n} = k_{gravel}^{v_g} k_{om\_wet}^{v_{om}} k_m^{v_m} \quad k_{om\_wet} = 0.25 \quad k_{gravel} = 0.039n^{-2.2} \]

\[ K_e = \begin{cases} 
0.7 \log S_r + 1, & \text{for unfrozen coarse-grained soils with } S_r > 0.05 \\
\log S_r + 1, & \text{for unfrozen fine-grained soils with } S_r > 0.1 \\
S_r, & \text{for frozen medium and fine sands and fine-grained soils} 
\end{cases} \]

Dai et al., 2019
Data and model

- **Validation data for soil thermal conductivity schemes:**
  Tarnawski et al., 2015 (40 Canadian soils and 21 other soils, which cover a wide diversity of soil conditions from loose to compact, organic to mineral, fine to coarse textured, and dry to wet.

- **Global soil basic data:** GSDE (Shangguan et al., 2014): soil texture, organic carbon, bulk density, Gravels.

- **Land surface model:** The Common Land Model (CoLM, Dai et al, 2003, 2014) CoLM can provide a full description of biogeophysical processes in land system, and the latest version concentrates mostly on the development of global land surface data and pedo-transfer functions for estimating soil hydraulic and thermal parameters.

- **Validation data for land surface modelling:** 12 in-situ sites, which represent most of global situations.
# Data and model

| Site   | Country     | Location          | Climate zone   | Soil type           | Land cover type (USGS)\(^a\) | Precipitation (mm/year) | Duration of data |
|--------|-------------|-------------------|----------------|---------------------|------------------------------|-------------------------|-----------------|
| US-FPe | United States | 48.3°N, 105.1°W  | Dry            | Loam                | Grassland                    | 335                     | 2000.01–2006.12 |
| Nagqu  | China       | 31.37°N, 91.9°E  | Dry            | Sand with gravel    | Grassland                    | 420                     | 2011.07–2015.07 |
| Arou   | China       | 38.0°N, 100.5°E  | Dry            | Loam with gravel    | Grassland                    | 449                     | 2014.01–2018.12 |
| FI-Kaa | Finland     | 69.1°N, 27.3°E  | Boreal         | Peat with sand      | Wetland                      | 454                     | 2004.01–2005.12 |
| ZA-Kru | South Africa | 25.0°S, 31.5°E  | Mediterranean  | Sand                | Savanna                      | 525                     | 2002.01–2003.12 |
| US-Var | United States | 38.4°N, 121.0°W | Mediterranean  | Clay                | Grassland                    | 544                     | 2001.01–2006.12 |
| FI-Hyy | Finland     | 61.8°N, 24.3°E  | Boreal         | Sand                | Evergreen needleleaf forest  | 620                     | 2001.01–2004.12 |
| DE-Tha | Germany     | 50.9°N, 13.5°E  | Temperate      | Loam with gravel    | Evergreen needleleaf forest  | 643                     | 1998.01–2005.12 |
| IT-Ro1 | Italy       | 42.4°N, 11.9°E  | Mediterranean  | Sand                | Deciduous broadleaf forest   | 764                     | 2002.01–2006.12 |
| US-Bo1 | United States | 40.0°N, 88.3°W  | Temperate      | Clay                | Cropland and Pasture         | 991                     | 1997.01–2006.12 |
| US-Ha1 | United States | 42.5°N, 72.2°W  | Temperate      | Sand                | Deciduous broadleaf forest   | 1,071                   | 1994.01–2001.12 |
| AU-How | Australia   | 12.5°S, 131.1°E | Tropical       | Loam                | Woody Savanna                | 1,449                   | 2002.01–2005.12 |

*Note.* CoLM = Common Land Model; USGS = U.S. Geological Survey.

\(^a\)The land cover types are defined by the USGS classification.
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Effects of STC schemes on LSMs

- The most significant differences of the simulated soil temperature appear over arid and semiarid regions at middle and high latitudes.
- The magnitudes of the differences increase with increasing soil depth.
- Ground heat flux can be significantly affected.

The differences of the CoLM simulated soil temp. with Balland and Arp (2005) and Johansen (1975) schemes.
STC schemes can have significant effects on soil temperature simulations and related variables.
Comparisons of STC schemes
Comparisons of STC schemes

Balland and Arp (2005) performs best in direct comparisons with STC measurements.
Comparisons of STC schemes

Balland and Arp (2005) performs best in simulating soil temperature at most soil layers.

Table 2
Root Mean Square Errors of the Simulated Soil Temperature by the CoLM Incorporating the Seven Soil Thermal Conductivity Schemes at the Nagqu Site

| Layer depth (cm) | Farouki (1981) | Johansen (1975) | Côté and Konrad (2005) | Balland and Arp (2005) | Lu et al. (2007) | Tarnawski and Leong (2012) | De Vries (1963) |
|------------------|----------------|-----------------|------------------------|------------------------|------------------|----------------------------|-----------------|
| 5                | 2.18           | 2.1             | 2.11                   | 2.06                   | 2.11             | 2.27                       | 2.23            |
| 10               | 1.77           | 1.71            | 1.73                   | 1.61                   | 1.71             | 1.88                       | 1.83            |
| 20               | 1.6            | 1.35            | 1.39                   | 1.31                   | 1.35             | 1.74                       | 1.51            |
| 40               | 1.44           | 1               | 1.06                   | 1.09                   | 1.02             | 1.8                        | 1.36            |
| Vertical average | 1.75           | 1.54            | 1.57                   | 1.52                   | 1.55             | 1.92                       | 1.74            |

Note. CoLM = Common Land Model. The values that indicate the most accurate simulations at each soil layer are highlighted in bold.
Comparisons of STC schemes

| Layer depth (cm) | Farouki (1981) | Johansen (1975) | Côté and Konrad (2005) | Ballard and Arp (2005) | Lu et al. (2007) | Tarnawski and Leong (2012) | De Vries (1963) |
|-----------------|---------------|-----------------|------------------------|------------------------|-----------------|-----------------------------|----------------|
| 2               | 2.63          | 2.73            | 2.78                   | 2.76                   | 2.76            | 2.77                        | 2.79           |
| 6               | 2.39          | **2.37**        | 2.46                   | 2.41                   | 2.43            | 2.57                        | 2.51           |
| 10              | 2.27          | 2.15            | 2.21                   | **2.14**               | 2.21            | 2.45                        | 2.33           |
| 15              | 2.84          | 2.67            | 2.66                   | **2.6**                | 2.72            | 3.05                        | 2.87           |
| 20              | 2.02          | 1.7             | 1.85                   | 1.77                   | 1.78            | 2.1                         | 1.92           |
| 30              | 1.93          | **1.5**         | 1.59                   | 1.51                   | 1.57            | 1.98                        | 1.77           |
| 60              | 1.7           | 1.2             | 1.1                    | **1.03**               | 1.2             | 1.79                        | 1.51           |
| 80              | 1.4           | 1.27            | 0.84                   | **0.81**               | 1.17            | 1.78                        | 1.55           |
| 160             | 1.4           | 1.95            | **1.24**               | 1.32                   | 1.78            | 2.47                        | 2.23           |
| Vertical average| 2.06          | **1.95**        | 1.86                   | **1.82**               | 1.96            | 2.33                        | 2.17           |

**Balland and Arp (2005) performs best in simulating soil temperature at most soil layers.**
### Comparisons of STC schemes

Balland and Arp (2005) performs best in simulating Bowen ratio at most in-situ sites.

| Sites     | Farouki (1981) | Johansen (1975) | Côté and Konrad (2005) | Ballard and Arp (2005) | Lu et al. (2007) | Tarnawski and Leong (2012) | De Vries (1963) |
|-----------|----------------|-----------------|------------------------|-----------------------|------------------|-----------------------------|-----------------|
| US-FPe    | 2.83           | 2.9             | 2.94                   | 2.91                  | 2.93             | 2.94                        | 2.94            |
| Nagqu     | 2.97           | 2.95            | 2.94                   | 2.93                  | 2.94             | 2.94                        | 3.03            |
| Arou      | 3.8            | 3.88            | 3.86                   | 3.87                  | 3.88             | 3.85                        | 3.89            |
| FI-Kaa    | 1.81           | 1.64            | 1.64                   | 1.63                  | 1.64             | 1.64                        | 1.64            |
| ZA-Kru    | 8.2            | 8.65            | 7.33                   | 7.44                  | 8.03             | 7.97                        | 7.95            |
| US-Var    | 2.9            | 2.88            | 2.88                   | 2.87                  | 2.88             | 2.88                        | 2.88            |
| FL-Hyy    | 2.35           | 2.38            | 2.37                   | 2.34                  | 2.39             | 2.35                        | 2.35            |
| DE-Tha    | 3.34           | 3.25            | 3.25                   | 3.24                  | 3.25             | 3.27                        | 3.3             |
| IT-Roi    | 2.32           | 2.34            | 2.33                   | 2.33                  | 2.33             | 2.33                        | 2.34            |
| US-Bo1    | 3.16           | 2.9             | 2.78                   | 2.75                  | 2.87             | 3.46                        | 2.88            |
| US-Ha1    | 2.95           | 2.96            | 2.95                   | 2.96                  | 2.95             | **2.94**                    | **2.94**        |
| AU-How    | 3.04           | 3.1             | 3.07                   | **3.03**              | 3.09             | 3.14                        | 3.14            |
| Average   | 3.31           | 3.32            | 3.2                    | **3.19**              | 3.27             | 3.31                        | 3.27            |

*Note. CoLM = Common Land Model. The values that indicate the most accurate simulations at each site are highlighted in bold.*
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Conclusions and Discussions

- The soil thermal conductivity schemes can be modified to include effects of more soil components.

- The soil thermal conductivity can have significant effects on LSMs, especially for soil thermal and hydraulic process modeling.

- Among the selected 7 soil thermal conductivity schemes, Balland and Arp (2005) scheme performs best not only in reproducing measured soil thermal conductivity, but also in simulating land surface processes.

- As a preliminary work, more soil thermal conductivity schemes with consideration of more soil components will be selected and evaluated with more observational datasets in the future.
Scheme 4 - Ballard and Arp (2005) model

\[ k = \left( k_{\text{sat}} - k_{\text{dry}} \right) K_e + k_{\text{dry}} \]

\[ k_{\text{dry}} = f_{\text{gravel}} k_{\text{gravel}} + f_{\text{minerals}} \frac{0.135 \rho_d + 0.0647}{2.7 - 0.947 \rho_d} + f_{\text{om}} k_{\text{om\_dry}} \]

\[ k_{\text{gravel}} = 0.039 n^{-2.2} \]

\[ k_{\text{om\_dry}} = 0.05 \]

\[ k_{\text{sat}} = k_s^{1-n} k_n^{n} \]

\[ k_s^{1-n} = k_{\text{gravel}}^{v_g} k_{\text{om\_wet}}^{v_{\text{om}}} k_{\text{m}}^{v_m} \]

\[ k_m = k_q^{v_q} k_o^{1-v_q} \quad k_q = 8.8 \quad k_o = 2.0 \text{ or } 3.0 \]

\[ K_e = S_r^{0.5(1+V_{\text{om}}-\alpha V_{\text{sand}}-V_{ef})} \left\{ \frac{1}{1+\exp(-\beta S_r)} \right\}^{3-1-V_{\text{om}}} \]

\[ \alpha = 0.24, \quad \beta = 18.1 \]