Equations and PFTs for soil thermal properties in LSMs:
Implications for the energy balance

Anne Verhoef, Jirka Simunek, Lutz Weihermuller, Michael Herbst, Kris Van Looy, Carsten Montzka, Harry Vereecken, plus LSM collaborators

LSM collaborators

**CABLE**: Mark Decker  
**Catchment**: Randy Koster, Gabriëlle De Lannoy (& Joe Santanello)  
**CLM**: David Lawrence  
**JSBACH**: Stefan Hagemann, inputs from Christian Beer and Philip de Vrese  
**JULES**: Anne Verhoef (inputs from Imtiaz Dharssi, Toby Marthews, Pier Luigi Vidale, Heather Ashton & John Edwards)  
**MPI-HM**: Tobias Stacke  
**NOAH-(MP)**: Yihua Wu and Michel Ek  
**OLAM**: Robert Walko  
**ORCHIDEE**: Agnès Ducharne and Fuxing Wang  
**SSiB**: Yongkang Xue, Qian Li  
**SURFEX-ISBA**: Aaron Boone and Sebastien Garrigues
OVERVIEW

• Joint ISMC and GEWEX communities: Initiatives to improve soil and subsurface processes in current climate and hydrological models.

• Evaluation of pedotransfer functions and related functional descriptions for calculation of hydraulic and thermal soil properties in global climate models.
**THERMAL CONDUCTIVITY, $\lambda$**

- Soil thermal conductivity depends on dry, $\lambda_{dry}$, and saturated conductivity, $\lambda_{sat}$, in combination with a soil moisture dependent weighting function, $F_\theta$
- Equations are required to estimate $\lambda_{dry}$, $\lambda_{sat}$ and $F_\theta$
- These parameters, and their intrinsic parameters all require ‘thermal’ PFTs

Most LSM models use:

$$\lambda = F_\theta \lambda_{sat} + (1 - F_\theta) \lambda_{dry}$$

Weighting function

One uses:

$$\lambda = \lambda_0 + \lambda_1 F_\theta + \lambda_2 (F_\theta)^2$$

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WEIGHTING FUNCTION, $F_\theta$

- The weighting function, $F_\theta$, is often the Kersten number, $K_e$, which is dependent on the relative saturation, $S_e$.
- Constant $\gamma$ varies between models.
- $S_e$ depends on moisture content, $\theta$, and saturated moisture content, $\theta_{sat}$, and residual SMC, $\theta_r$ (for VG).

Most LSMS: $F_\theta = \text{Kersten number, } K_e$

$$K_e = \gamma \log(S_e) + 1$$

$$F_\theta = S_e \text{ for 2 others}$$

where $\gamma$ is generally one, but for some models is set to 0.7 for coarse soils.

Others use $\gamma = 0.7$ for $0.05 < S_e \leq 0.1$.

Clapp & Hornberger/Brooks & Corey

$$S_e = \frac{\theta}{\theta_{sat}}$$

Van Genuchten, VG

$$S_e = \frac{\theta - \theta_r}{\theta_{sat} - \theta_r}$$
**Dry Thermal Conductivity, $\lambda_{dry}$**

- Generally dependent on (some of) the soil texture fractions (sand, silt, clay), either explicitly or implicitly (via soil class look-up tables, LUTs).

- Porosity, $\theta_{sat}$, is an important parameter, and depends on hydraulic PFTs (in blue).

Alternatively

$$\lambda_{dry, min} = 0.19$$

Most LSMs use Johansen (1975), as also used by Peters-Lidard et al. (1998)

$$\lambda_{dry, min} = \frac{0.135 \rho_{min} + 64.7}{\rho_{min} - 0.947 \rho_{b,min}}$$

One uses (Cox et al., 1999)

$$\lambda_{dry, min} = \lambda_{air} \theta_{sat} X_{cl} X_{sa} X_{si}$$

$$X_j = C_j f_j (1 - \theta_{sat})$$

$C_j$ is a constant (1.16 for clay, 1.57 for silt and sand), and $f_j$ is the fraction of $j = \text{clay, silt, or sand}$

Or Lu et al., 2007

$$\lambda_{dry, min} = -0.56 \theta_{sat} + 0.51$$

**THERMAL PROPERTIES THEORY**

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Saturated Thermal Conductivity, $\lambda_{sat}$

- The saturated thermal conductivity generally depends on the thermal conductivities of the solid soil material, $\lambda_{soil}$, liquid soil water, $\lambda_{liq}$, and ice, $\lambda_{ice}$, sometimes on $\lambda_{air}$.

Most LSMs use (from Johansen, 1975?):

$$\lambda_{sat} = \lambda_{soil}^{1-\theta_{sat}} \lambda_{ice}^{\theta_{sat}} \lambda_{liq}^{\theta_u} \lambda_{air}^{\theta_{sat}}$$

Soil solid conductivity (see next slide)

One uses

$$\lambda_{sat} = \lambda_{dry}^{\theta_{sat}} (\lambda_{liq}^{\theta_{sat}} \lambda_{ice}^{f_{sat}}) / \lambda_{air}^{\theta_{sat}}$$

Or

$$\lambda_{sat} = \begin{cases} 
1.58 & \lambda_{dry} < 0.25 \\
1.58 + 12.4(\lambda_{dry} - 0.25) & 0.25 < \lambda_{dry} < 0.3 \\
2.2 & \lambda_{dry} > 0.3
\end{cases}$$
SOIL SOLID THERMAL CONDUCTIVITY, $\lambda_{soil}$

- The saturated thermal conductivity generally depends on the thermal conductivities of the solid soil material, $\lambda_{soil}$, liquid soil water, $\lambda_{liq}$, and ice, $\lambda_{ice}$, sometimes of $\lambda_{air}$.

In a number of LSMs, $\lambda_{soil}$ is assumed to be dependent only on the thermal conductivity of the mineral soil solids as given by (Johansen, 1975):

$$\lambda_{soil} = \lambda_{qu} f_{qu} \lambda_{o}^{1-f_{qu}}$$

Some use:

$$\lambda_{soil} = \frac{\lambda_{qu} f_{sand} + \lambda_{clay} f_{clay}}{f_{sand} + f_{clay}}$$

$f_{qu} = 0.038 + 0.0095 f_{SA}$

$\lambda_{qu}$ the thermal conductivity of quartz, having a value of 8.8 or 7 W m$^{-1}$ K$^{-1}$

$\lambda_{o}$ is the thermal conductivity of other minerals, generally set to 2 or 3 W m$^{-1}$ K$^{-1}$
SOIL HEAT CAPACITY, $C_h$

• Theory (e.g. Van Wijk & de Vries, 1963) states soil heat capacity depends on the specific heat capacities ($c_i$) of the solid soil material, liquid soil, water, ice, and air, their densities ($\rho_i$) and volume fractions ($\phi_i$).

• Alternatively we can use the volumetric heat capacity

• Some models use a constant $C_h (= 2.19 \times 10^6$; independent of soil type), i.e. its values remain unchanged despite changes in $\theta$, whereas others uses values ranging between $1.93 \times 10^6$ for sand to $2.48 \times 10^6$, for clay.

\[
C_h = \phi_{min}\rho_{min}c_{min} + \phi_{org}\rho_{org}c_{org} + \phi_{liq}\rho_{liq}c_{liq} + \phi_{ice}\rho_{ice}c_{ice} + \phi_{air}\rho_{air}c_{air}
\]

\[
C_h = \phi_{min}c_{min} + \phi_{org}c_{org} + \phi_{liq}c_{liq} + \phi_{ice}c_{ice} + \phi_{air}c_{air}
\]

\[
\phi_{min} = (1 - \theta_{sat}) \quad \phi_{liq} = \theta \quad \phi_{min} + \phi_{org} + \phi_{liq} + \phi_{ice} + \phi_{air} = 1.0
\]
**CALCULATION OF MINERAL HEAT CAPACITY, \( c_{min} \) OR \( C_{min} \)**

- The main PTF for heat capacity relates to the way \( c_{min} \) or \( C_{min} \) is calculated. There are a number of options used in the LSMs:
  - (i) Employ the same value for all soil types
  - (ii) Use different values (tabulated) for each soil class,
  - (iii) Use different values per soil class, calculated as a function of texture:

(i) One uses \( C_{min} = 1.942 \times 10^6 \) (Johansen, 1975), as one of its options. Others use \( C_{min} = 2.0 \times 10^6 \); \( c_{min} = 850 \text{ J kg}^{-1} \text{ K}^{-1} \), or \( c_{min} = 733 \text{ J kg}^{-1} \text{ K}^{-1} \)

(ii) Two LSMs use the same values for \( C_{min} = \rho_{min} c_{min} \) for 11 USDA soil type as given in Pielke (2002) based on McCumber (1980), see also McCumber and Pielke (1981)

(iii) A range of PTFs can be found, e.g.:

\[
\begin{align*}
C_{min} &= (f_{\text{sand}} C_{\text{sand}} + f_{\text{clay}} C_{\text{clay}})/(f_{\text{sand}} + f_{\text{clay}}) \\
C_{min} &= f_{\text{clay}} C_{\text{clay}} + f_{\text{sand}} C_{\text{sand}} + f_{\text{silt}} C_{\text{silt}}
\end{align*}
\]
**RESULTS:** Thermal Conductivity

- Per soil type: large difference in $\lambda$ between models
- Considerably different functional shapes between models

**RESULTS, thermal conductivity**

- Sand
- Loam
- Clay

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RESULTS, HEAT CAPACITY

- Per soil type: considerable difference in $C_h$ between models
- In some cases, different slopes between models
Model runs, using model-specific thermal (& hydraulic) properties

- Runs with Hydrus 1-D for 14 years (2001-2014) of half-hourly data from Avignon, model outputs are hourly
- 2 LSMs are compared in the next slides
- Bare soil, soil profile of 50 cm, no vapour flow, free drainage
- Sand, Loam, clay
- LSM thermal equations have been implemented into Hydrus-1D
- Effects on energy- and water balance have been investigated
- Effect on soil (surface) temperature and soil moisture content
Net radiation, Sand, multi-year diurnal monthly average

- Time (hours)
- Net radiation (W m$^{-2}$)

- July
- August
- September
- October
- November
- December

OLAM_VG

Comparision using HYDRUS Model
Evaporation, Sand, multi-year diurnal monthly average

- July
- August
- September
- October
- November
- December

Latent heat flux (W m\(^{-2}\))

Time (hours)
Sensible heat flux, sand, multi-year diurnal monthly average

- Sensible heat flux (W m\(^{-2}\))
- Time (hours)

July
August
September
October
November
December

Tessel
OLAM_VG
Soil heat flux, sand, multi-year diurnal monthly average

Time (hours)

Surface Soil heat flux (W m$^{-2}$)

-200 -100 0 100 200

July
August
September
October
November
December

Tessel
OLAM_VG

Soil heat flux, sand, multi-year diurnal monthly average using HYDRUS MODEL.
Surface temperature, sand, multi-year diurnal monthly average
Surface SMC, sand, multi-year diurnal monthly average

- July
- August
- September
- October
- November
- December

Surface Moisture content

Time (hours)
Below: exact same hydraulic functions, but two different thermal functions, (solid line LSM 1, dashed line LSM 2)
Small effect on EB fluxes and $T_s$, but considerable effect on deeper soil temperatures

Causes differences values, amplitudes and phase-shifts: implications for soil freezing and permafrost applications
CONCLUSIONS

• Very different shapes for $\lambda(\theta)$ curve, and considerable differences in $C_h(\theta)$, between LSM models

• Some LSM models have errors in their basic equations; some model teams have now corrected these

• PTFs for parameters in these thermal property functions vary considerably between models.

• They include a hydraulic PFT for porosity

• PFTs depend on soil texture and porosity/dry bulk density, as well as quartz content
CONCLUSIONS, c’ed

• The combined effect of the choice of thermal and hydraulic equations on the energy and water balance is large.

• When only the thermal properties differ, the main effect is on deeper soil temperatures.

• This has implications for modelling of permafrost regions or soil respiration, for example.
Next steps

- Assess influence for vegetated surfaces (reduced)
- Use measured thermal properties to test validity of models
- Select preferred and/or adjust equations/PTFs
- Make recommendations to LS and Hydrological modellers