TITLE SLIDE

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

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JÜLICH FORSCHUNGSZENTRUM

ISMC conference/workshop on the future of PedoTransfer Functions, New Orleans 10 December 2017

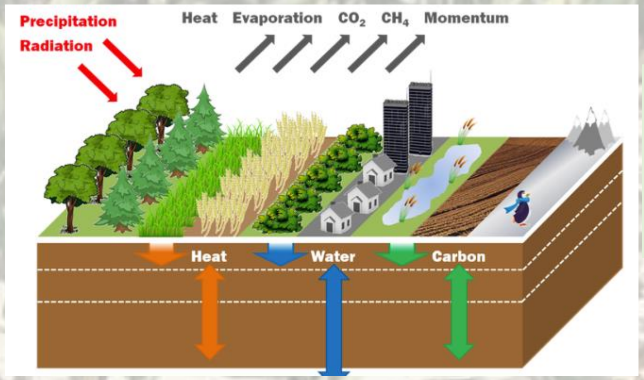
University of Reading

OVERVIEW

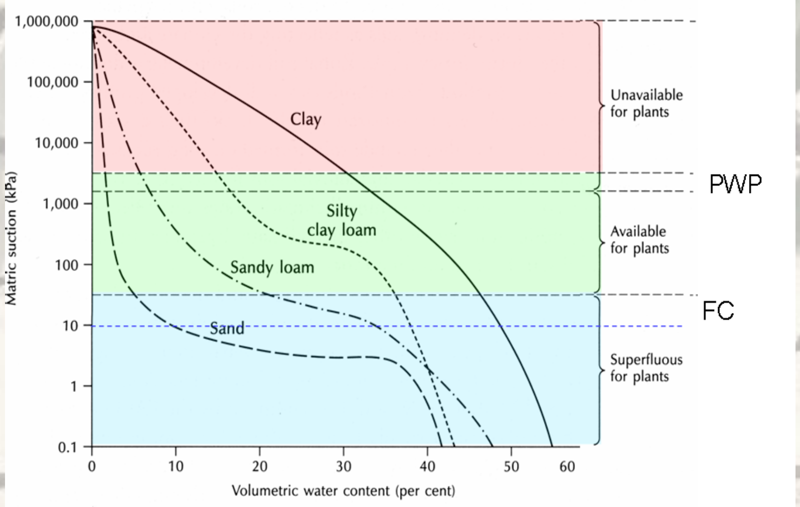
Overview

- 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.



land surface model



THERMAL PROPERTIES THEORY

THERMAL CONDUCTIVITY, λ

- Soil thermal conductivity depends on dry, λ_{dry}, and saturated conductivity, λ_{sat}, in combination with a soil moisture dependent weighting function, F_θ

- Equations are required to estimate λ_{dry}, λ_{sat} and F_θ

- 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:

$$\lambda = \lambda_0 + \lambda_1 F_\theta + \lambda_2 [F_\theta]^2$$

WEIGHTING FUNCTION, F_θ

- The weighting function, F_θ, is often the Kersten number, K_e, which is dependent on the relative saturation, S_e
- Constant γ varies between models
- S_e depends on moisture content, θ, and saturated moisture content, θ_{sat}, and residual SMC, θ_r (for VG).

Most LSMs: F_θ = Kersten number, K_e

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

$F_\theta = S_e$ for 2 others

where γ 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, λ_{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, θ_{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)

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

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* = clay, silt, or sand**

Or Lu et al., 2007

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

THERMAL PROPERTIES THEORY

SATURATED THERMAL CONDUCTIVITY, λ_{sat}

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

Most LSMs use (from Johansen, 1975?):

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

Soil solid conductivity (see next slide)

One uses

$$\lambda_{sat} = \lambda_{dry} \left(\lambda_{liq}^{\theta_{sat}^u} \lambda_{ice}^{\theta_{sat}^f} \right) / \lambda_{air}^{\theta_{sat}}$$

Or

$$\lambda_{sat} = \begin{cases} 1.58 & \lambda_{dry} < 0.25 \\ 1.58 + 12.4(\lambda_{dry} - 0.25) & 0.25 < \lambda_{dry} < 0.3 \\ 2.2 & \lambda_{dry} > 0.3 \end{cases}$$

THERMAL PROPERTIES THEORY

SOIL SOLID THERMAL CONDUCTIVITY, λ_{soil}

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

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

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

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

Some use:

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

$$\lambda_{soil} = 7.0$$

$$\lambda_{soil} = 3.44$$

λ_{qu} the thermal conductivity of quartz, having a value of 8.8 or 7 W m^{-1} K^{-1}
λ_{o} is the thermal conductivity of other minerals, generally set to 2 or 3 W m^{-1} K^{-1}

THERMAL PROPERTIES THEORY

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 (ρ_i) and volume fractions (ϕ_i).
- Alternatively we can use the volumetric heat capacity
- Some models use a constant C_h(= 2.19×10^6; independent of soil type), i.e. its values remain unchanged despite changes in θ, whereas others uses values ranging between 1.93 ×10^6 for sand to 2.48×10^6, for clay.

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

$$C_h = \phi_{min}C_{min} + \phi_{org}C_{org} + \phi_{liq}C_{liq} + \phi_{ice}C_{ice} + \phi_{air}C_{air}$$

$$\phi_{min} = (1 - \theta_{sat})$$

$$\phi_{liq} = \theta$$

$$\phi_{min} + \phi_{org} + \phi_{liq} + \phi_{ice} + \phi_{air} = 1.0$$

THERMAL PROPERTIES THEORY

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

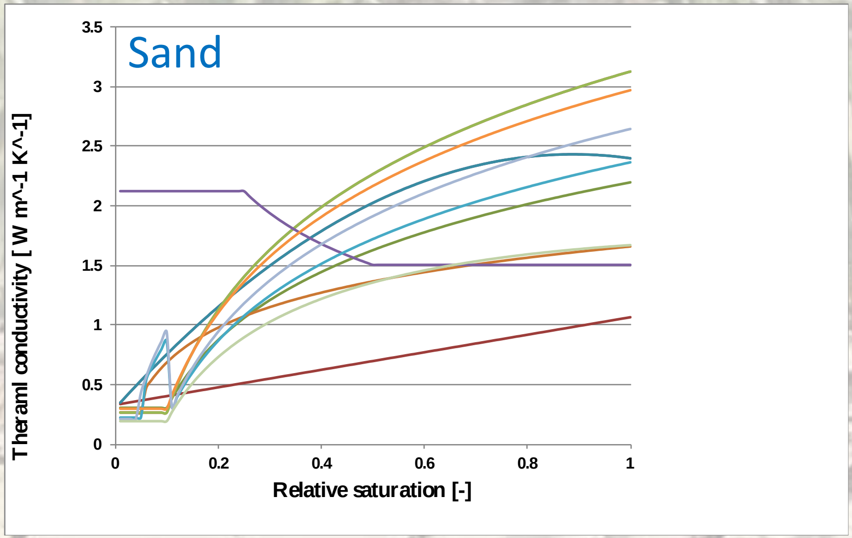
(ii) Two LSMs use the same values for $C_{min} = \rho_{min} c_{min}$ for 11 USDA soil type as given in Pielke (2002) based on McCumber (1980), see also McCumber and Pielke (1981)

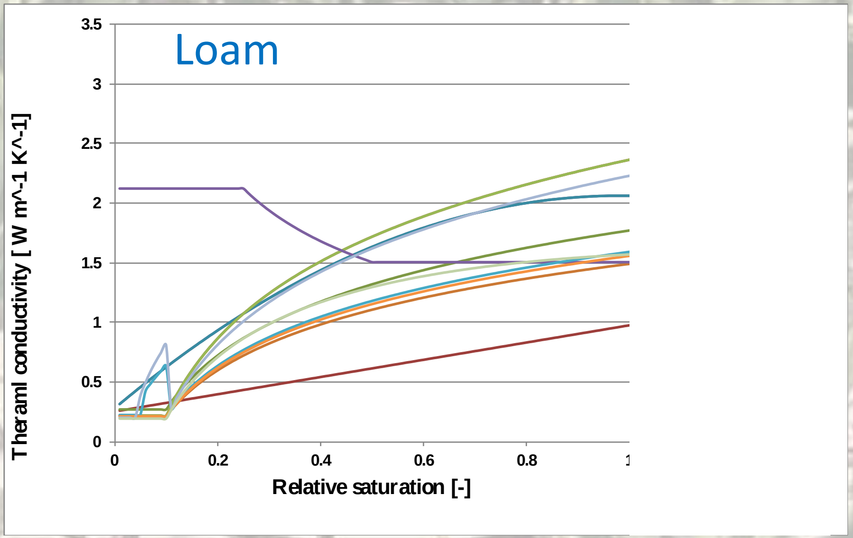
(iii) A range of PTFs can be found, e.g. :

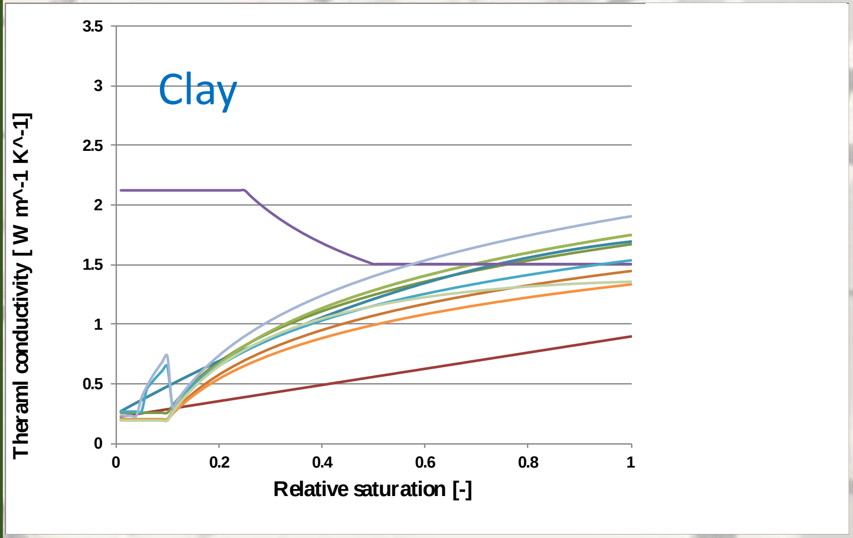
$$C_{min} = (f_{sand} C_{sand} + f_{clay} C_{clay})/(f_{sand} + f_{clay})$$

$$C_{min} = f_{clay} C_{clay} + f_{sand} C_{sand} + f_{silt} C_{silt}$$

Results: Thermal Conductivity



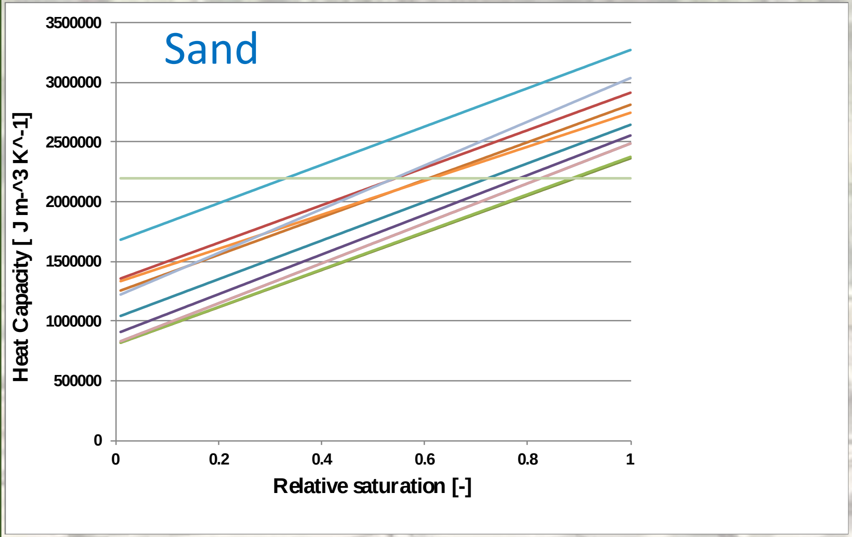


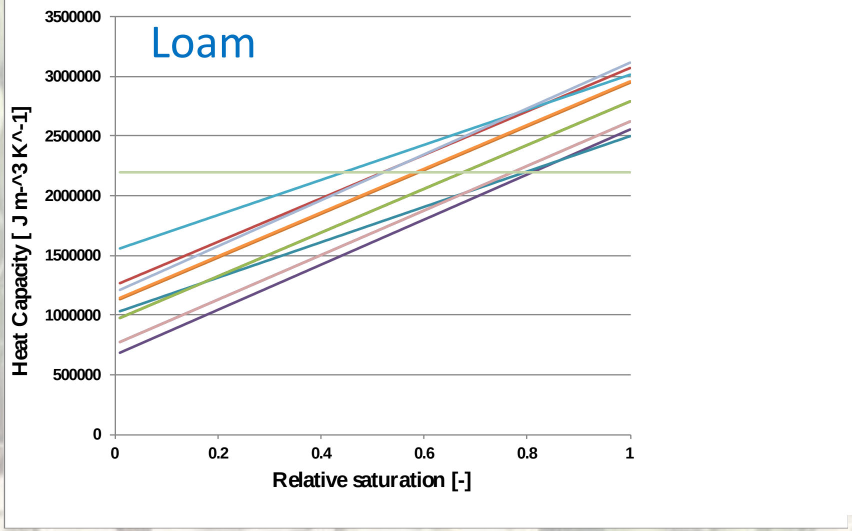


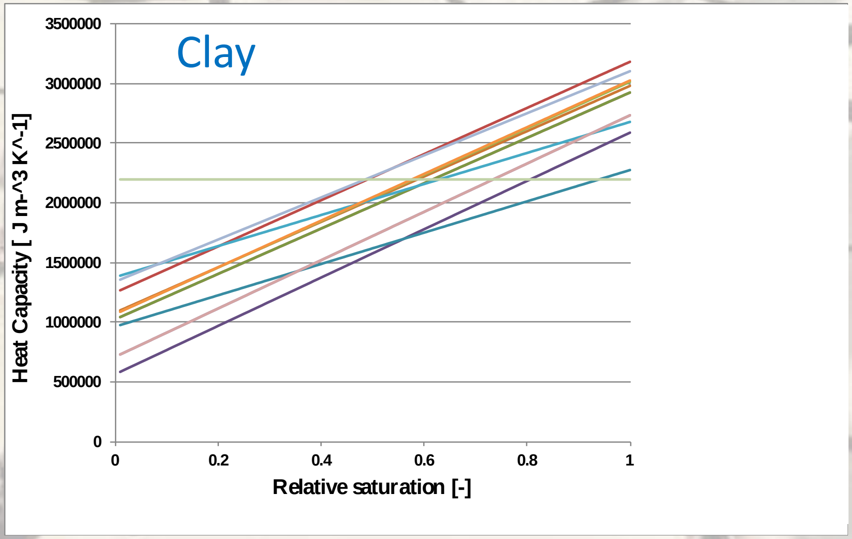
Results, thermal conductivity

- Per soil type: large difference in λ between models
- Considerably different functional shapes between models

RESULTS: HEAT CAPACITY







RESULTS, HEAT CAPACITY

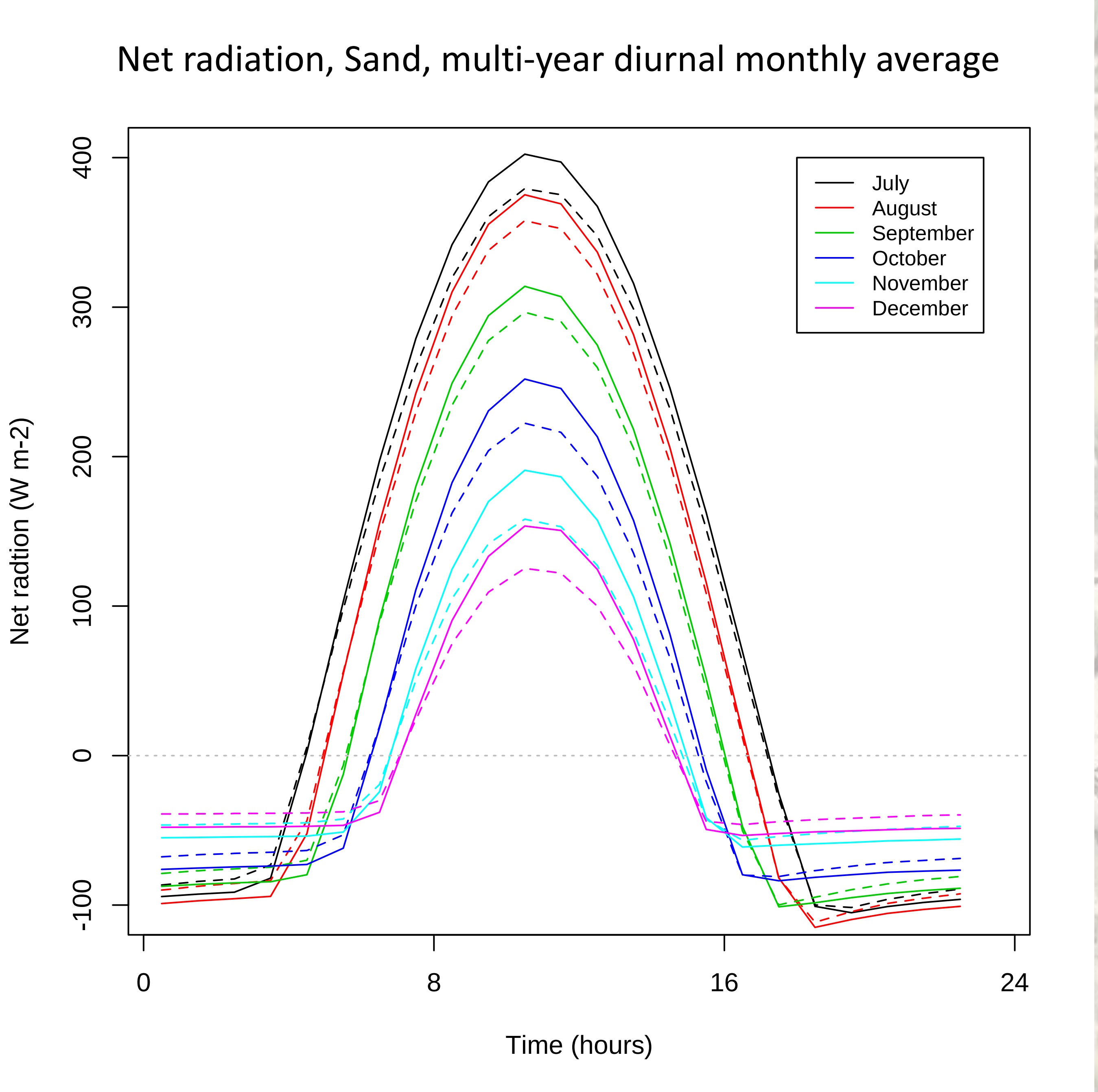
- Per soil type: considerable difference in C_h between models
- In some cases, different slopes between models

COMPARISON USING HYDRUS MODEL

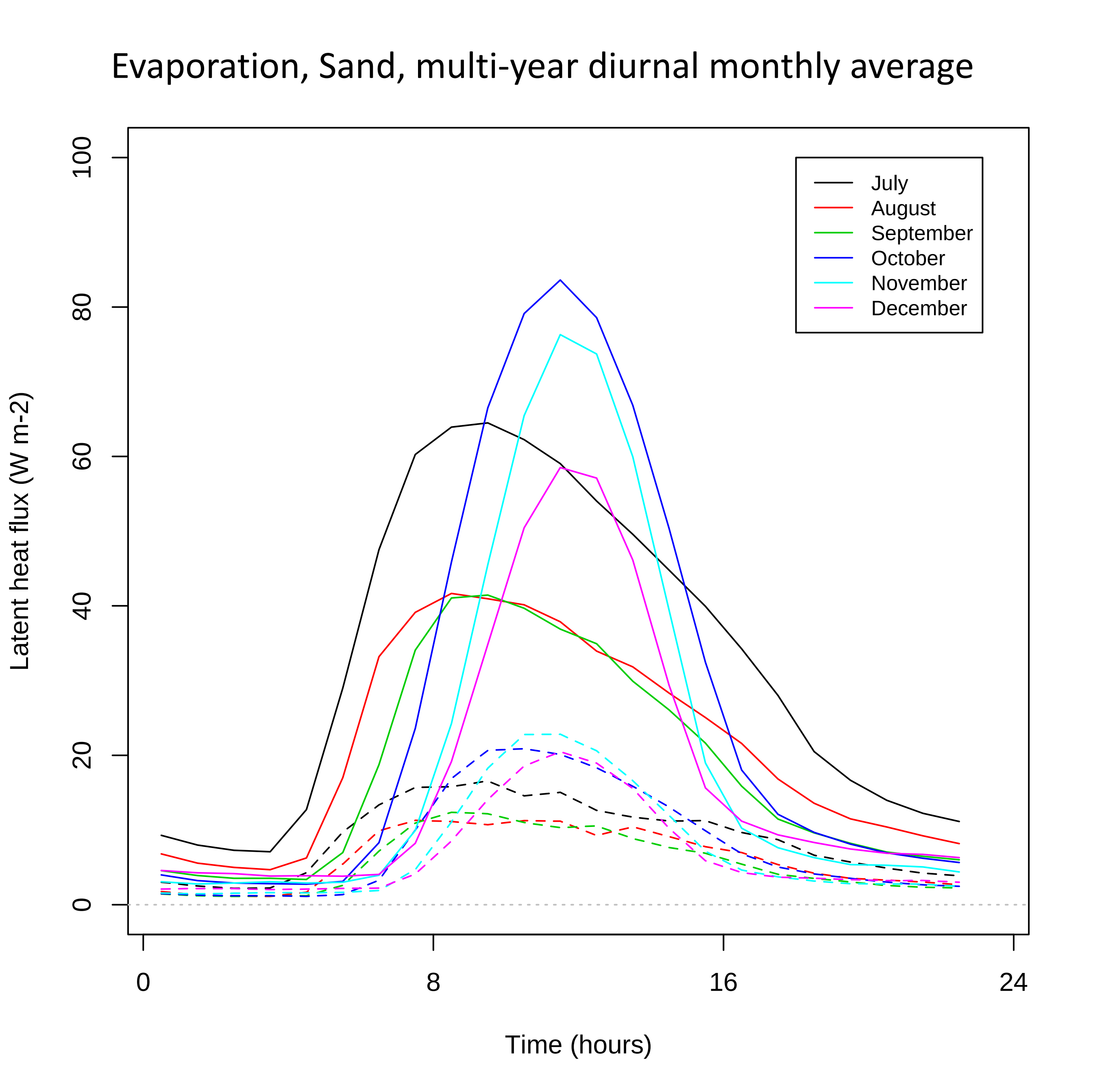
MODEL RUNS, USING MODEL-SPECIFIC THERMAL (& hydraulic) properties

- 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

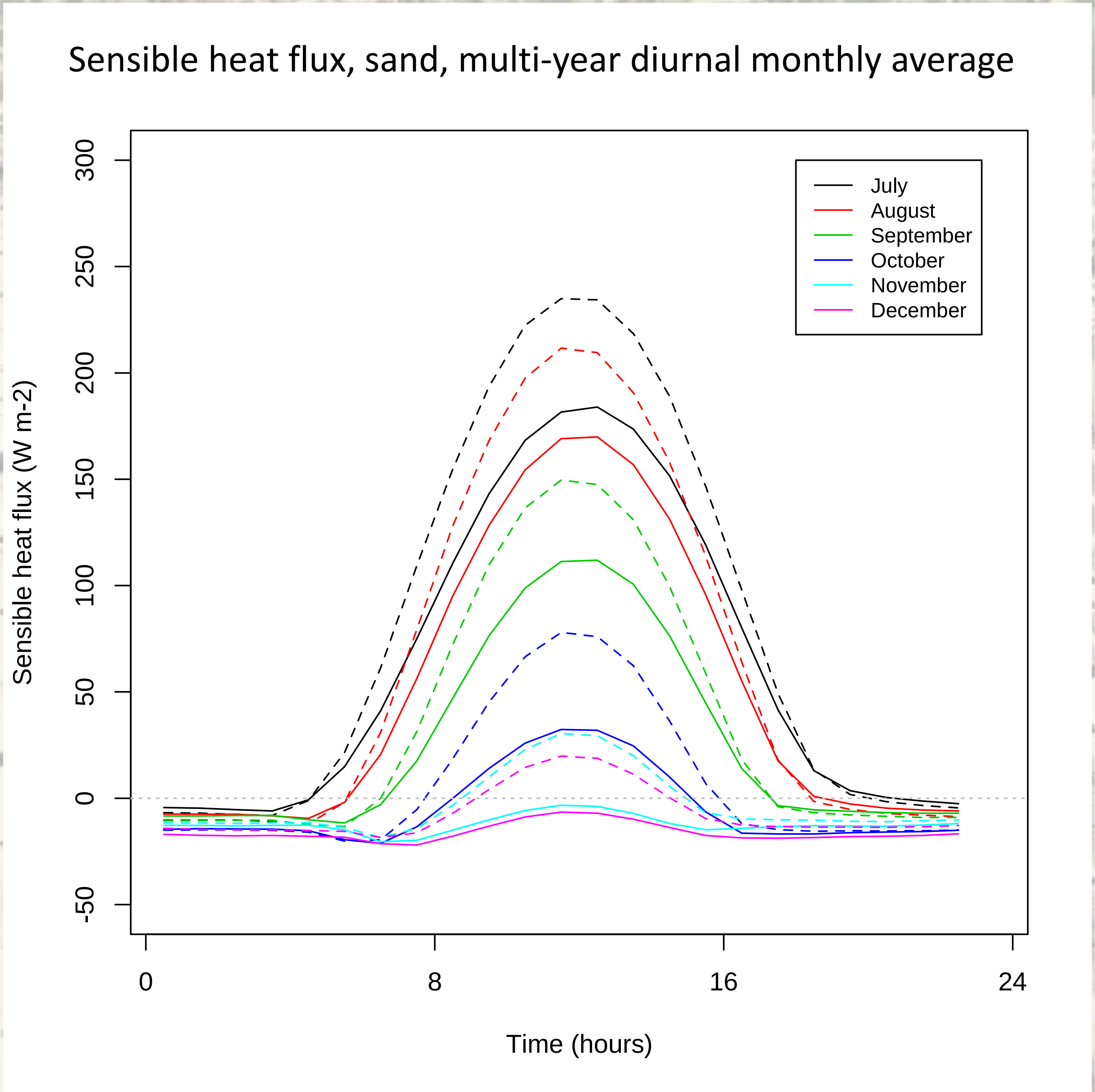
Comparison using Hydrus model



Comparison using Hydrus model

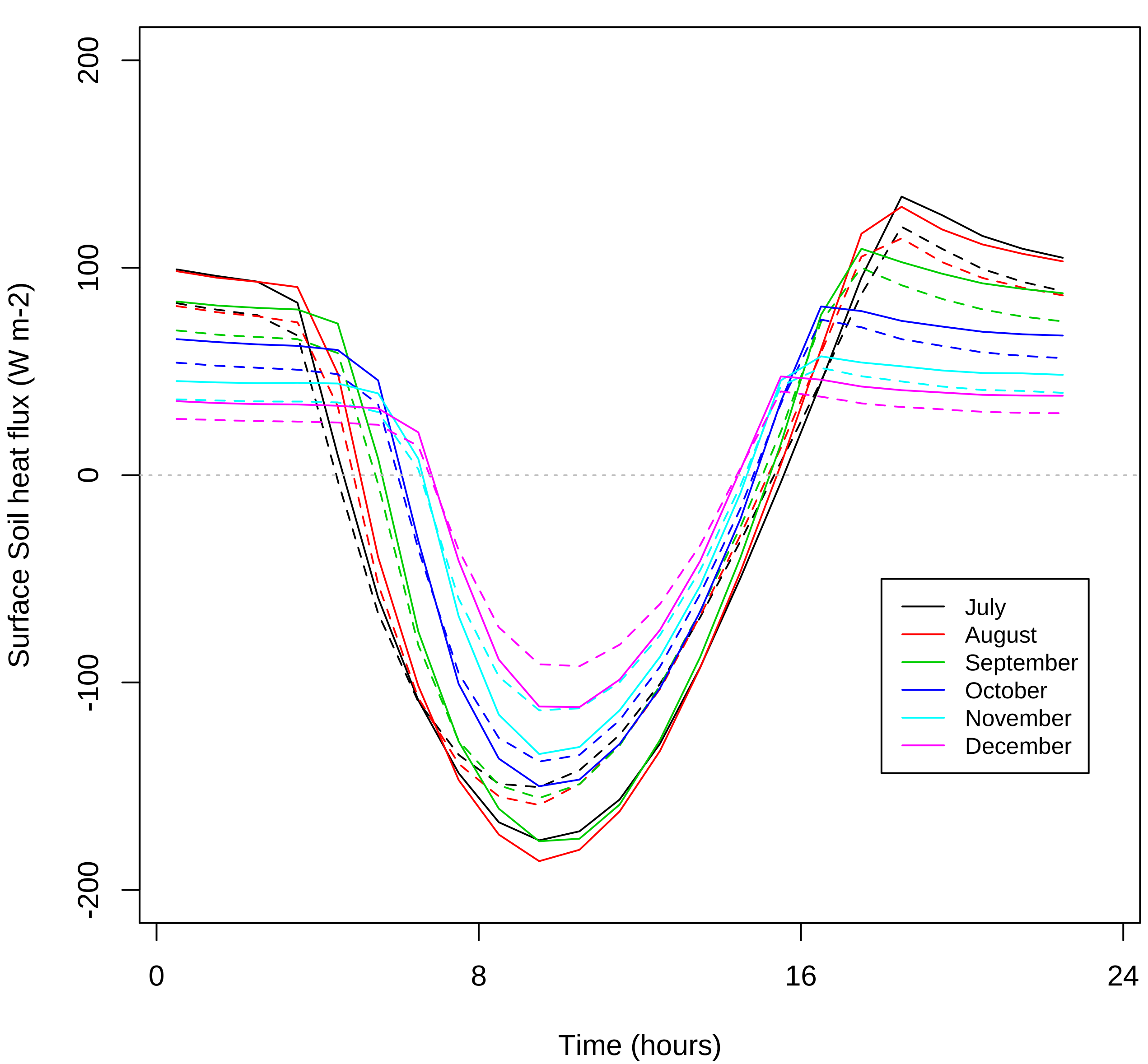


Comparison using Hydrus model



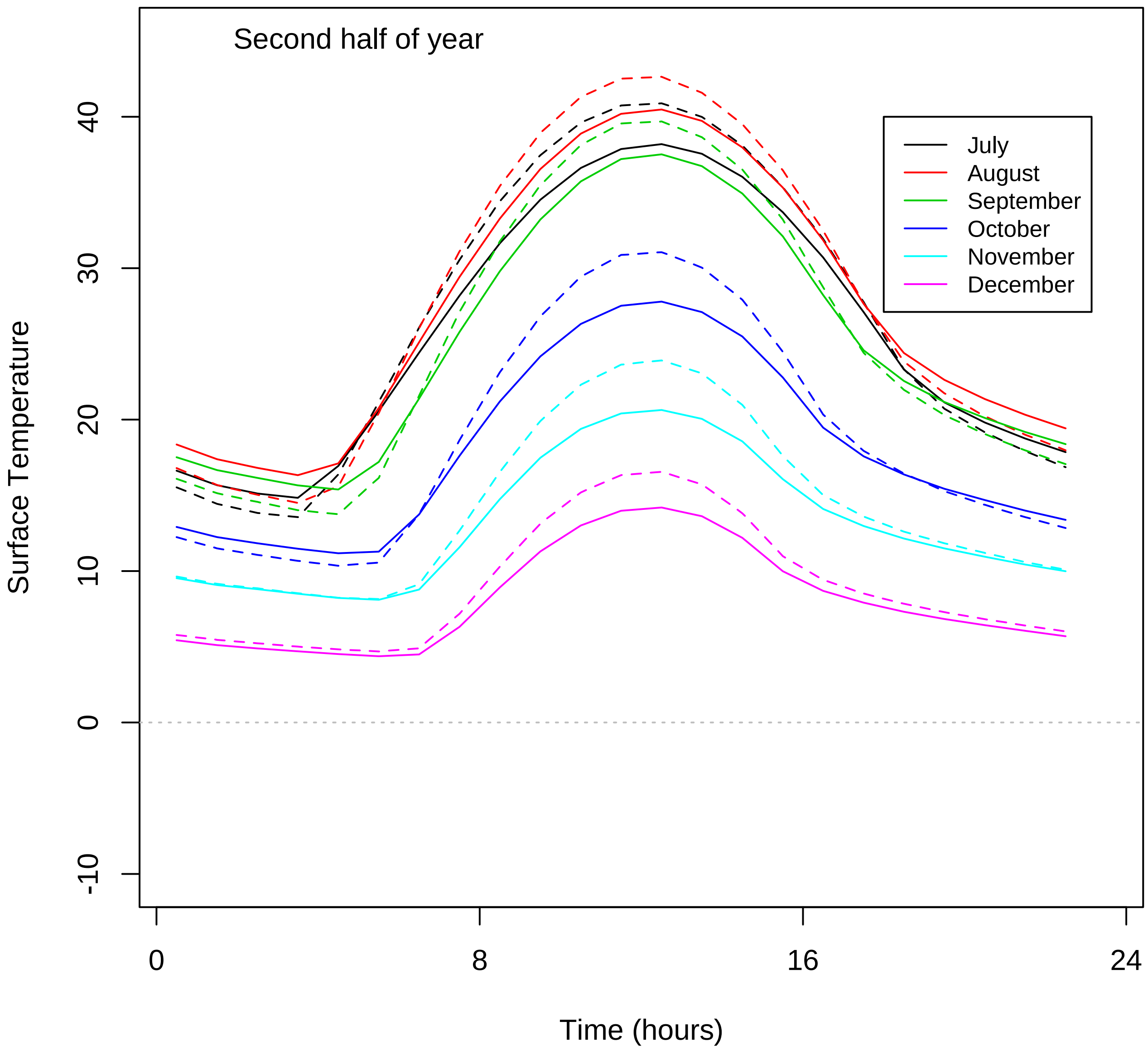
COMPARISON USING HYDRUS MODEL

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



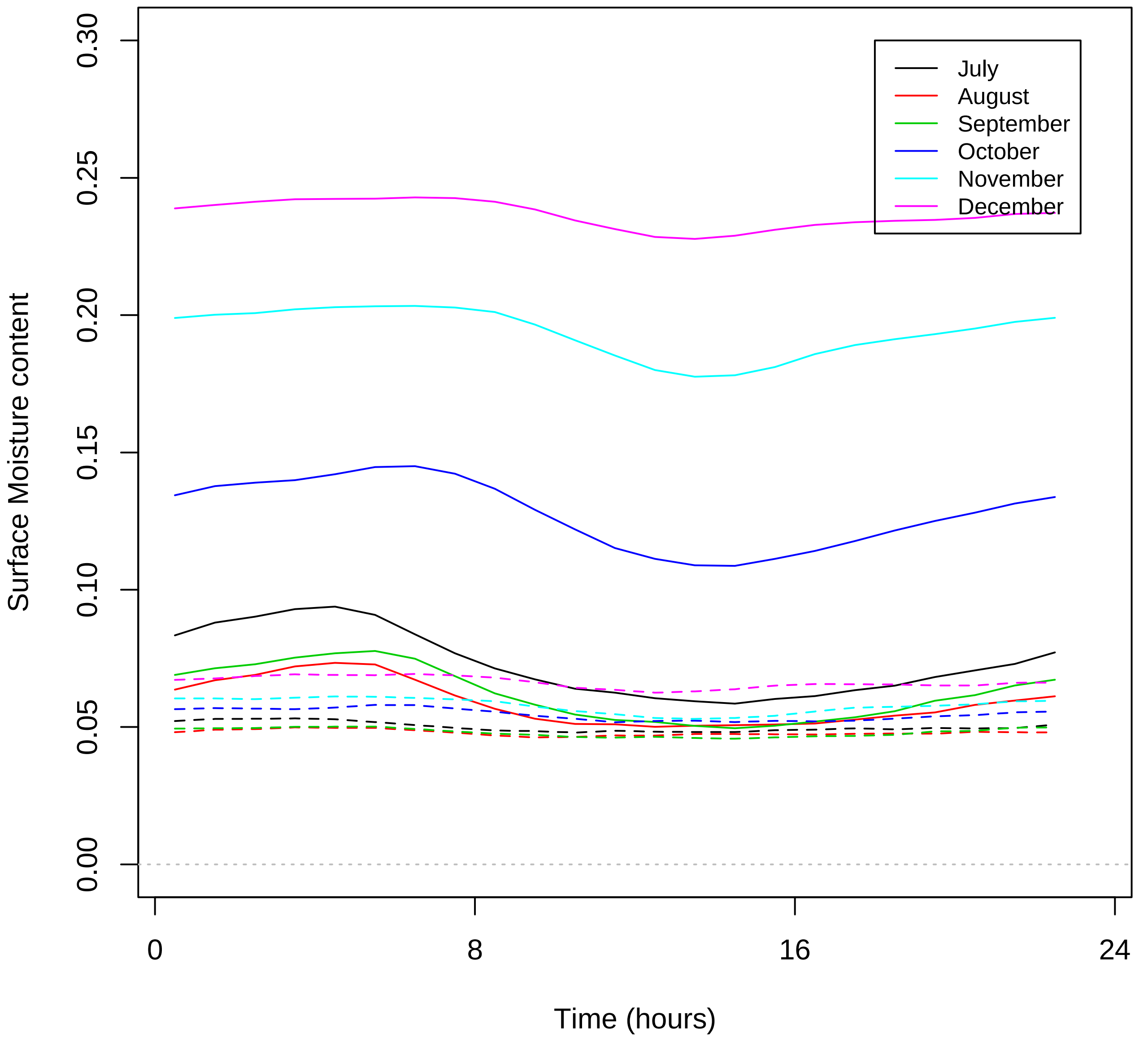
COMPARISON USING HYDRUS MODEL

Surface temperature, sand, multi-year diurnal monthly average



Comparison using Hydrus model

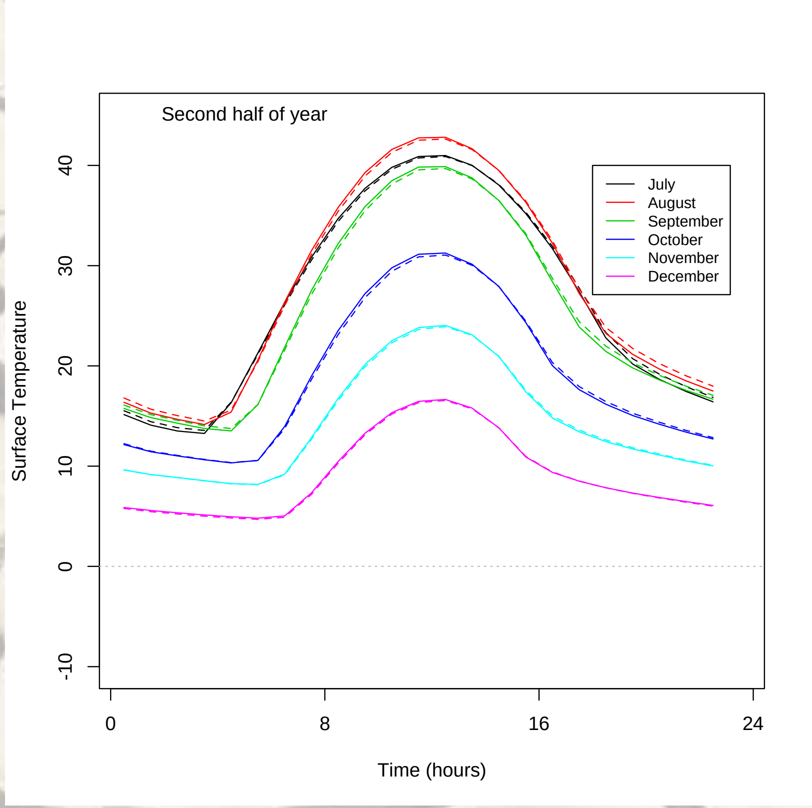
Surface SMC, sand, multi-year diurnal monthly average

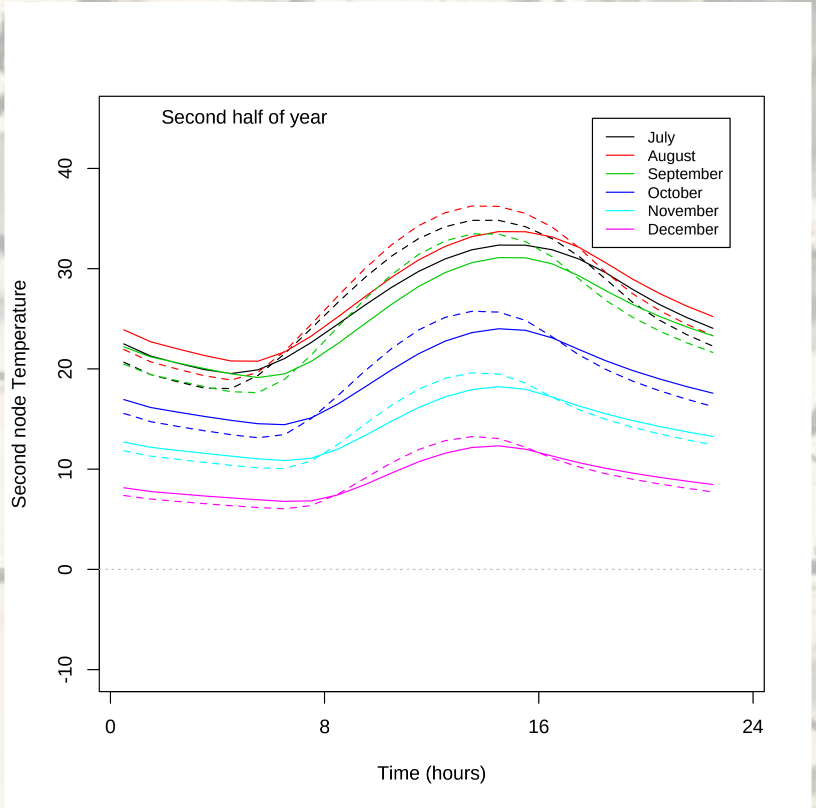


Comparison using Hydrus model

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

CONCLUSIONS

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