Principles of soil water and heat transfer in JULES

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Overview of presentation

- Summary of theory
  - Calculation of water and heat flow
  - Parameterisation of water retention curve
  - Parameterisation of thermal soil properties
  - Importance of texture maps

- Examples of some research in this area

JULES Schematic

Schematic of JULES model (Blyth et al.; 2006)

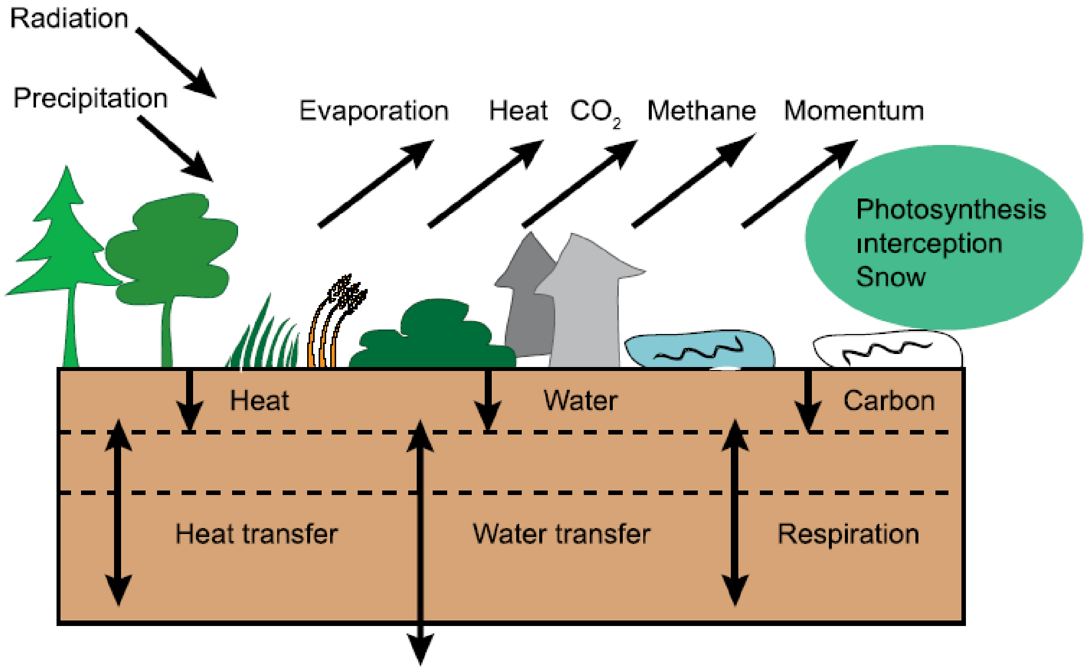
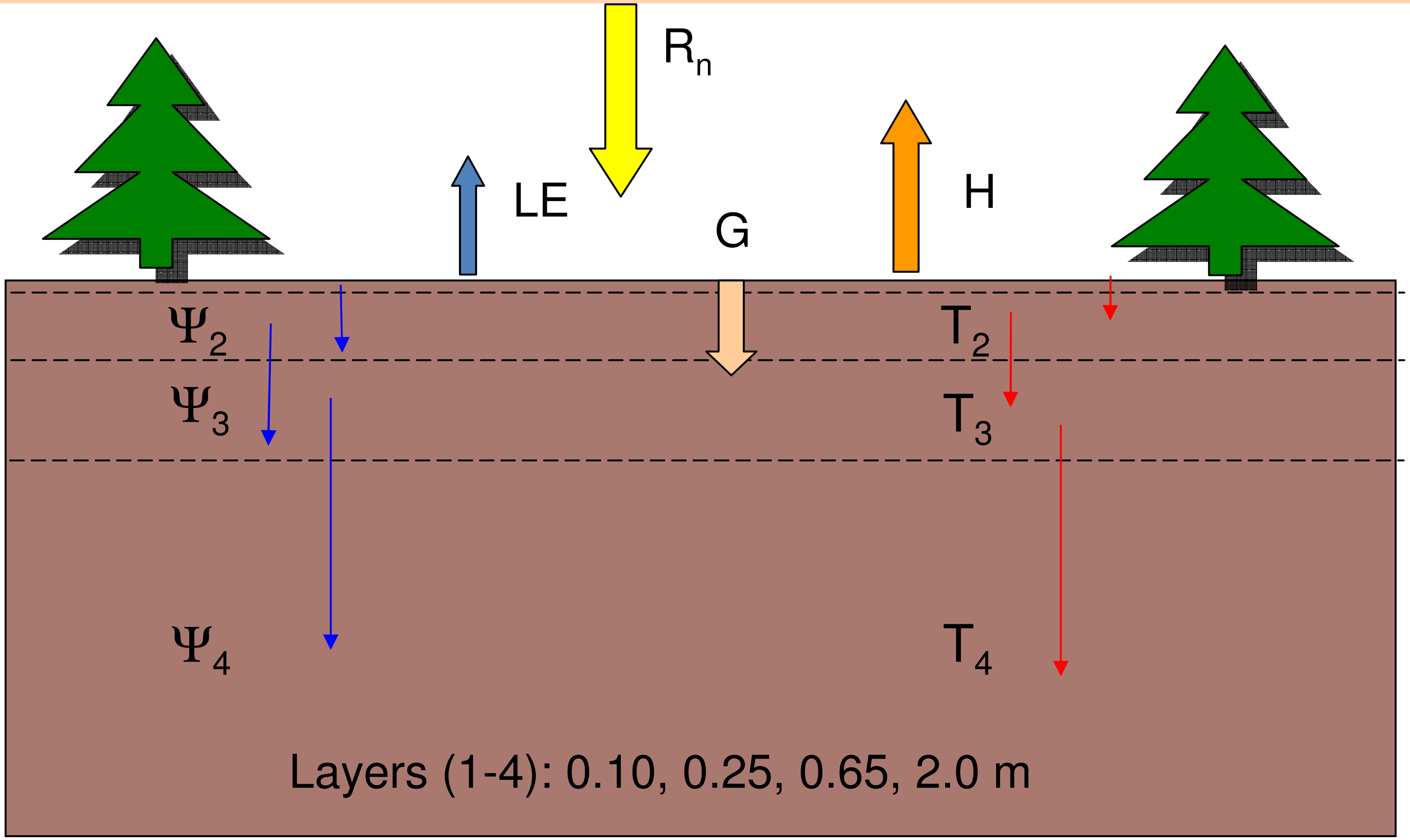


Figure 1. Schematic diagram of the new Land Surface Model, JULES.

JULES Soil hydrology and thermodynamics

Within-soil transfer



Layers (1-4): 0.10, 0.25, 0.65, 2.0 m

$$W = K\left\{\frac{\Delta\psi}{\Delta z} + 1\right\}$$

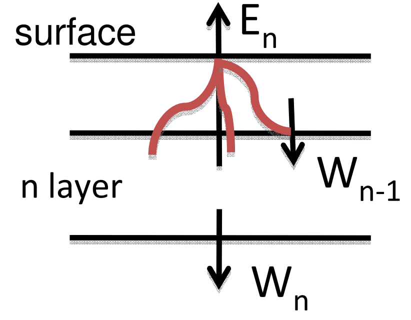
$$G = \lambda\frac{\Delta T}{\Delta z}$$

Plus
advective
heat transfer

How does JULES simulate soil hydrology and heat transfer ?

$$M = \rho_w \Delta z \theta_s \{S_u + S_f\}$$

$$W = K\left\{\frac{\partial \psi}{\partial z} + 1\right\}$$ Darcy's law



Capillary capacity

$$\frac{dM_n}{dt} = W_{n-1} - W_n - \boxed{E_n} \longleftrightarrow C_{h,n}\frac{\partial \psi_n}{\partial t} = \frac{\partial}{\partial z}\left(K_n \frac{\partial \psi_n}{\partial z} - K_n\right) - \frac{E_n}{\rho_w \Delta z_n}$$

(as in JULES documentation)

(standard Richard's equation)

Some models consider coupled heat and water movement in the soil

$$C_A \Delta z_n \frac{dT_n}{dt} = G_{n-1} - G_n - J_n \Delta z_n \begin{cases} G = \lambda \dfrac{\partial T}{\partial z} & \text{Diffusive flux, Fourier's law} \\ J = c_w W \dfrac{\partial T}{\partial z} & \text{Advective flux} \end{cases}$$

Apparent volumetric heat capacity

Recent addition of vapour transport..

Due to <u>soil water potential</u> (isothermal) and <u>thermal gradients</u>…

$$C_{h,n}\frac{\partial \psi_n}{\partial t}=\frac{\partial}{\partial z}\left(\left(K_n+D_{\psi,v,n}\right)\frac{\partial \psi_n}{\partial z}+D_{T,v,n}\frac{\partial T_n}{\partial z}-K_n\right)-\frac{E_n}{\rho_w \Delta z_n}$$

Isothermal vapour conductivity

Thermal vapour diffusivity

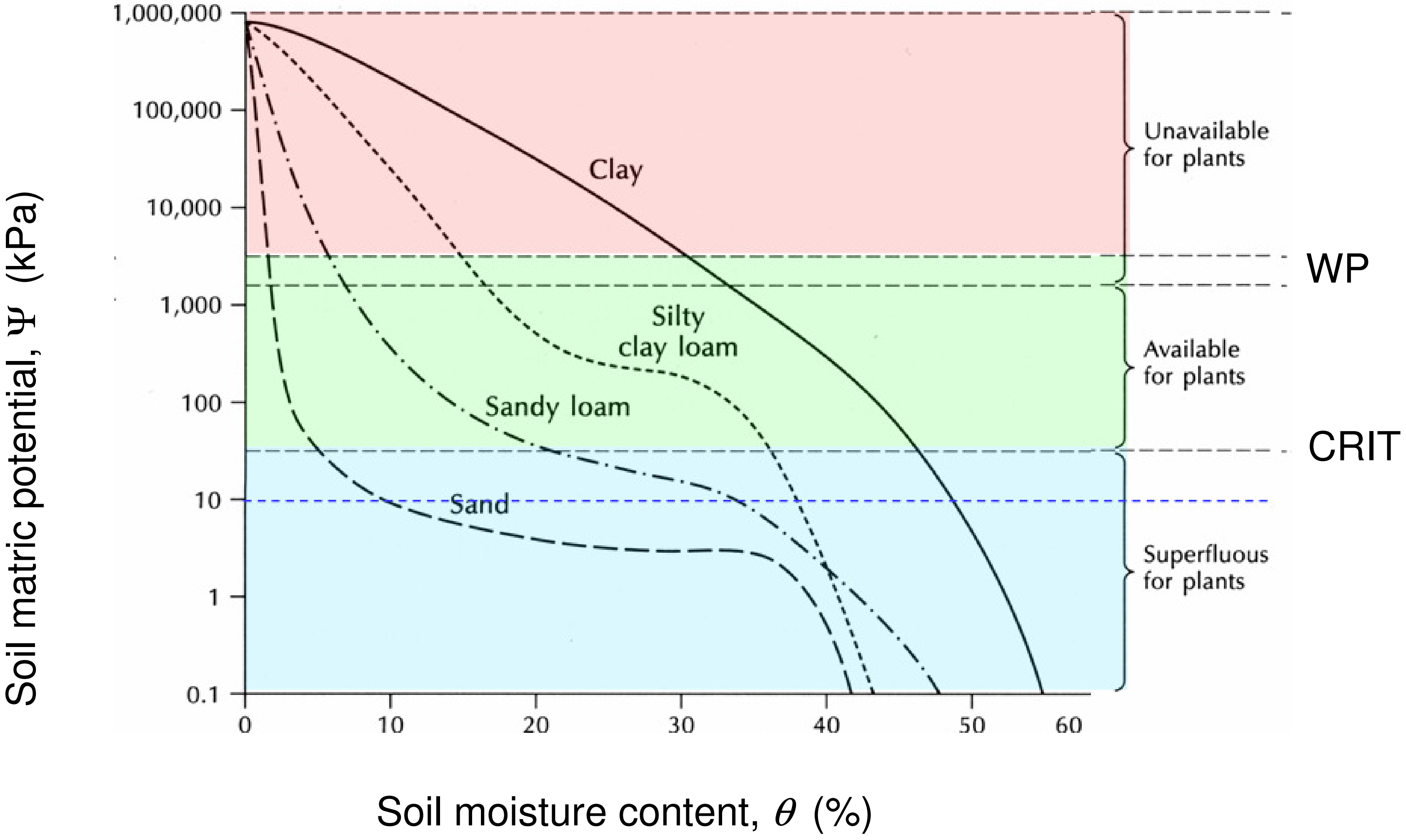
$$C_A\frac{\partial T_n}{\partial t}=\frac{\partial}{\partial z}\left[\lambda_n\frac{\partial T_n}{\partial z}+\rho_w L D_{\psi,v,n}\frac{\partial \psi_n}{\partial z}\right]-c_w W\frac{\partial T_n}{\partial z}$$

These gradients will induce soil moisture transport and
affect soil moisture distribution, which in turn will affect heat flow

Milly, et. 1982, 1984

Water retention curve

How tightly is water held in the soil?

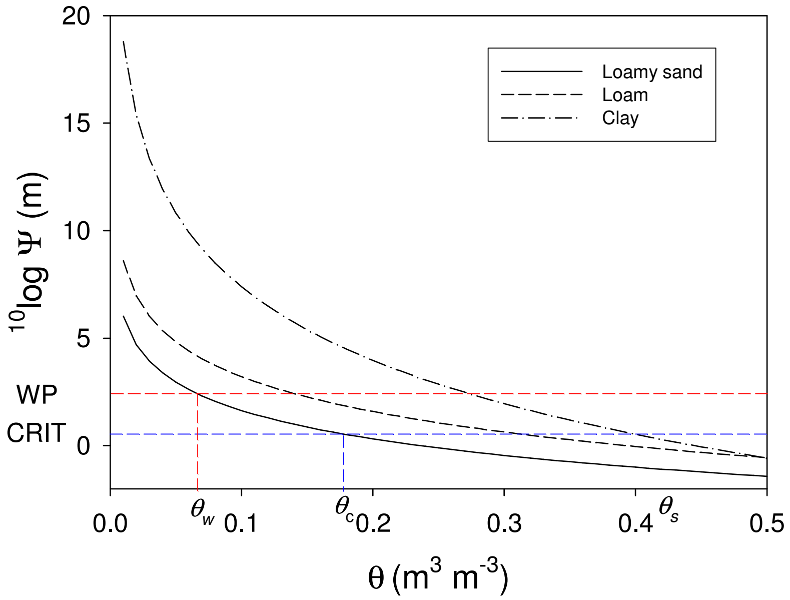


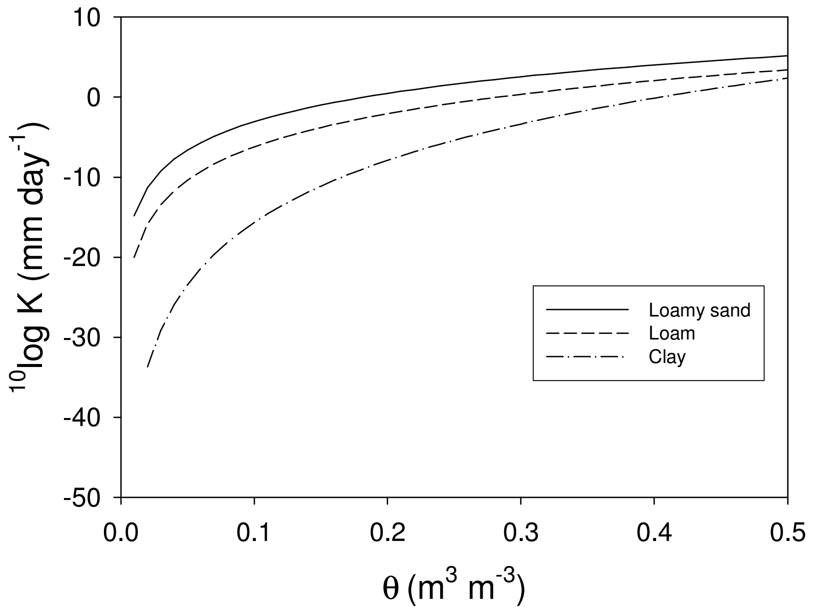
How do we get Ψ and K ??

Clapp & Hornberger (1978):

$$\psi = \psi_s (\theta / \theta_s)^{-b}$$

$$K = K_s (\theta / \theta_s)^{2b+3}$$





Soil texture	f_{sand} (%)	f_{silt} (%)	f_{clay} (%)
Loamy sand	82	12	6
Loam	43	39	18
Clay	22	20	58

How do we get Ψ and K ??

Van Genuchten (1981):

$$\psi = \frac{\left(\Theta^{-1/m} - 1\right)^{1/n}}{\alpha}$$

$$K = K_s \frac{\left[1 - (\alpha\psi)^{n-1}\left\{1 + (\alpha\psi)^n\right\}^{-m}\right]^2}{\left[1 + (\alpha\psi)^n\right]^{m/2}}$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$m = 1 - {}^{1}\!/_{n}$$

When using van Genuchten soil hydraulics, the UM/JULES only stores the free soil water θ-θ_r and uses the approximation $\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$

Soil Hydraulic parameters

Clapp and Hornberger parameters

Soil texture	b (-)	θ_s (m^3 m^{-3})	ψ_s (m)	QC (-)	K_s (cm/min)
Sand	4.05	0.395	-0.121	0.92	1.056
Loamy sand	4.38	0.410	-0.090	0.82	0.938
Sandy loam	4.90	0.435	-0.218	0.60	0.208
Silt loam	5.30	0.485	-0.786	0.25	0.0432
Loam	5.39	0.451	-0.478	0.40	0.0417
Sandy clay loam	7.12	0.420	-0.299	0.60	0.0378
Silty clay loam	7.75	0.477	-0.356	0.10	0.0102
Clay loam	8.52	0.476	-0.630	0.35	0.0147
Sandy clay	10.40	0.426	-0.153	0.52	0.013
Silty clay	10.40	0.492	-0.490	0.52	0.013
Clay	11.40	0.482	-0.405	0.25	0.0062

Pedotransfer functions

Cosby pedotransfer functions (PTFs)

- based on MLRA (multiple linear regression analysis)
- dependent on percentages of sand, silt and clay

$$b = 3.1 + 0.157 f_{clay} - 0.003 f_{sand}$$

$$\theta_s = \left(50.5 - 0.142 f_{sand} - 0.037 f_{clay}\right)/100$$

$\psi_s = 0.01 e^{1.54 - 0.0095 f_{sand} + 0.0063 f_{silt}}$	$\psi_s = 0.01 \times 10^{1.54 - 0.0095 f_{sand} + 0.0063 f_{silt}}$
$K_s = a \times e^{-0.6 - 0.0064 f_{clay} + 0.0126 f_{sand}}$	$K_s = a \times 10^{-0.6 - 0.0064 f_{clay} + 0.0126 f_{sand}}$

Pedotransfer functions

Van Genuchten pedotransfer functions (PTFs)

Wosten et al. (1999) Geoderma 90, 169–185

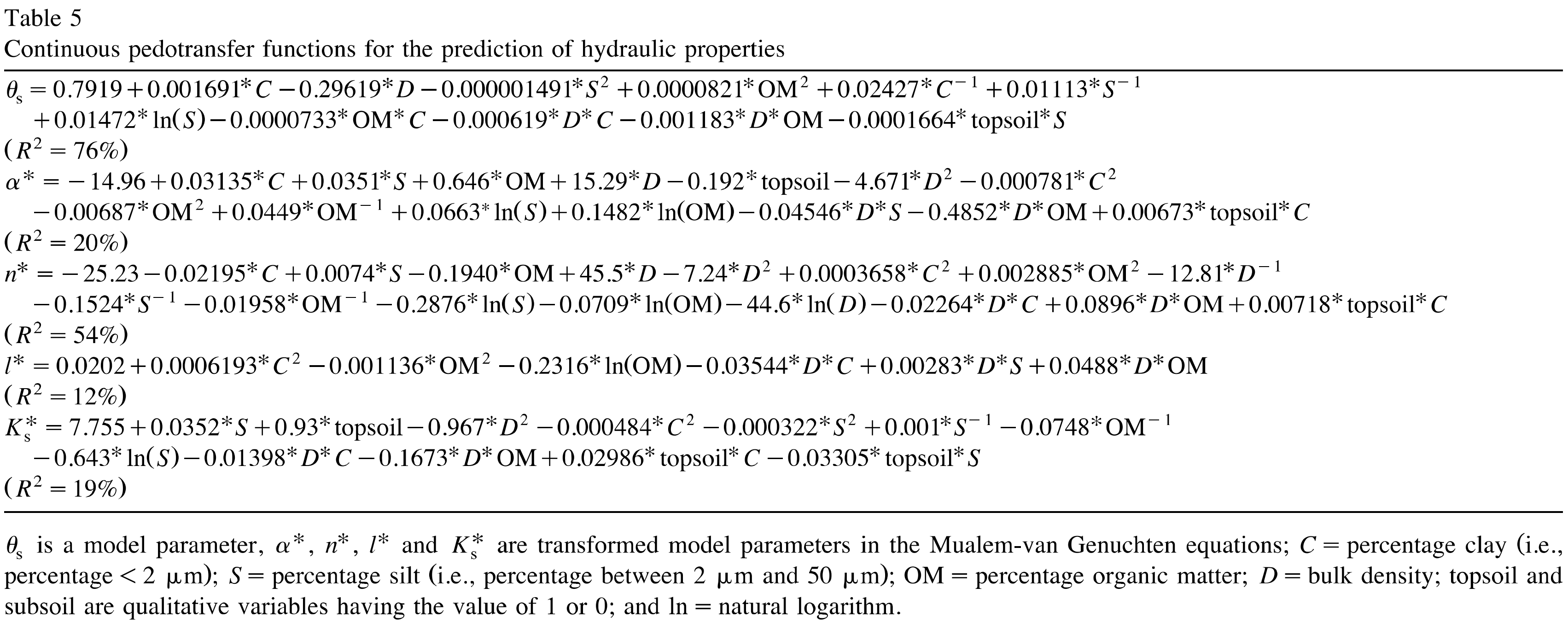


Table 5

Continuous pedotransfer functions for the prediction of hydraulic properties

$$\theta_s = 0.7919 + 0.001691 * C - 0.29619 * D - 0.000001491 * S^2 + 0.0000821 * \mathrm{OM}^2 + 0.02427 * C^{-1} + 0.01113 * S^{-1} + 0.01472 * \ln(S) - 0.0000733 * \mathrm{OM} * C - 0.000619 * D * C - 0.001183 * D * \mathrm{OM} - 0.0001664 * \mathrm{topsoil} * S$$

$(R^2 = 76\%)$

$$\alpha^{*} = -14.96 + 0.03135 * C + 0.0351 * S + 0.646 * \mathrm{OM} + 15.29 * D - 0.192 * \mathrm{topsoil} - 4.671 * D^2 - 0.000781 * C^2 - 0.00687 * \mathrm{OM}^2 + 0.0449 * \mathrm{OM}^{-1} + 0.0663 * \ln(S) + 0.1482 * \ln(\mathrm{OM}) - 0.04546 * D * S - 0.4852 * D * \mathrm{OM} + 0.00673 * \mathrm{topsoil} * C$$

$(R^2 = 20\%)$

$$n^{*} = -25.23 - 0.02195 * C + 0.0074 * S - 0.1940 * \mathrm{OM} + 45.5 * D - 7.24 * D^2 + 0.0003658 * C^2 + 0.002885 * \mathrm{OM}^2 - 12.81 * D^{-1} - 0.1524 * S^{-1} - 0.01958 * \mathrm{OM}^{-1} - 0.2876 * \ln(S) - 0.0709 * \ln(\mathrm{OM}) - 44.6 * \ln(D) - 0.02264 * D * C + 0.0896 * D * \mathrm{OM} + 0.00718 * \mathrm{topsoil} * C$$

$(R^2 = 54\%)$

$$l^{*} = 0.0202 + 0.0006193 * C^2 - 0.001136 * \mathrm{OM}^2 - 0.2316 * \ln(\mathrm{OM}) - 0.03544 * D * C + 0.00283 * D * S + 0.0488 * D * \mathrm{OM}$$

$(R^2 = 12\%)$

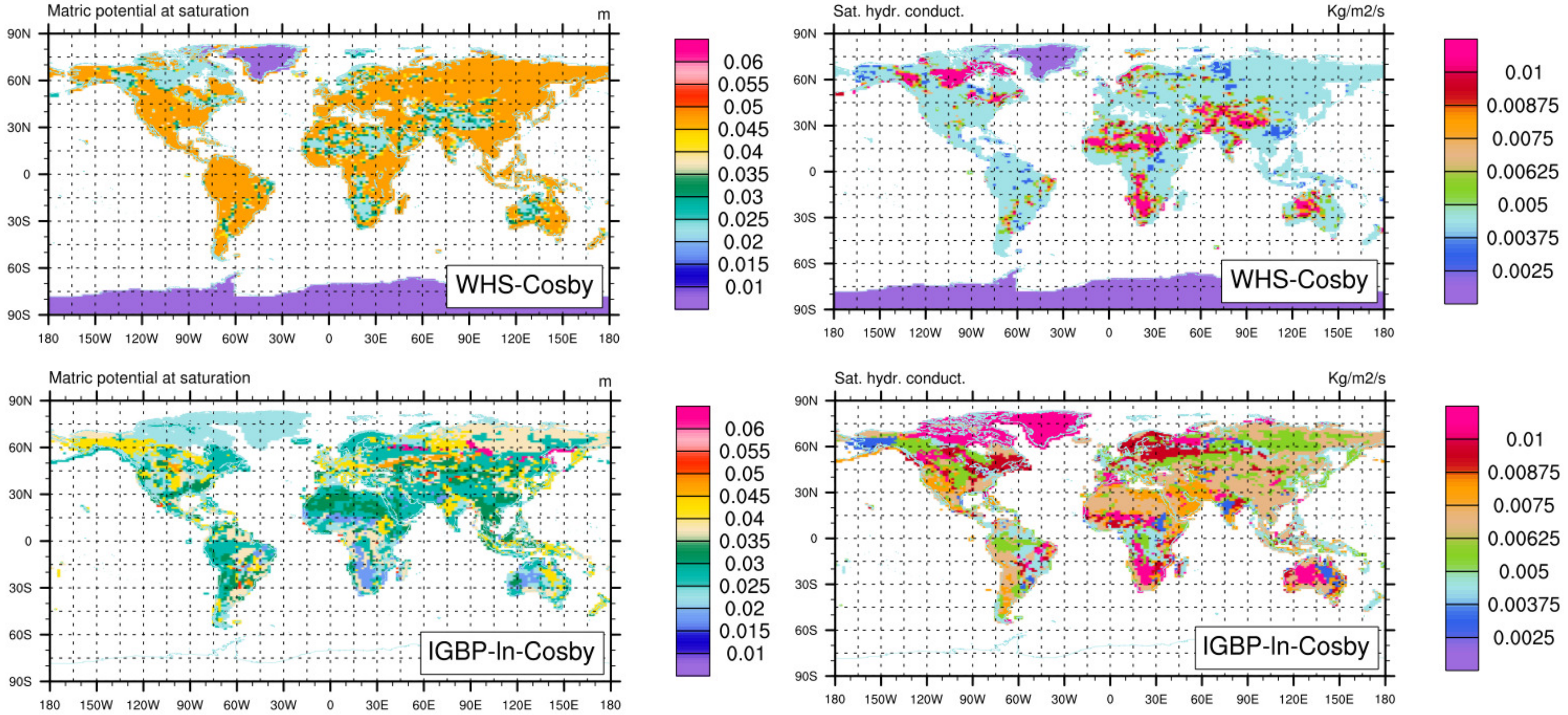
$$K_s^{*} = 7.755 + 0.0352 * S + 0.93 * \mathrm{topsoil} - 0.967 * D^2 - 0.000484 * C^2 - 0.000322 * S^2 + 0.001 * S^{-1} - 0.0748 * \mathrm{OM}^{-1} - 0.643 * \ln(S) - 0.01398 * D * C - 0.1673 * D * \mathrm{OM} + 0.02986 * \mathrm{topsoil} * C - 0.03305 * \mathrm{topsoil} * S$$

$(R^2 = 19\%)$

θ_s is a model parameter, α^{*}, n^{*}, l^{*} and K_s^{*} are transformed model parameters in the Mualem-van Genuchten equations; C = percentage clay (i.e., percentage < 2 µm); S = percentage silt (i.e., percentage between 2 µm and 50 µm); OM = percentage organic matter; D = bulk density; topsoil and subsoil are qualitative variables having the value of 1 or 0; and ln = natural logarithm.

Global soils distribution, effect of soil map

IGBP-DIS map has a higher resolution than Wilson-Henderson- Sellers map and retains more heterogeneity in soil types.

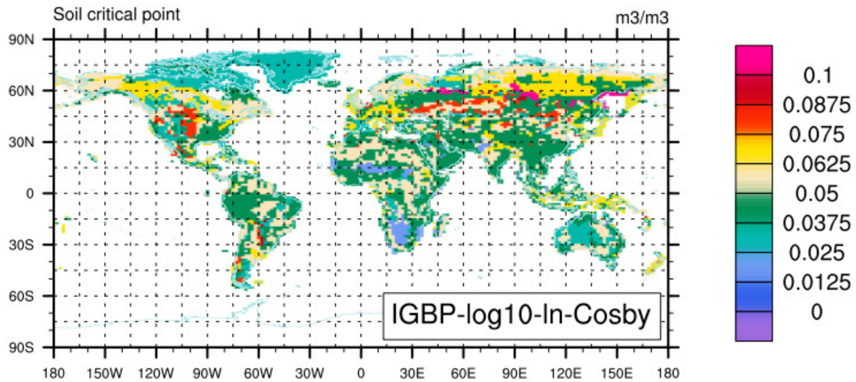


$$\psi = \boxed{\psi_s}(\theta / \theta_s)^{-b}$$

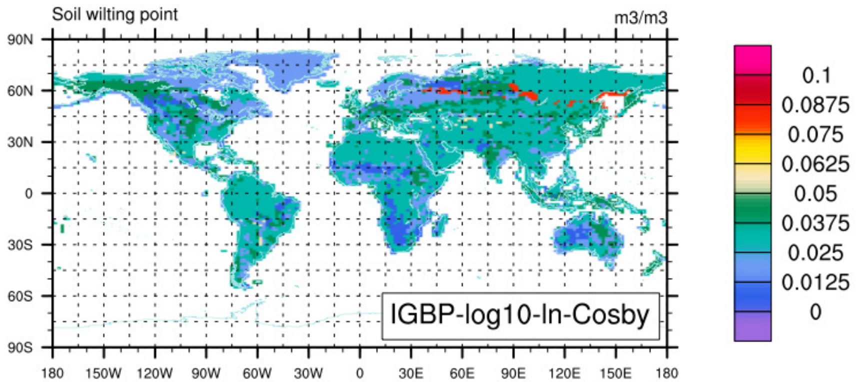
$$K = \boxed{K_s}(\theta / \theta_s)^{2b+3}$$

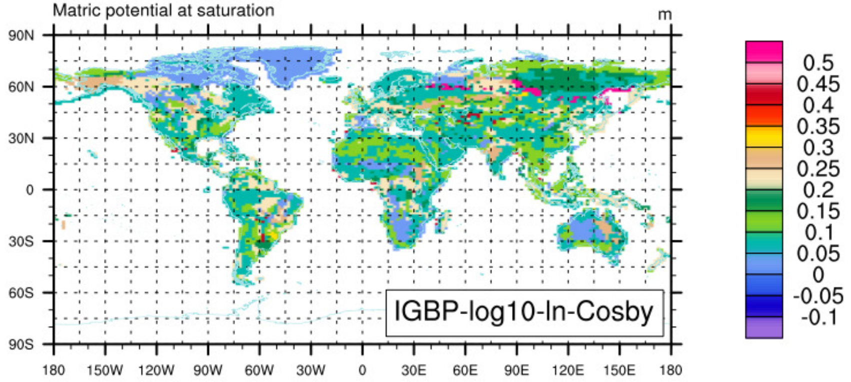
Importance of using the right PTFs

$\Delta\theta_c$

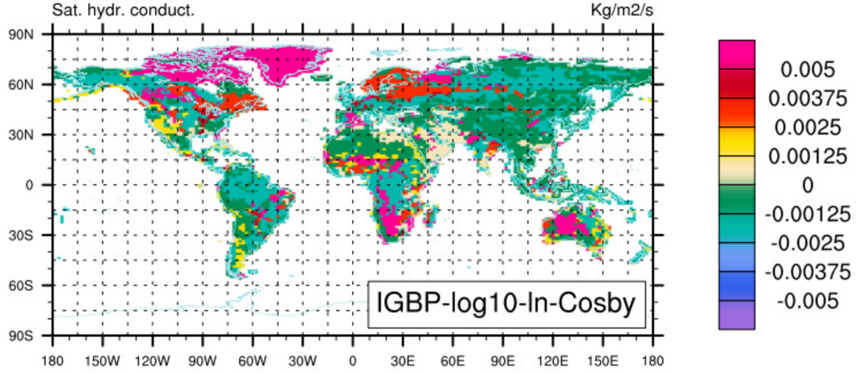


$\Delta\theta_w$





$\Delta\Psi_s$



ΔK_s

JULES soil physical parameters

Table 3. The parameters of the JULES soil hydrology and thermodynamic modules

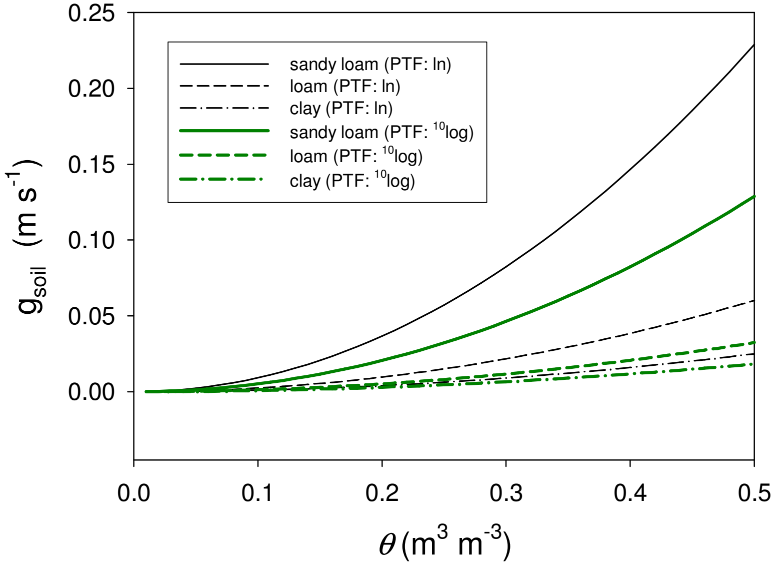
Symbol VG	 CH	JULES code variable	description
$1/\alpha$	Ψ_s	SATHH	van Genuchten/Clapp & Hornberger model parameter (m)
$1/(n-1)$	b	B_EXP	van Genuchten/Clapp & Hornberger model parameter (dimensionless)
C_{dry}		HCAP	Heat capacity of dry soil (J K^{-1} m^{-3})
λ_{dry}		HCON	Thermal conductivity of dry soil (W m^{-1} K^{-1})
K_s		KS	Saturated hydraulic conductivity (kg/m^2/s)
θ_c-θ_r		V_CRIT	Volumetric soil water content above which stomata are not sensitive to soil water (m^3 H_2O/m^3 soil)
θ_s-θ_r		V_SAT	Volumetric soil water content at saturation (m^3 H_2O/m^3 soil)
θ_w-θ_r		V_WILT	Volumetric soil water content below which stomata will close fully (m^3 H_2O/m^3 soil)

Original table courtesy of Jon Finch

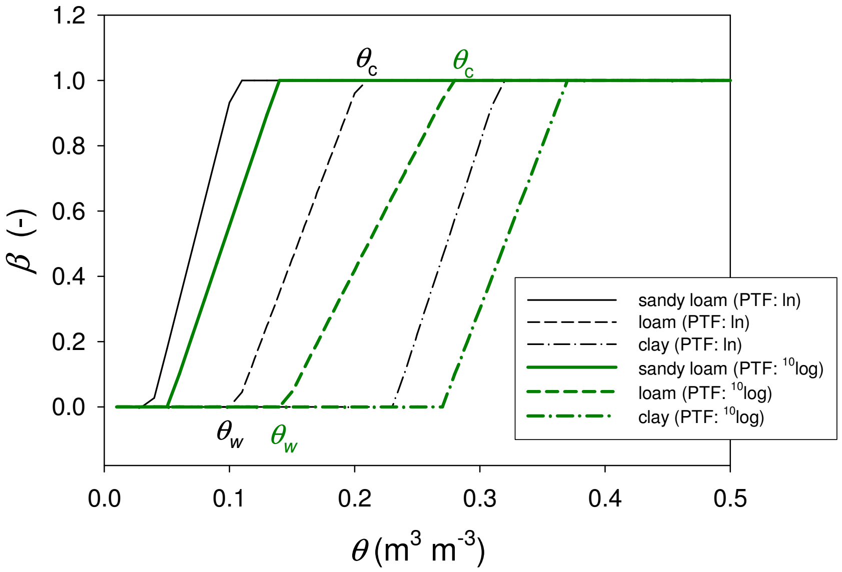
Role of key moisture contents

$$g_{soil} = \frac{1}{100}\left(\frac{\theta_1}{\theta_c}\right)^2$$

Affects soil evaporation



Affects photosynthesis, g_c and transpiration



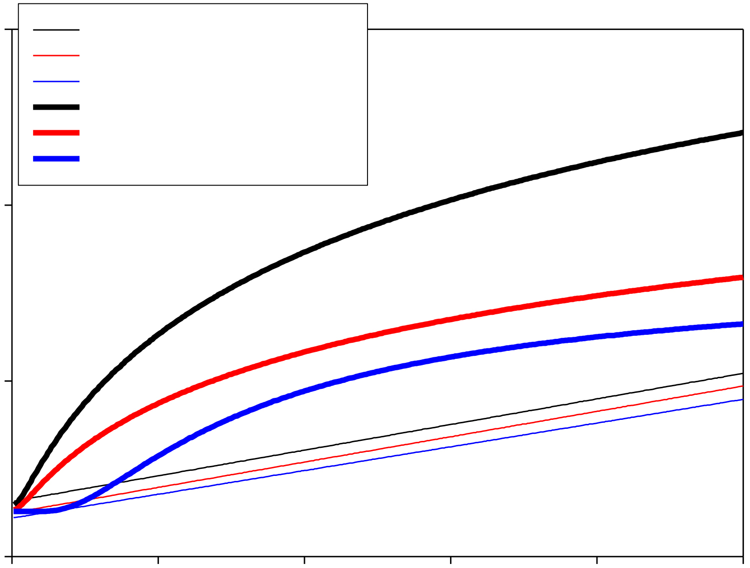
$$\beta = \begin{cases} 1 \\ \dfrac{\Theta - \Theta_w}{\Theta_c - \Theta_w} \\ 0 \end{cases}$$

$$A = A' \beta(\theta)$$

Thermal conductivity parameterisation

Original JULES model

$$\lambda = \left(\lambda_{sat} - \lambda_{dry}\right)\left(\frac{\theta}{\theta_s}\right) + \lambda_{dry}$$



Lu et al. model

$$\lambda = (\lambda_{\mathrm{sat}} - \lambda_{\mathrm{dry}})K_{\mathrm{e}} + \lambda_{\mathrm{dry}}$$

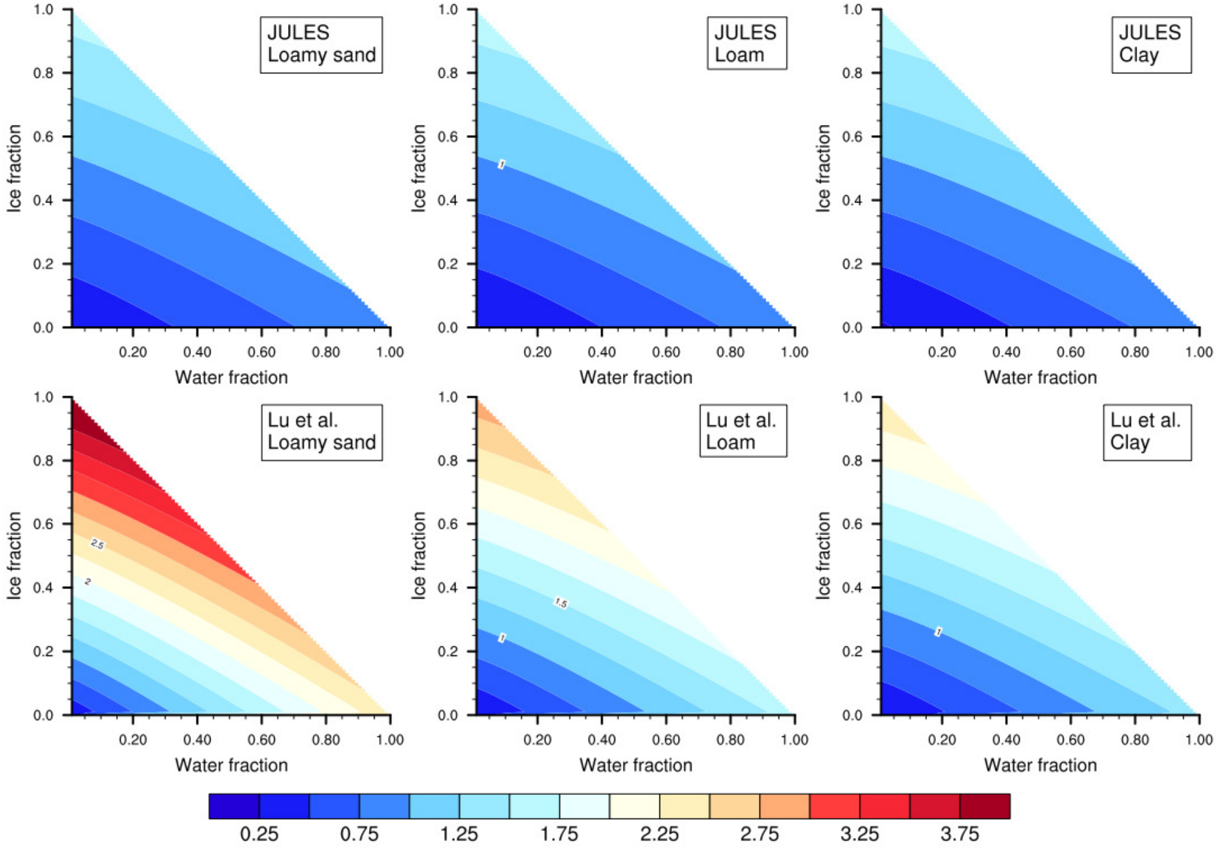
$$K_{\mathrm{e}} = \exp\left\{\alpha\left[1-\left(\frac{\theta}{\theta_s}\right)^{\alpha-1.33}\right]\right\}$$

Theoretical background

Thermal soil property values of soil components at 10 °C

	C_h MJ m^{-3} K^{-1}	λ W m^{-1} K^{-1}
quartz	2.0	8.8
clay minerals	2.0	2.9
organic matter	2.5	0.25
water	4.2	0.57
ice (0 °C)	1.9	2.18
air (saturated with water vapour)	0.0013	0.025

Thermal conductivity JULES versus Lu et al.

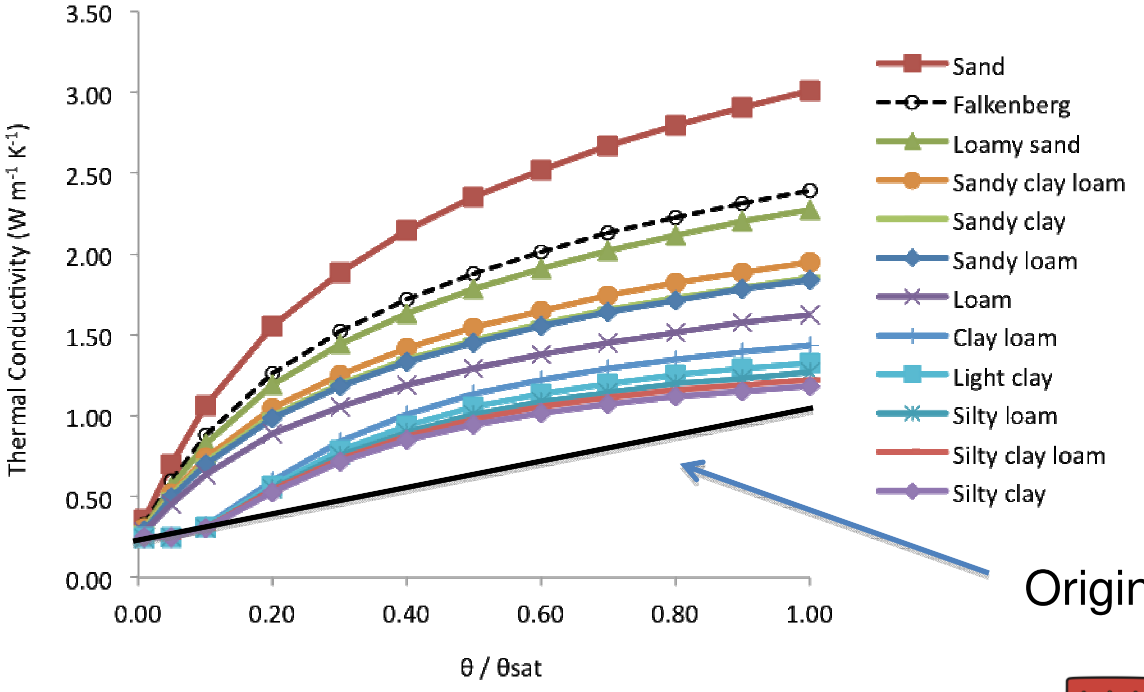


Theoretical background

Standard soils: Cosby et al. (1986), thermal conductivity

$$\lambda = (\lambda_{\mathrm{sat}} - \lambda_{\mathrm{dry}})K_{\mathrm{e}} + \lambda_{\mathrm{dry}}$$

$$K_{\mathrm{e}} = \exp\left\{\alpha\left[1-\left(\frac{\theta}{\theta_{sat}}\right)^{\alpha-1.33}\right]\right\}$$



Original Jules λ

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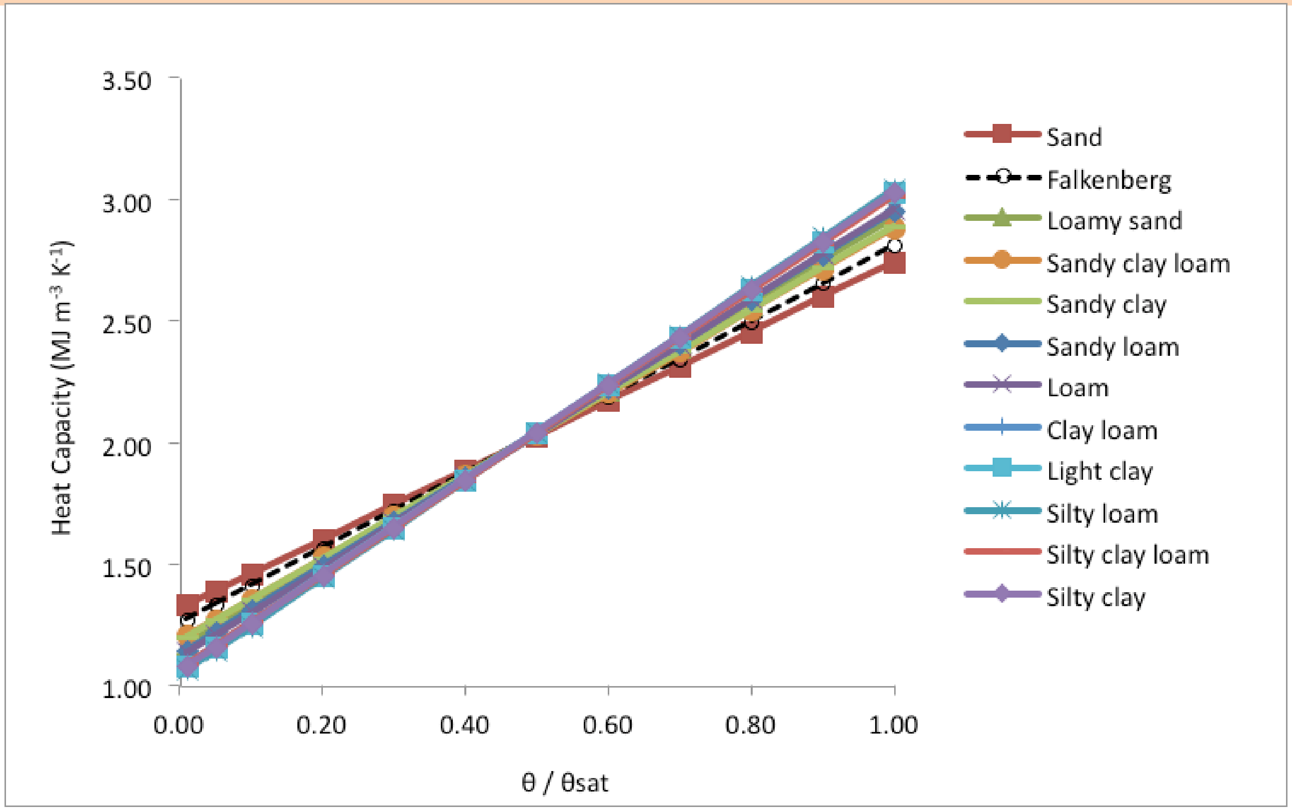
Theoretical background

Standard soils: Cosby et al. (1986), heat capacity



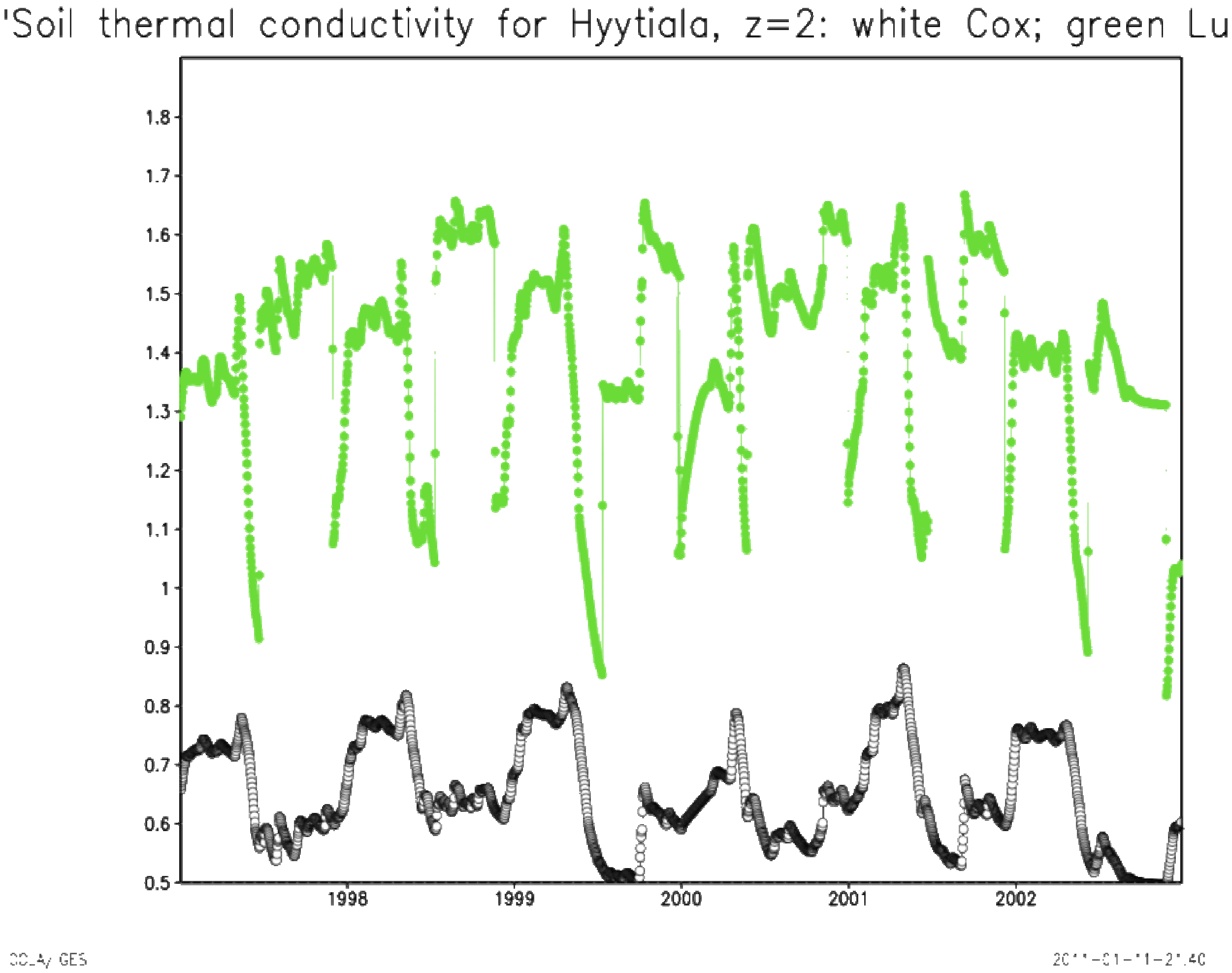
$$C_{\mathrm{h}} = \left(1-\theta_{sat}\right) C_{\mathrm{h,s}} + \theta C_{\mathrm{h,w}}$$

Associated with phase changes

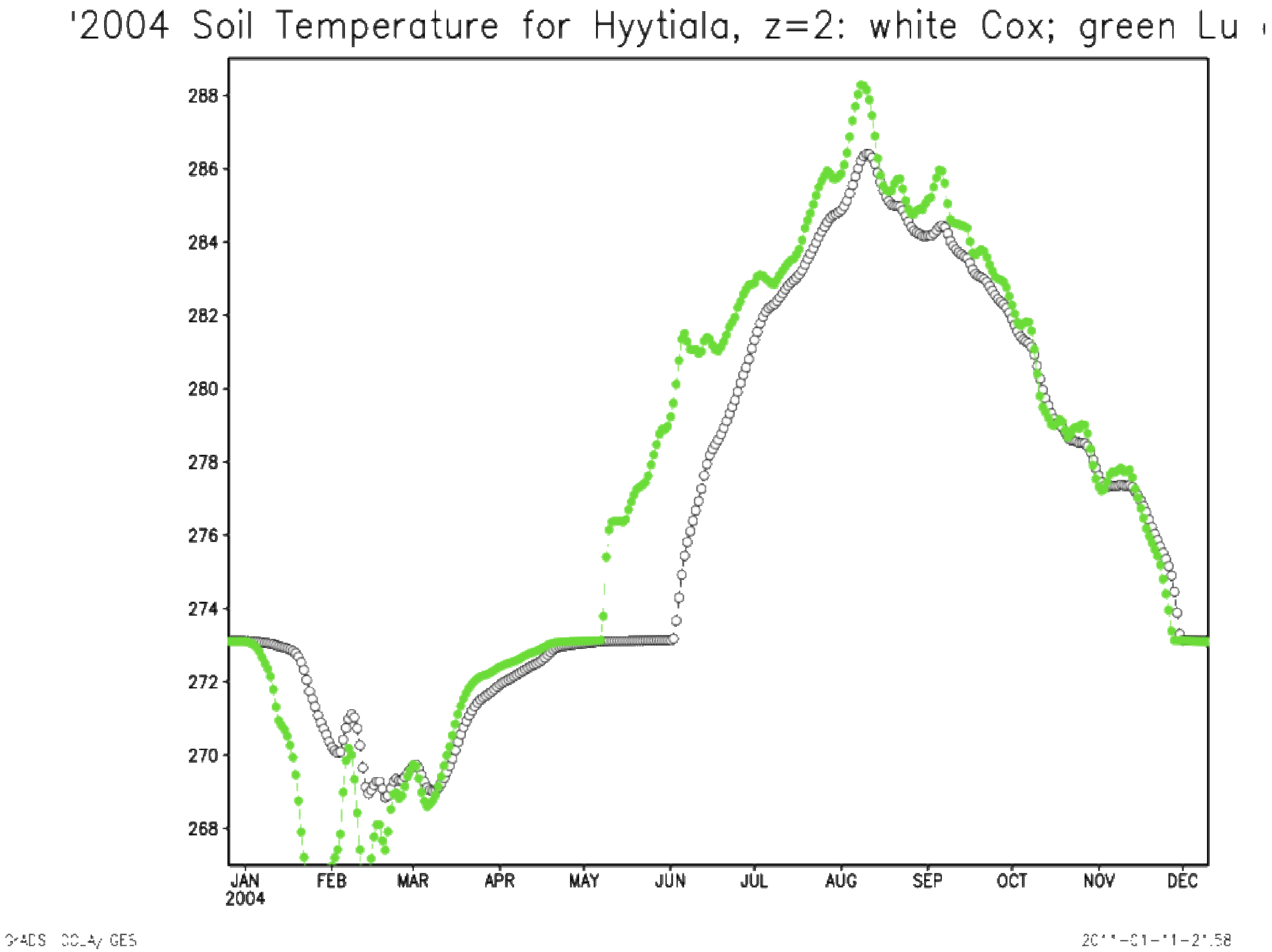
$$C_A = C_s + \rho_w c_w \theta_u + \rho_i c_i \theta_f + \rho_w \left\{ \left(c_w - c_i\right) T + L_f \right\} \frac{\partial \theta_u}{\partial T}$$

University of Reading

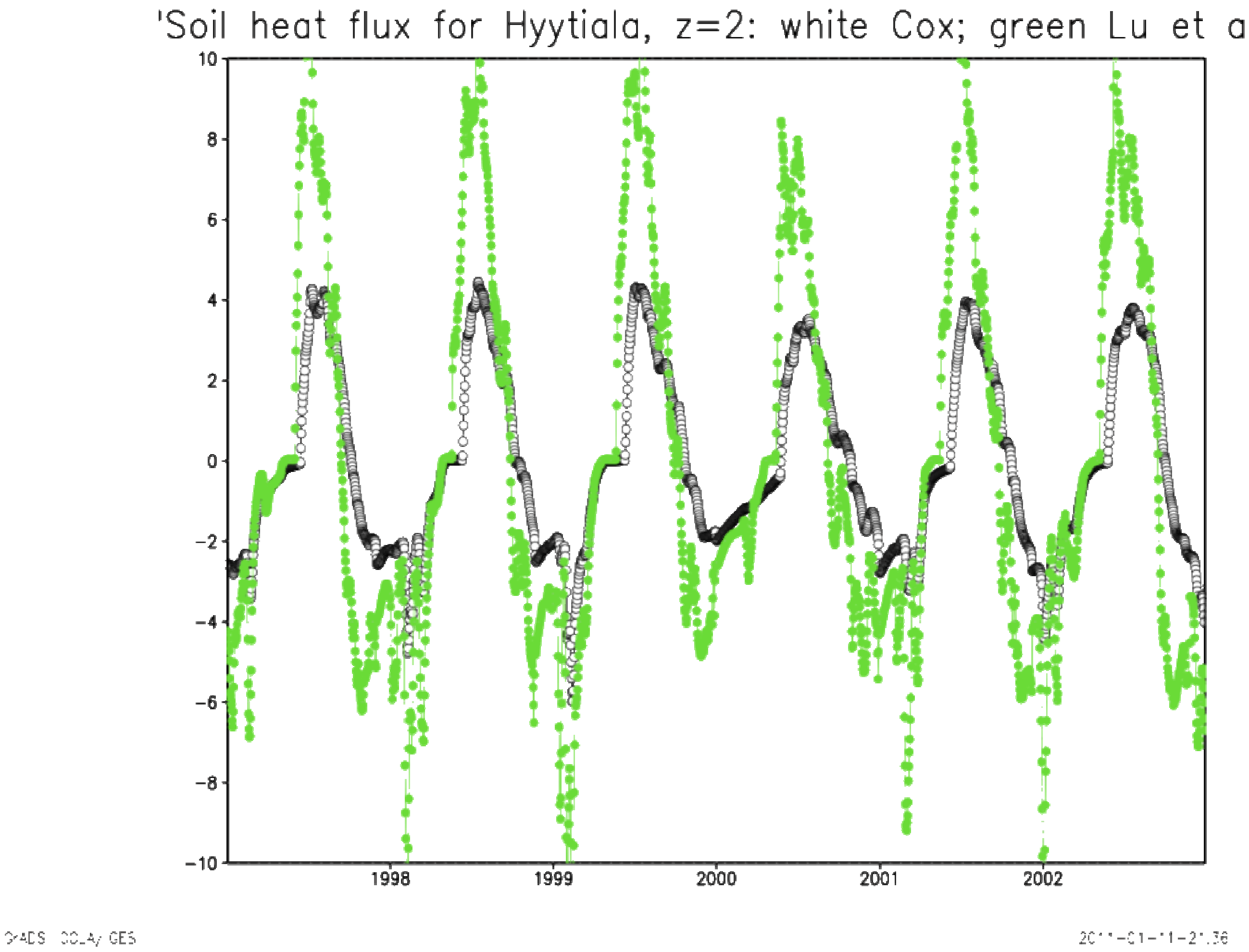
Timeseries comparison



Timeseries comparison



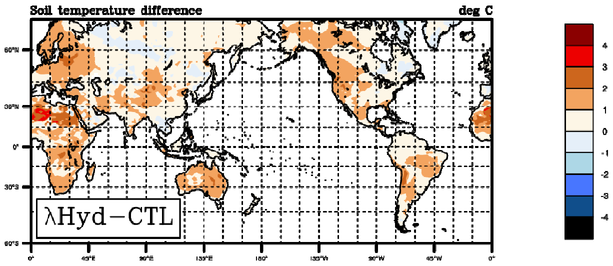
Timeseries comparison



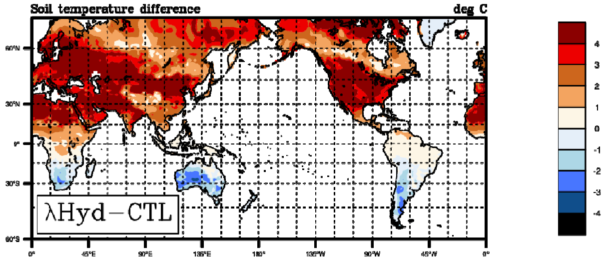
HadGAM1 AGCM runs, soil temperature

Average JJA Soil temperature difference (deg C)

Layer 1 (0-0.10 m)

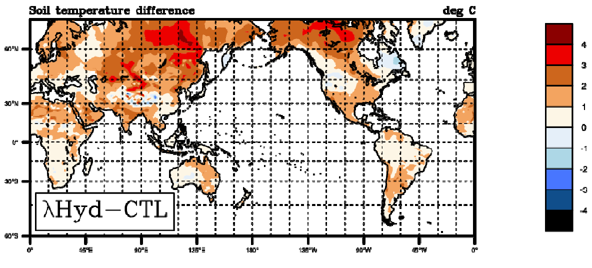


Layer 4 (2.0-3.0 m)

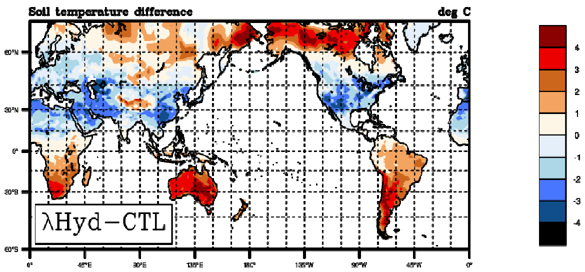


Average DJF Soil temperature difference (deg C)

Layer 1 (0-0.10 m)



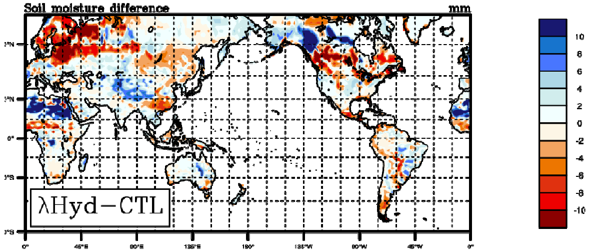
Layer 4 (2.0-3.0 m)



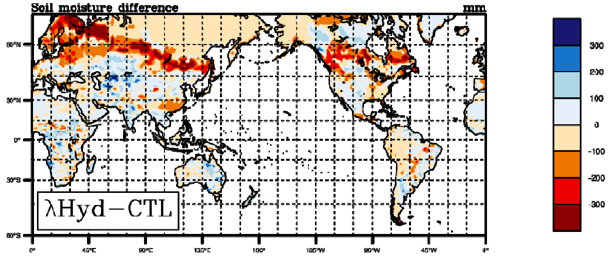
HadGAM1 AGCM runs, soil moisture content

Average JJA Soil moisture difference (mm)

Layer 1 (0-0.10 m)

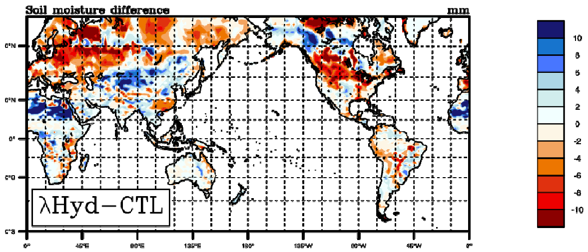


Layer 4 (2.0-3.0 m)

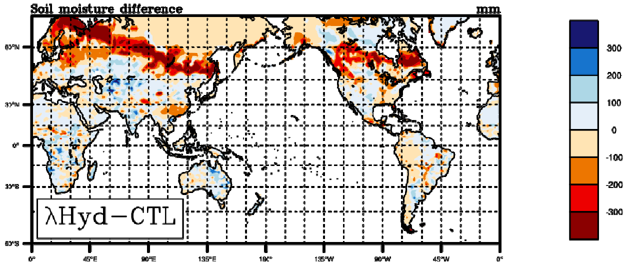


Average DJF Soil moisture difference (mm)

Layer 1 (0-0.10 m)



Layer 4 (2.0-3.0 m)



Reduction of UM 2m Temp cold bias

UKMO R&D
Technical report
528, 2009.

New soil physical
properties
implemented in
the Unified Model at
PS18 by Dharssi et
al.

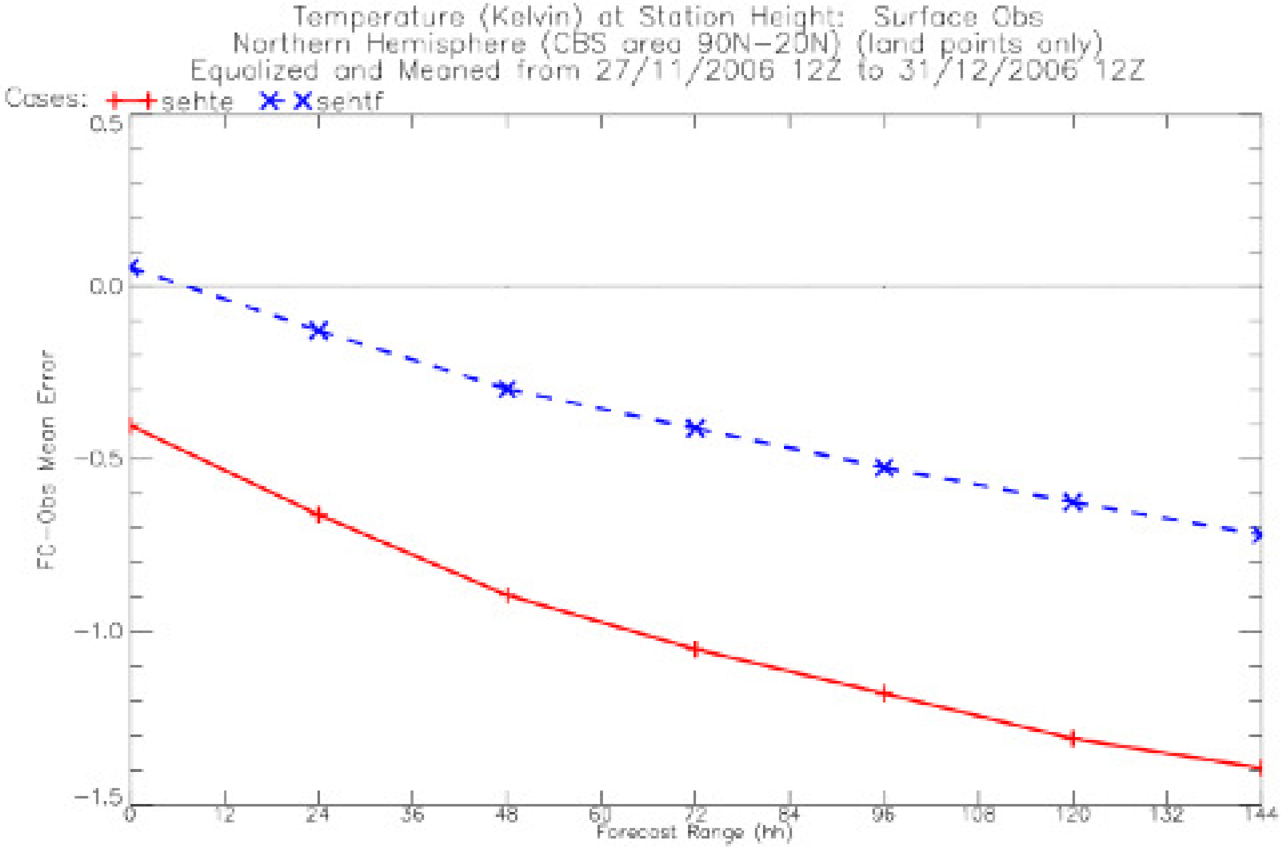


Figure 7: Bias in UM forecasts of screen temperature from the pre-operational winter trials. Both trials are run at a resolution of N216L50, use 3D-VAR atmospheric data assimilation and PS15 model parametrisations. The control (red curve - sehte) uses the old soil physical properties. The test (blue curve - sehtf) uses the new soil hydraulic and thermal properties. The new soil physical properties reduce the UM winter cold bias by about 0·6 K.

Reduction of UM winter 2m Temp RMSE

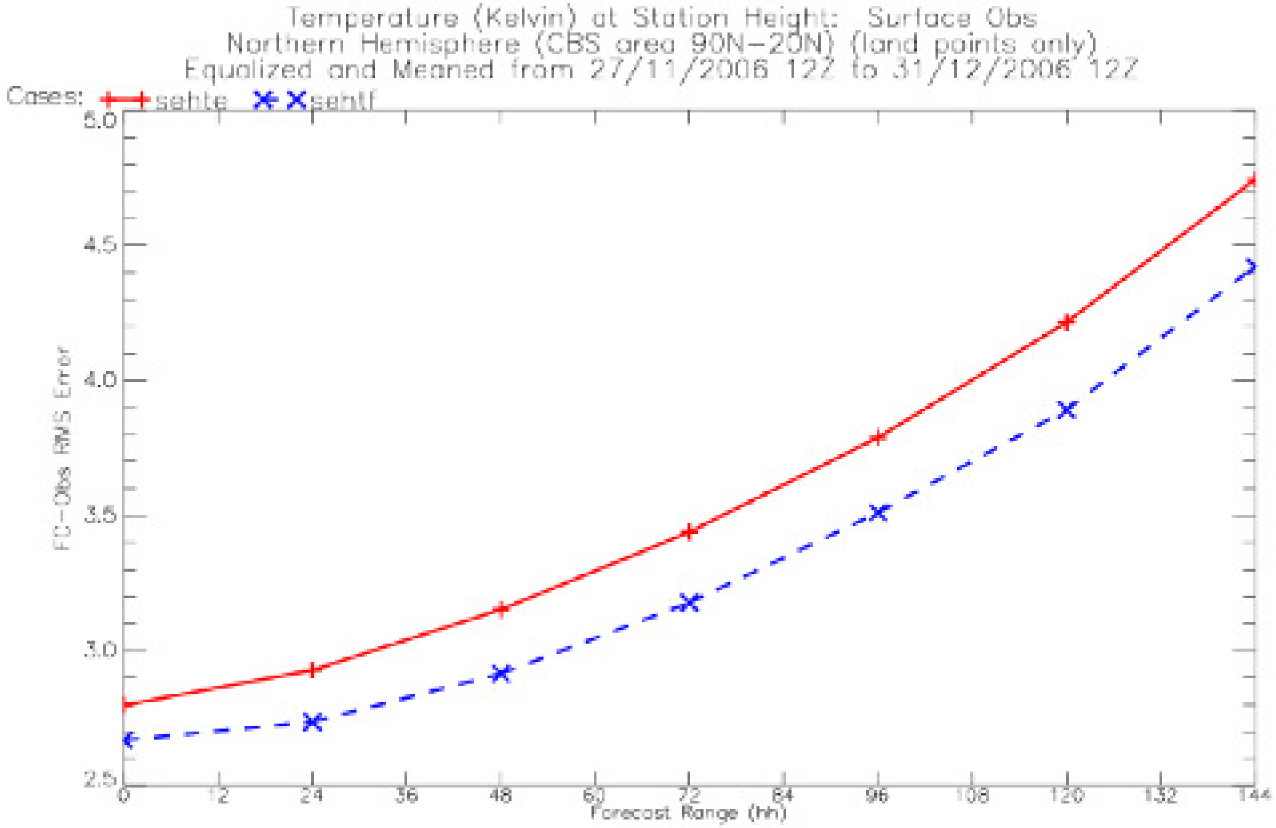


Figure 8: RMS errors in UM forecasts of screen temperature from the pre-operational winter trials. The control (red curve - sehte) uses the old soil physical properties, the test (blue curve - sehtf) uses the new soil hydraulic and thermal properties. The new soil physical properties reduce RMS errors by about 10%.

Final remarks

Other processes that require further testing/development

- Infiltration
- Parameterisation of groundwater table
- Within/below canopy aerodynamic transfer
- Soil gas transfer