New soil physical properties implemented in the Unified Model

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1 Introduction

Knowledge of soil is essential for meteorological, climatological, agronomic and hydrological applications. The properties of soil can have a significant impact on near surface temperature and humidity, low clouds and precipitation by influencing the exchange of heat and water between the land surface and the atmosphere.

The soil hydraulic properties affect the soils ability to hold water and the rate at which water moves through the soil. The soil moisture together with the soil hydraulic properties control transpiration from plants and direct evaporation from bare soil. Also, the soil thermal conductivity and heat capacity both depend on soil moisture and soil texture, so that these properties in turn influence the land surface temperature. Thus, soil moisture and the soil physical properties control the partitioning of net surface radiation into sensible, latent and ground heat fluxes.

In early 2007, a long-standing error was found in the way that Met Office programs use the Cosby et al. (1984) equations to calculate the soil hydraulic parameters. At the time, it was thought that this error might significantly contribute to the summer warm bias[1] of the global Unified Model. In addition, Verhoef and Vidale (2009) suggested that the Unified Model calculates values of soil thermal conductivity that are too low and that this has a significant impact on the model ground heat fluxes.

2 Soil Hydraulic properties

The Unified Model (UM) has three soil textural types; coarse, medium and fine. The soil hydraulic properties are calculated using the Cosby et al. (1984) regression relationships from the soil sand/silt/clay fractions. The sand/silt/clay fractions are derived from the $1^o \times 1^o$ soil classes data of Wilson and Henderson-Sellers (1985). The Clapp and Hornberger (1978) equations are used to describe the soil water retention curve and the relationship between soil moisture and soil hydraulic conductivity[2].

Correcting the error in the way that Met Office programs use the Cosby relationships causes a large change to the UM soil hydraulic properties, as shown in tables 1 and 2. Note the order of magnitude increase in SATHH (soil suction at saturation) and the large increase to $\theta_c - \theta_w$ of the medium soil type. The new values of SATHH are now in much better agreement with observations (for example see Table 2 of Clapp and Hornberger, 1978). Note that the UM sand/silt/clay fractions have not been changed.

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[1] However, work using the off-line UM land surface model shows that the error in the interpretation of the Cosby equations, actually causes evaporation/latent heat flux to be over-estimated (Compton, 2008). Climate and numerical weather prediction (NWP) simulations also show that correcting this error causes the UM summer warm bias to become worse.

[2] We are about to implement operationally new high resolution UM soil properties and switch to using van Genuchten soil

3 Soil thermal conductivity

The old UM parametrisation of soil thermal conductivity is described by Appendix B of Cox et al (1999) and page 16 of UM documentation paper 70 (Jones, 2004). The effective thermal conductivity is given by

$$\lambda_s = (\lambda_{sat} - \lambda_{dry})\frac{\theta}{\theta_s} + \lambda_{dry} \tag{1}$$

where λ_{dry} is the dry thermal conductivity. The thermal conductivity when the soil is saturated is given by

$$\lambda_{sat} = \lambda_{water}^{\theta_u^s} \times \lambda_{ice}^{\theta_f^s} \times \lambda_{dry}/\lambda_{air}^{\theta_s}\ , \tag{2}$$

θ_s is the volumetric soil moisture at saturation. λ_{air}, λ_{water} and λ_{ice} are the thermal conductivities of air, water and ice. $\theta_f^s = \theta_s[S_f/(S_u + S_f)]$, $\theta_u^s = \theta_s - \theta_f^s$ and S_u and S_f are the fractional saturation of unfrozen and frozen water.

Verhoef and Vidale (2009) have suggested that the Cox et al (1999) parametrisation predicts too low values of soil thermal conductivity and that parameterisations based on Johansen (1975) are more accurate. The Johansen parametrisation is described by Peters-Lidard et al. (1998). Implementing the Johansen parametrisation in the UM would require a substantial amount of recoding. Therefore a simplified parametrisation based on Johansen (1975) has been implemented in the UM.

$$\lambda_s = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \tag{3}$$

where the Kersten number

$$K_e = \begin{cases} \log\frac{\theta}{\theta_s} + 1.0 & \frac{\theta}{\theta_s} \geq 0.1 \\ 0 & \text{otherwise} \end{cases} . \tag{4}$$

$$\lambda_{sat}^{u} = 1.58 + 12.4 \times (\lambda_{dry} - 0.25) \ \text{ with the constraint } \ 1.58 \leq \lambda_{sat}^{u} \leq 2.2\ . \tag{5}$$

$$\lambda_{sat} = \frac{\lambda_{water}^{\theta_u^s} \times \lambda_{ice}^{\theta_f^s}}{\lambda_{water}^{\theta_s}} \times \lambda_{sat}^{u} \tag{6}$$

Values of λ_{dry} are calculated off-line based on UM soil texture (Jones, 2004); $\lambda_{dry} = \lambda_{air}^{\theta_s} \times \lambda_m^{(1-\theta_s)}$, $\lambda_m = \lambda_{clay}^{F_c} \times \lambda_{silt}^{F_{st}} \times \lambda_{sand}^{F_s}$ where $\lambda_{air} = 0.025\ Wm^{-1}K^{-1}$, $\lambda_{clay} = 1.16025\ Wm^{-1}K^{-1}$ and $\lambda_{silt} = \lambda_{sand} = 1.57025\ Wm^{-1}K^{-1}$.

F_c, F_{st} and F_s are the soil clay, silt and sand fractions.

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hydraulics.

Table 1: Old UM soil hydraulic properties, for the three UM soil textural types. SATHH is the soil suction at saturation, K_s is the hydraulic conductivity at saturation, the critical point θ_c is the volumetric soil moisture for a soil suction of 3.364 m, the wilting point θ_w is the volumetric soil moisture for a soil suction of 152.9 m.

	Critical point θ_c	Wilting point θ_w	Critical minus Wilting $\theta_c - \theta_w$	SATHH (m) $-\Psi_s$	K_s (mm/s)
Fine	0.310	0.221	0.090	0.045	0.0036
Medium	0.242	0.136	0.106	0.049	0.0047
Coarse	0.096	0.033	0.062	0.022	0.0110

Table 2: New UM soil hydraulic properties calculated using the correct Cosby equations, for the three UM soil textural types.

	Critical point θ_c	Wilting point θ_w	Critical minus Wilting $\theta_c - \theta_w$	SATHH (m) $-\Psi_s$	K_s (mm/s)
Fine	0.370	0.263	0.107	0.324	0.0015
Medium	0.332	0.187	0.145	0.397	0.0028
Coarse	0.128	0.045	0.083	0.062	0.0195

4 Pre-operational trials

Pre-operational trials with the global UM were performed to assess the impact of the new soil hydraulic and thermal properties on forecast performance. These trials were run for one month periods; either June 2006 or December 2006. In these trials the UM has a horizontal resolution of about 60 km and 50 vertical levels. 3DVAR atmospheric data assimilation is used. Observations of screen temperature and humidity are used to analyse the model soil moisture (a nudging scheme). The parameterisations used in these trials are similar to those used operationally for the global UM during May 2007.

Improvements to the calculation of the soil thermal conductivity result in a reduction of the UM northern hemisphere (NH) summer warm bias by about 0.2 K and a reduction in the UM NH winter cold bias by over 0.5 K, figure 3. RMS errors in screen temperature for the NH winter are reduced by about 10%, figure 3. During the summer, the new soil thermal conductivity gives a greater flow of heat from the surface into the ground which results in atmospheric cooling. While in winter, there is a greater flow of heat from the ground towards the surface resulting in a warming of the atmosphere. Improvements to the UM soil hydraulic parameters are found to significantly increase the UM soil moisture, by reducing evaporation. The new soil hydraulic properties also significantly reduce errors in screen temperature and humidity. However, by reducing evaporation, the new soil hydraulic parameters cause the UM to become warmer during the summer. This warming is offset by a new multi-layer photosynthesis scheme (Mercado et al., 2007) which reduces the model NH summer warm bias by about 0.25 K. In our trials, the effect of the full changes is to eliminate the UM NH summer warm bias. See Dharssi et al. (2009) for full details and results from all the pre-operational trials.

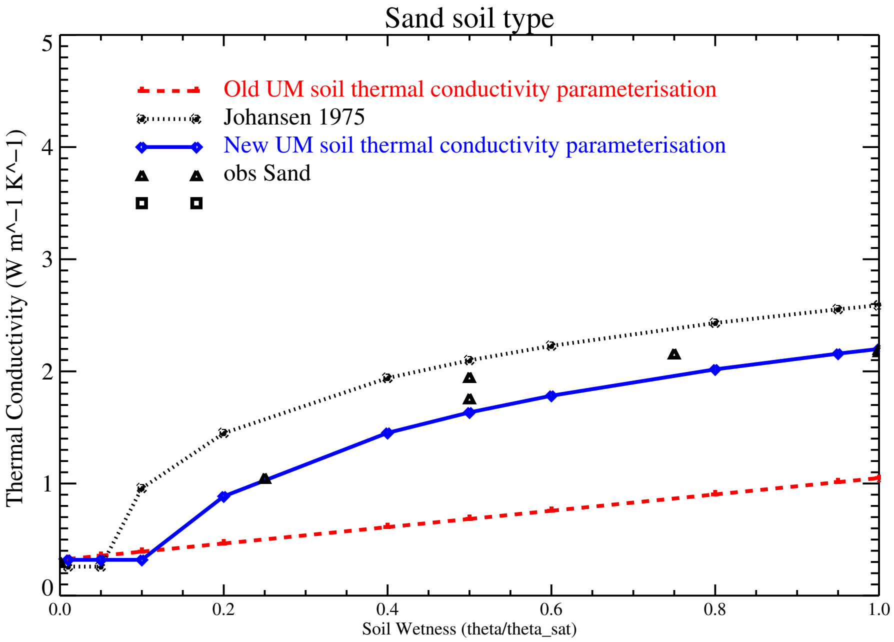

Figure 1: Inter-comparison of the parameterisations of soil thermal conductivity for the UM coarse soil type. The red dashed curve shows results for old UM parametrisation used operationally before April 2008. The black dotted curve shows results for the Johansen (1975) parametrisation. The blue solid curve shows results for the new UM parametrisation used operationally since April 2008. The black triangular symbols show the observed values of soil thermal conductivity and are the reference values given in table 3 of Peters-Lidard et al (1998) for sandy soil.

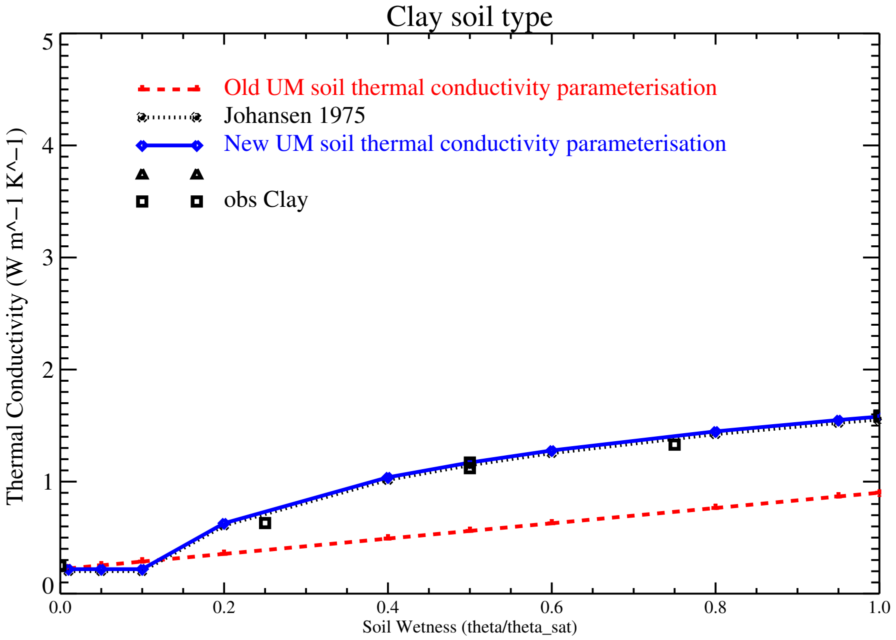

Figure 2: Inter-comparison of the parameterisations of soil thermal conductivity for the UM fine soil type. The curves have the same meaning as in figure 1. The black square symbols show the observed values of soil thermal conductivity and are the reference values given in table 3 of Peters-Lidard et al (1998) for clay soil.

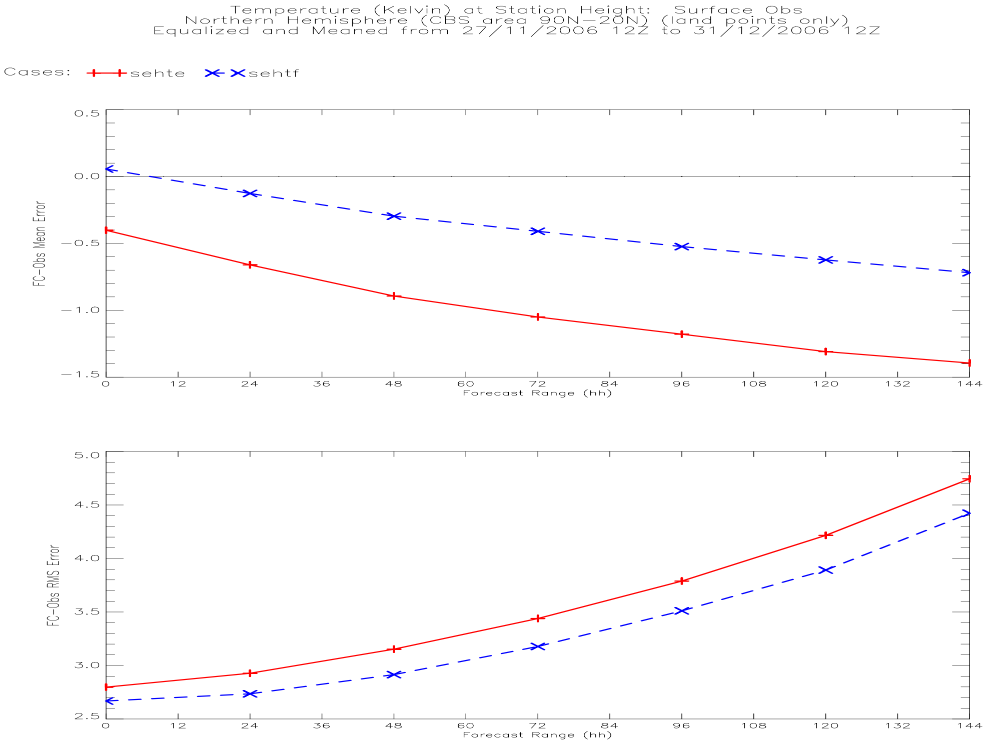

Figure 3: Bias (top panel) and RMS errors (lower panel) in UM forecasts of NH screen temperature from the pre-operational Dec 2006 trial. The control (red solid curve) uses the old soil physical properties. The test (blue dashed curve) is identical to the control except that it uses the new soil hydraulic and thermal properties. The new soil physical properties reduce the winter cold bias by about 0.6 *K and reduce RMS errors by about 10%.*

5 Operational Implementation

The improved UM soil physical properties were implemented operationally in the global UM, the North Atlantic European (NAE) and United Kingdom 4km (UK4) models at Parallel Suite 18 (PS18) that started mid-February 2008 and became operational at the start of April 2008. PS18 shows that all models benefit significantly from the new UM soil physical properties. Figure 4 shows the improvement in forecasts of screen temperature in PS18 for the NAE model and global UM.

6 Conclusions

Operational verification shows that there has been a clear improvement in operational UM forecasts of screen temperature and relative humidity since April 2008 and that the operational UM performance for screen temperature forecasts is now as good as, or better than, other leading NWP centres. The magnitude of the improvement seen in the operational verification is similar to the magnitude of the improvement shown by the pre-operational trials. Figure 5 shows operational verification of NH screen temperature RMS errors. Results are shown for the global UM and two other leading NWP centres. Figure 6 shows operational verification for the tropics.

Note that PS18 implemented other changes in addition to the improvements to the UM soil physical properties and these will also have contributed to the observed operational improvements. At PS18 the global UM also implemented soil temperature nudging and assimilation of SYNOP screen temperature,

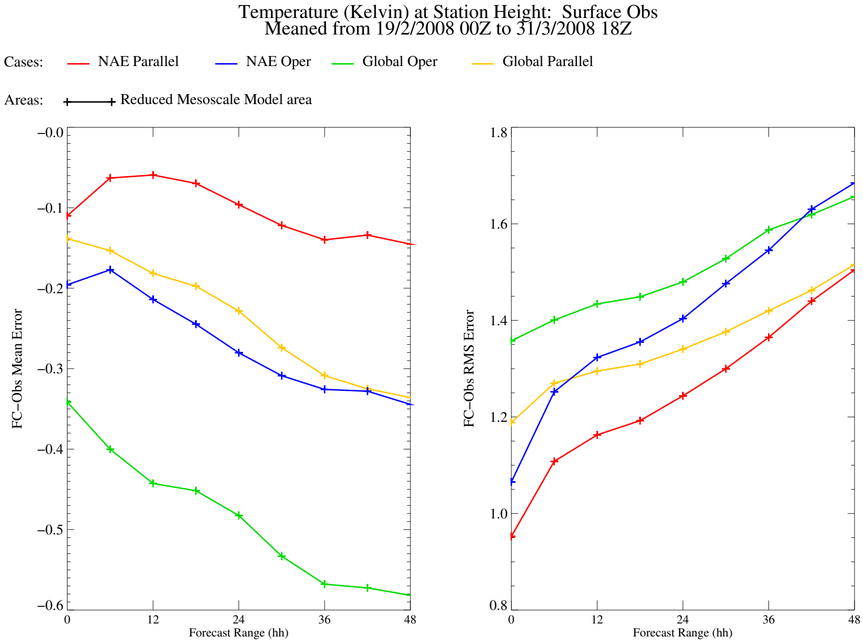

Figure 4: Bias and RMS errors in screen temperature from PS18 for the United Kingdom area. Results are shown for both the NAE and global UM models. The Parallel models (red and yellow lines) implement the new soil physical properties. The Operational models (blue and green lines) use the old soil physical properties.

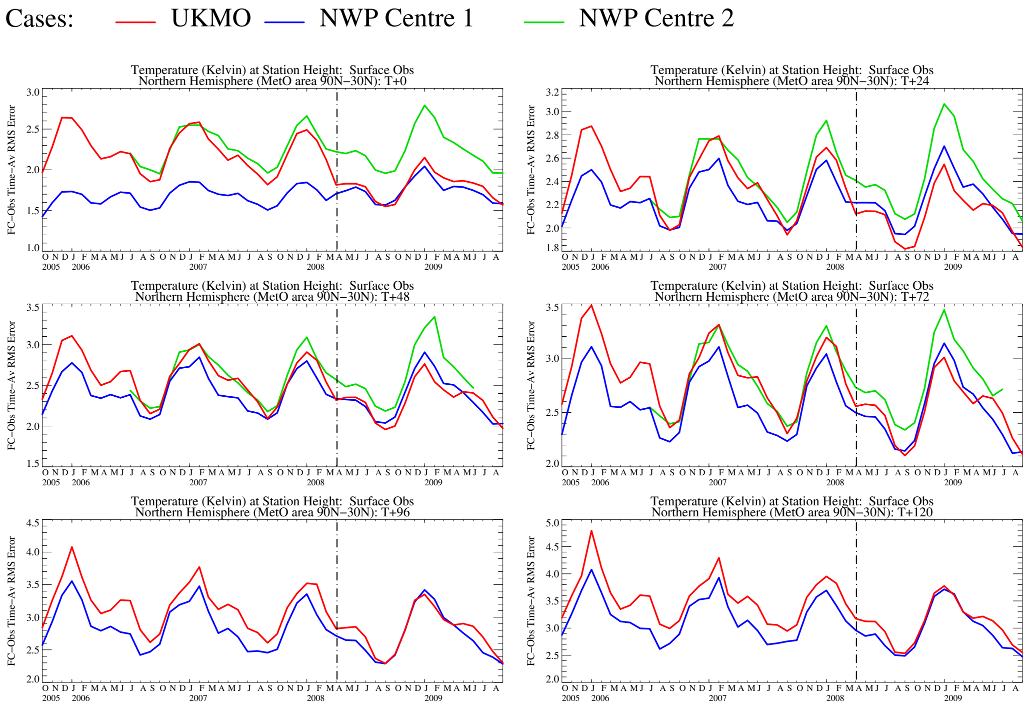

Figure 5: Operational verification of screen temperature RMS errors for the northern hemisphere. Results are shown for the global UM (red curve, label UKMO) and global models from two leading NWP centres (blue and green curves). The vertical dot-dashed lines mark the first month of verification after the new UM soil properties were implemented operationally.

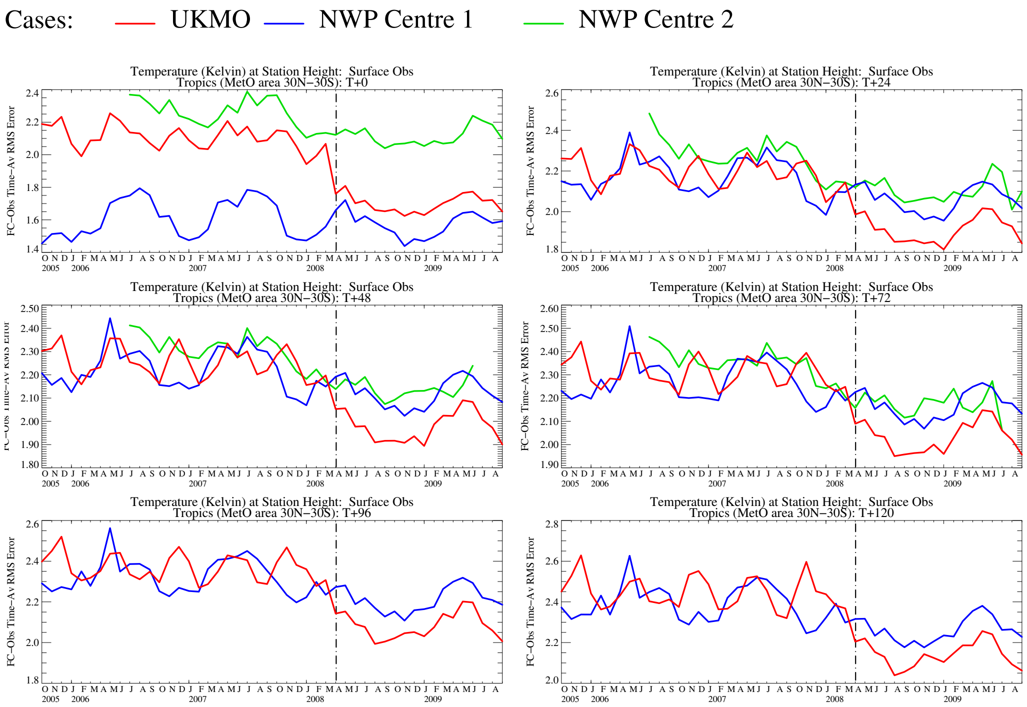

Figure 6: Operational verification of screen temperature RMS errors for the tropics. Results are shown for the global UM (red curve, label UKMO) and global models from two leading NWP centres (blue and green curves).The vertical dot-dashed lines mark the first month of verification after the new UM soil properties were implemented operationally.

relative humidity (RH) and wind observations. The NAE and UK4 regional models already used soil temperature nudging and assimilation of SYNOP screen T/RH/wind observations, before PS18. Pre-operational trials with the global UM indicate that for forecasts of screen T/RH, the assimilation of SYNOP screen T/RH/wind observations has the largest benefit in the tropics and for shorter forecast ranges; in the tropics improvement is seen for forecast times up to about T+72 while for the extra-tropics most of the improvement is at T+24. The new UM soil physical properties give improvements at all forecast times from T+24 to T+144, for the tropics and extra-tropics regions; the biggest improvements are at the longer forecast times and for the extra-tropics winter hemisphere.

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