Met Office

New Soil Physical Properties Implemented into the UKPP MOSES-PDM-RFM at PS25

Weather Science Technical Report No 563

March 1, 2012

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1 Abstract

Improvements to the soil physical properties in the Met Office's UKPP MOSES-PDM-RFM system are found to produce soil ancillaries that are of higher resolution and spatially more realistic than previous datasets. The soil hydraulic properties affect the soils ability to hold water and the rate of water flow into surface runoff and subsurface runoff. The soil physical properties and soil moisture control the evapotranspiration leaving the soil and plants and in turn influence land surface temperature and the surface energy balance.

Pre-operational trials show an enhancement of surface runoff over topography and over a 50% reduction in sub-surface runoff. The net decrease in runoff, has lead to an increase in soil moisture especially at lower levels. More available soil moisture has enhanced evaporation during the summer, but this has minimal impact during the autumn.

In addition, trials were conducted using the offline MOSES-PDM. This was run at 40km resolution for 50 years with the new ancillaries and improved soil moisture deficit formulations. Significant improvements in soil moisture deficits are shown, making them more comparable with data from the MORECS dataset.

Overall UKPP MOSES-PDM-RFM is producing results that are consistent with and explainable by the new ancillaries and the change has been implemented successfully into parallel suite 25.

2 Introduction

Information about the soil is crucial for hydrological and meteorological applications. The physical properties of the soil can impact the heat and water exchange between the land surface and atmosphere through subtle changes in surface temperature, humidity and precipitation. The partitioning of net radiation into sensible, latent and ground heat fluxes is controlled by the soil physical properties and soil moisture. Soil moisture on its own has been shown to have a large influence on the local weather over land in summer. Fischer et al. [2007] have shown that summer weather is hugely dependent on the accumulations of soil moisture during the previous winter and spring. A drying out of soil moisture in spring may lead to warmer, dryer summers.

Soil moisture is extremely variable over space, making measurements difficult. This variability can partly be attributed to variability in hydrological inputs such as rainfall and snow melt. However most variability is attributable to variations in soil physical properties, vegetation and topography.

The Met Office's United Kingdom Post Processing (UKPP) System is run routinely to downscale the output from the Unified Model (UM) and provide further outputs for forecasters and customers. The resulting high resolution products are used internally and by government agencies and commercial customers to meet specific needs. UM meteorological data is presently downscaled from 4km to 2km to be used to drive the MOSES-PDM-RFM.

MOSES, the Met Office Surface Exchanges Scheme, (Cox et al. [1999],Essery et al. [2001]) is the land surface model of the Unified Model. It has also been implemented into the UKPP system to provide hourly updates to snow melt, surface and subsurface runoff, net surface radiation, actual and potential evaporation, soil temperature, soil moisture and soil moisture deficit on the UK post processing systems 2km x 2km grid. Soil moisture and temperature are represented on four subsurface layers. Surface fluxes are calculated for ten surface types (tiles) within a grid square as well as grid square means calculated using the fractions of each tile within the grid square. It has been modified to include the Centre for Ecology and Hydrology (CEH) Probability Distributed Moisture (PDM) [Moore, 1985] scheme for calculating surface runoff. The surface types are prescribed using land use ancillary fields, based on the CEH 25m resolution land cover data (for Great Britain) [Fuller et al., 1994] and the IGBP 1km resolution land use data (for non-GB land areas) [Loveland et al., 2000].

The surface and subsurface runoff from MOSES-PDM are input to a grid-to-grid River Flow Model (RFM) developed by CEH and run with a grid length of 1km. The RFM provides values of river flow and a closeness to flooding indicator. The RFM assumes rivers are natural, i.e. their paths are determined by terrain gradients and their flow wave speeds are unaffected by man-made controls.

The UKPP-MOSES-PDM currently uses soil physical properties based on the IGBP 5 minute resolution soil type data [Soil Data Task Group, 2000] and the van Genuchten parameters [van Genuchten, 1980] for the dominant soil type within each gridsquare. The sand, silt and clay fractions prescribed from each soil type are used to calculate the soil physical parameters using the van Genuchten equations. Using a soil water retention curve, the van Genuchten equations can calculate the soil saturated soil hydraulic conductivity.

A new soil moisture nudging scheme was introduced to the global Unified Model (UM) in 2009, highlighting many deficiencies in the land surface model. This prompted work by Dharssi et al. [2009] to provide a better specification of UM soil physical properties. The new soil properties are calculated using van Genuchten (VG) soil hydraulics [van Genuchten, 1980] instead of Clapp and Hornberger (CH), with sand, silt and clay fractions derived from a merge of three different soils data sources; The Harmonised World Soils Database, current observations of sand, silt and clay fractions and the US State Soil Geographic (STATSGO) Database.

The Harmonized World Soil Database (HWSD) [FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008] provides global soil data at a resolution of 30 arc seconds x 30 arc seconds; about 1 km x 1 km (21600 rows x 43200 cols). The reliability of the data is variable. The regions with the highest reliability data are believed to be Southern Africa, Latin America and the Caribbean and Europe. Regions with the least reliable data are believed to be North America, Australia, West Africa and South Asia.

Observations of soil sand, silt and clay fractions were downloaded from the ISRIC World Soil Information Database. Observations for the United States have been downloaded on a state by state basis from the USDA National Soil Survey Centre.

This report will display and check the realism of the new HWSD-based soil ancillary dataset. The impacts of new soil ancillaries on UKPP-MOSES-PDM-RFM products will be assessed by showing results from a trial run of 2km MOSES-PDM-RFM with these ancillaries. A new diagnosis of the soil moisture deficit (SMD) and B_PDM parameter (which also controls the modelled degree of soil heterogeneity) will also be assessed.

In order to assess the impact of the new HWSD-based soil ancillaries further, a rerun of a 50-year historical (1961-present) offline-MOSES-PDM with new 40km soil ancillaries has been done. The 40km ancillaries have been generated by aggregation of the HWSD-based UKPP 2km soil ancillaries. This rerun included a revised SMD calculation and B_PDM parameters. The results from this "v3.0" offline run are described in section 4.3. These could be used by the Environment Agency who have been the customer for the previous versions of the offline-MOSES-PDM.

3 Methods

The HWSD-based soil ancillaries had been pre-processed (by Imtiaz Dharssi and Keir Bovis) prior to using in the UM, in order to merge the three different soils data sources together. This was done using a method called optimal interpolation which blends a background field i.e. the HWSD and STATSGO, with observations in an optimal way. These new soil ancillaries were implemented in the Unified Model at Parallel Suite 18 [Dharssi et al., 2009].

The ancillary files for the MetUM were mapped onto a regular lat/long and were in a fields file format. In order for these files to be suitable for use with the UKPP system, they have been modified, using code from the FCM UKPP suite, to be on national grid coordinates and in Nimrod format. The realism of the new ancillaries has been checked and the fields are displayed below. They have been compared with the current operational fields and the original fields prior to conversion (not shown).

A trial run of the 2km UKPP-MOSES-PDM using the new soil ancillaries was setup. This runs MOSES hourly on the IBM supercomputer, using real time inputs from the operational suite and is started using a cronjob. MOSES-PDM-RFM was initialised with soil moisture prognostics reset to field capacity values. This allowed the system to spin up (or down) from a state unbiased by the previous soil ancillaries and produce reasonable magnitudes for runoffs after a few weeks. The output was plotted at real time on the development server and is displayed on the Post Processing output web page. The results from this trial run are shown in the next section.

4 Results

4.1 New Soil Ancillaries

Figures 1 to 4 show the new and current operational UKPP ancillary fields respectively. Overall the values in the new ancillary fields are sensible and the spatial patterns realistic. The resolution is greater than the current UKPP operational fields and they contain a higher degree of geographic detail. The current operational fields in contrast have the detail which is questionable, the range of values is too large and there are many suspected erroneous values in the fields. Table 1 shows the domain mean values for the new and old operational ancillaries.

Ancillary	Domain Mean Values	
	New	Old
Saturated Hydraulic Conductivity	0.00372	0.02118
Saturated Soil Water Suction	0.3526	0.5588
Soil Water Conc. at Saturation	0.4519	0.4674
Soil Water Conc. at Critical Point	0.3231	0.2996

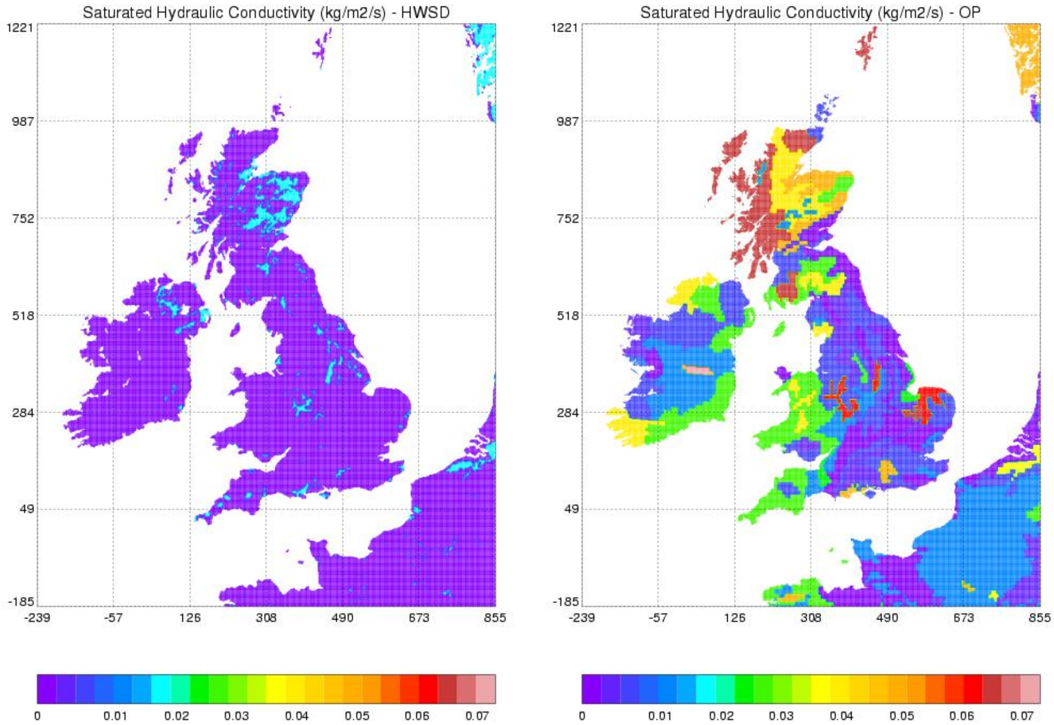
Table 1: Domain mean values for the new HWSD-based ancillaries and the old operational ancillaries

The new saturated soil water suction ancillary (see figure 2, the reciprocal of α) is on average lower than the old ancillary, suggesting that these soils are able to lose or gain moisture more freely due to soil water being under less tension.

The domain mean values of soil water concentration at saturation (theta sat) for the new and old ancillaries are very similar. However spatially there are small scale differences which could be attributed to local variations in the soil type. In areas of the south east, central and northern England, the new theta sat is higher than the old values suggesting that the soil can hold more water at saturation than previous. In areas of south west England , Wales and northern Scotland there are small decreases in the water held at saturation. Overall this will have a small impact on the output fields such as soil moisture and evaporation.

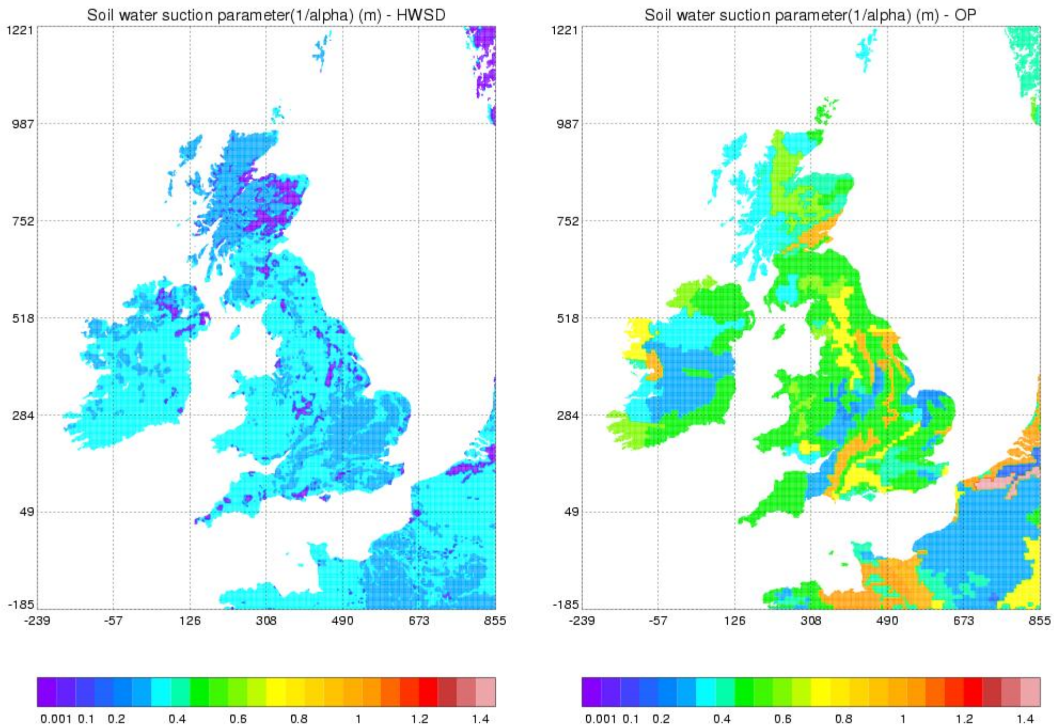
The domain mean values of soil water concentration at critical point (theta crit) from the new ancillary field, have increased compared to the old ancillary field. The critical point is defined as the soil moisture below which transpiration will begin to be restricted. The differences suggest that transpiration will become restricted at higher soil moistures.

The largest difference in the ancillary fields has been seen for the saturated hydraulic conductivity parameter(figure 1). The new field is considerably lower than the old operational ancillary field. This could have the effect of reducing the vertical flow of water and may impact evaporation rates.



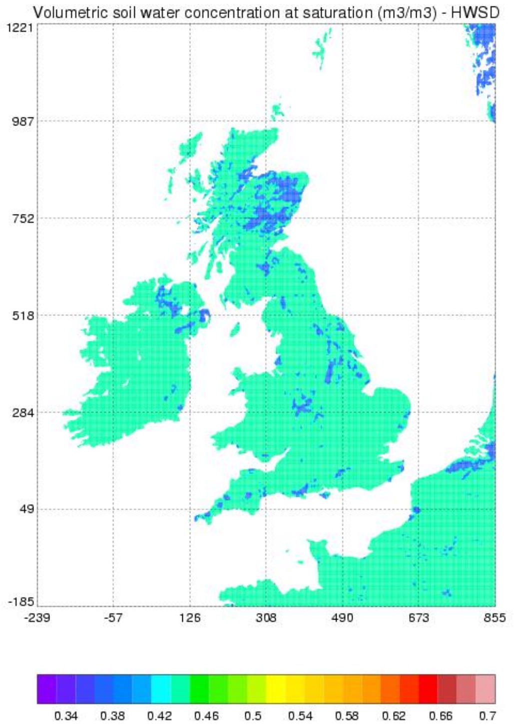
(a) HWSD (b) Operational

Figure 1: Saturated Hydraulic Conductivity (kg m^{-2} s^{-1})

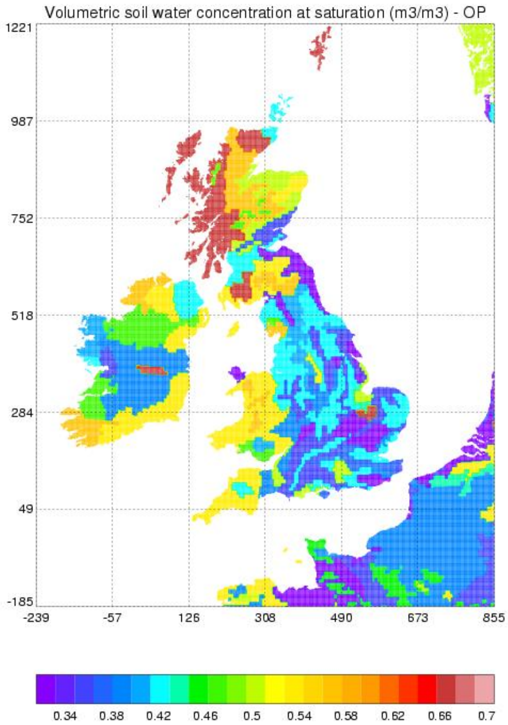


(a) HWSD (b) Operational

Figure 2: Saturated Soil Water Suction, $1/\alpha$ (m)

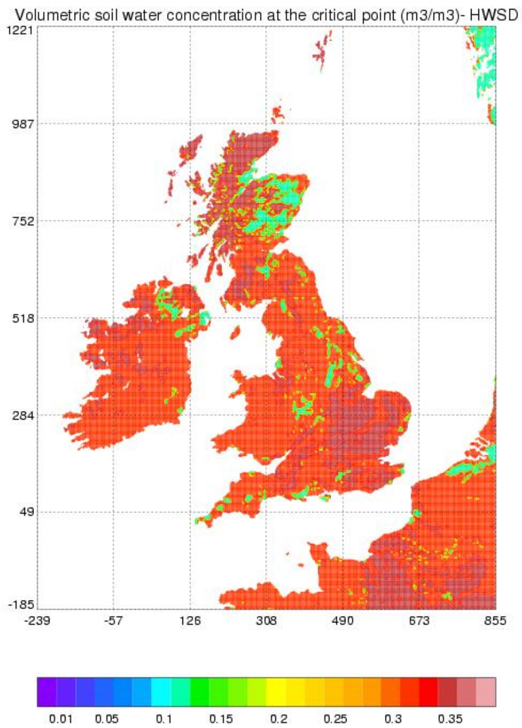


(a) HWSD

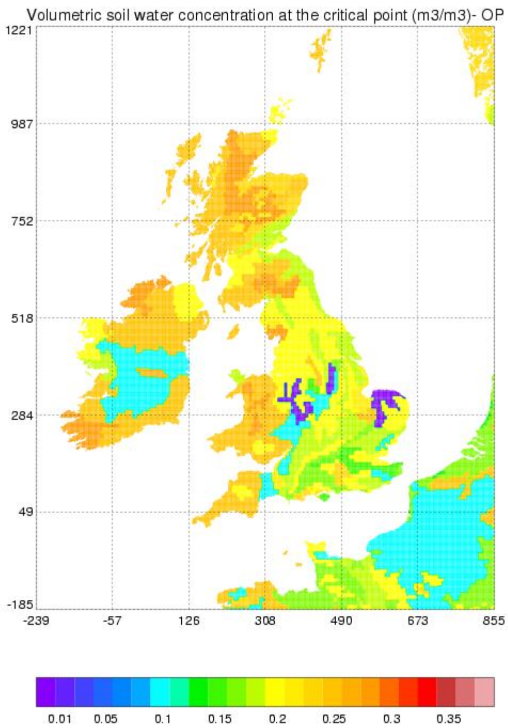


(b) Operational

Figure 3: Volumetric soil water concentration at saturation (m$^3_{water}$m^{-3})



(a) HWSD



(b) Operational

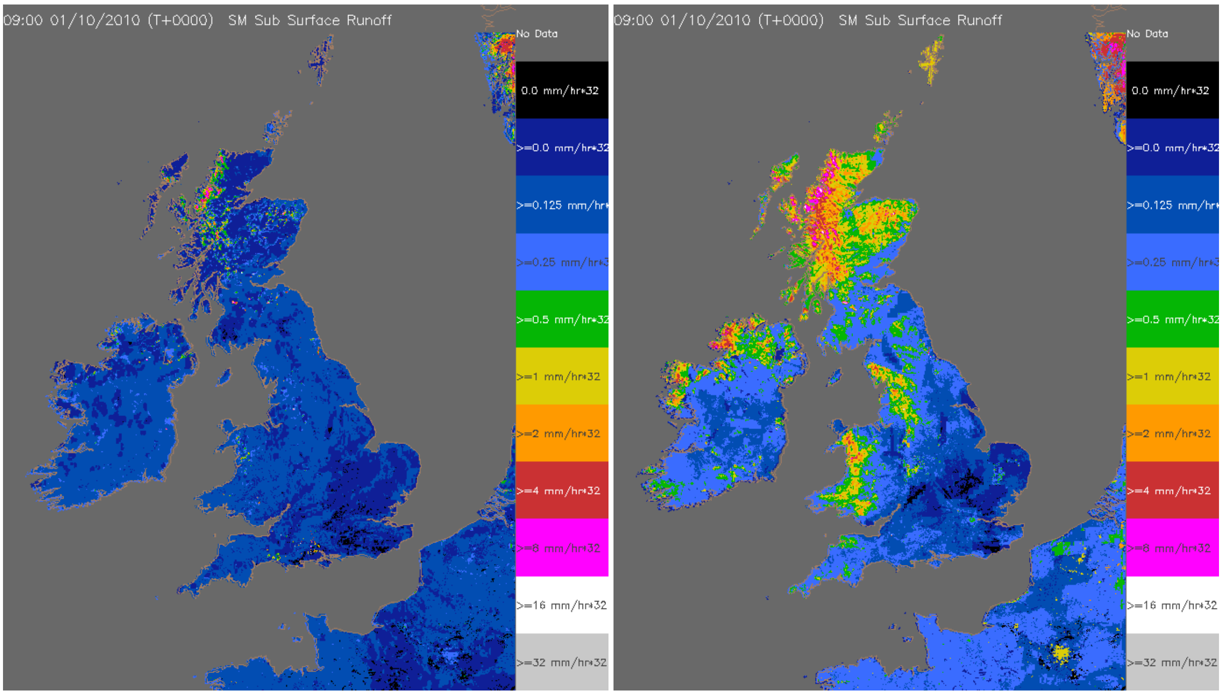
Figure 4: Volumetric soil water concentration at critical point(m$^3_{water}$m^{-3})

4.2 Impacts on MOSES-PDM-RFM outputs

This section presents the results from the trial run. Figures 5 to 13 show the differences to the MOSES-PDM-RFM outputs for the trial and operational runs for the 1st October 2010 (with the exception of figure 11 which shows the evaporation for 28th June 2010). The impacts on the outputs are discussed below.

4.2.1 Sub-Surface Runoff

Figure 5 shows the subsurface runoff for the trial (HWSD-based soil ancillaries) and the operational (IGBP soil ancillaries) runs for the 1st October 2010. The subsurface runoff has been reduced with the implementation of the new HWSD-based soil ancillaries. This maybe due to the large decrease in the saturated hydraulic conductivity (figure 1), which has reduced the absolute value of the hydraulic conductivity for a given soil moisture. The sub-surface runoff, is equal to the hydraulic conductivity of this layer, since there is a free drainage lower boundary condition. A decrease in hydraulic conductivity will reduce the amount of sub-surface runoff. This is likely to lead to a reduction in that part of the river flow derived from subsurface drainage.



(a) Trial (b) Operational

Figure 5: Sub-Surface Runoff 201010010900

4.2.2 Surface Runoff

The initial test run with the new-HWSD based soil ancillaries had shown a large increase in surface runoff (not shown). This is likely to have been caused by an increase in soil moisture which has

Parameter	Current Operational Setup	New Soil Ancillary Setup
B_PDM_MIN	0.5	0.3
B_PDM_MAX	2.0	0.8
SLOPE_PDM_MAX	47.3	21

Table 2: Summary of the B-PDM parameter changes required for the new HWSD-based ancillaries

occured due to the decrease in hydraulic conductivity reducing drainage from the soil column. This has subsequently lead to an overestimation of the saturation excess runoff in the PDM scheme.

It was suspected that these increases in surface runoff were too large and unrealistic. Therefore the method of calculating surface runoff was investigated. The fractional area of saturated runoff producing soil is modelled through the B_PDM parameter. The B_PDM parameter is not well calibrated for the new data and gives more runoff for a given rainfall due to higher soil moisture values. In order to address these issues, a second test run was done to investigate the effects of changing the B_PDM_MIN, B_PDM_MAX and SLOPE_PDM_MAX. These parameters control the rate of runoff occurring over topography. A larger B_PDM parameter indicates a steeper slope and more surface runoff. B_PDM is calculated using the following formulation:

If $\bar{g} < g_{max}$ then

$$b = min\left(b_{max}, b_{min} + \frac{\frac{\bar{g}}{g_{max}}}{\left(1 - \frac{\bar{g}}{g_{max}}\right)}\right) \tag{1}$$

where $\bar{g}$ is the PDM slope (SLOPE_PDM) and g_{max} is the maximum PDM slope (SLOPE_PDM_MAX).

Else

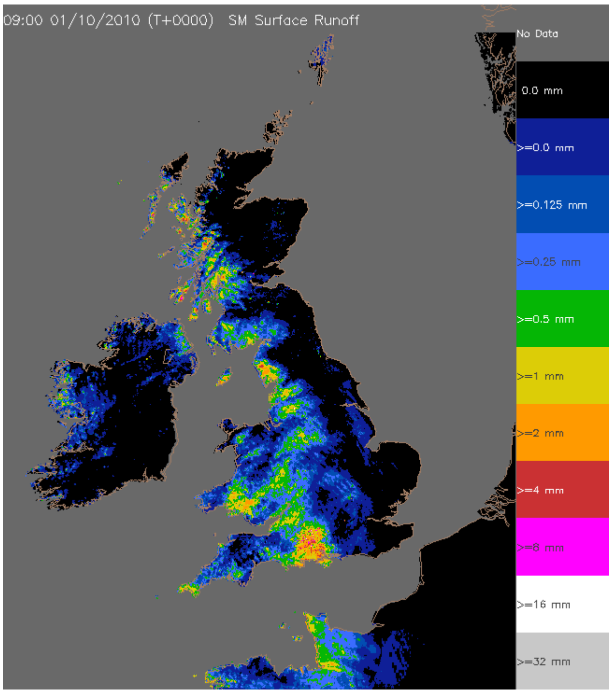
$$b = b_{max} \tag{2}$$

If $\bar{g} < 0$ then

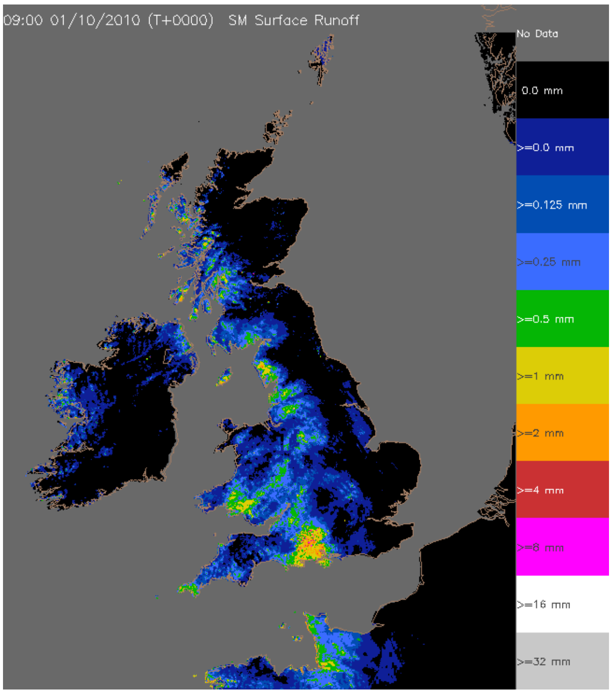
$$b = b_{min} \tag{3}$$

where b is B_PDM parameter, b_{min} is B_PDM_MIN, b_{max}, B_PDM_MAX.

Mapping the B_PDM parameter onto the UKPP 2km grid after the new soil ancillaries were implemented, has revealed that values of B_PDM should have a greater range of values with more mountainous regions having values at or near B_PDM_MAX. The SLOPE_PDM_MAX has been reduced to give a more realistic range for the B_PDM parameter. Table 2 summarises the changes made to B_PDM parameters. Figure 6 shows that the combination of new soil ancillaries and the changes to the B_PDM parameter, still results in an increase in runoff. It is not as big as it was but it may still be too large if the total volume of water that is entering the river channel is taken into account.



(a) Trial

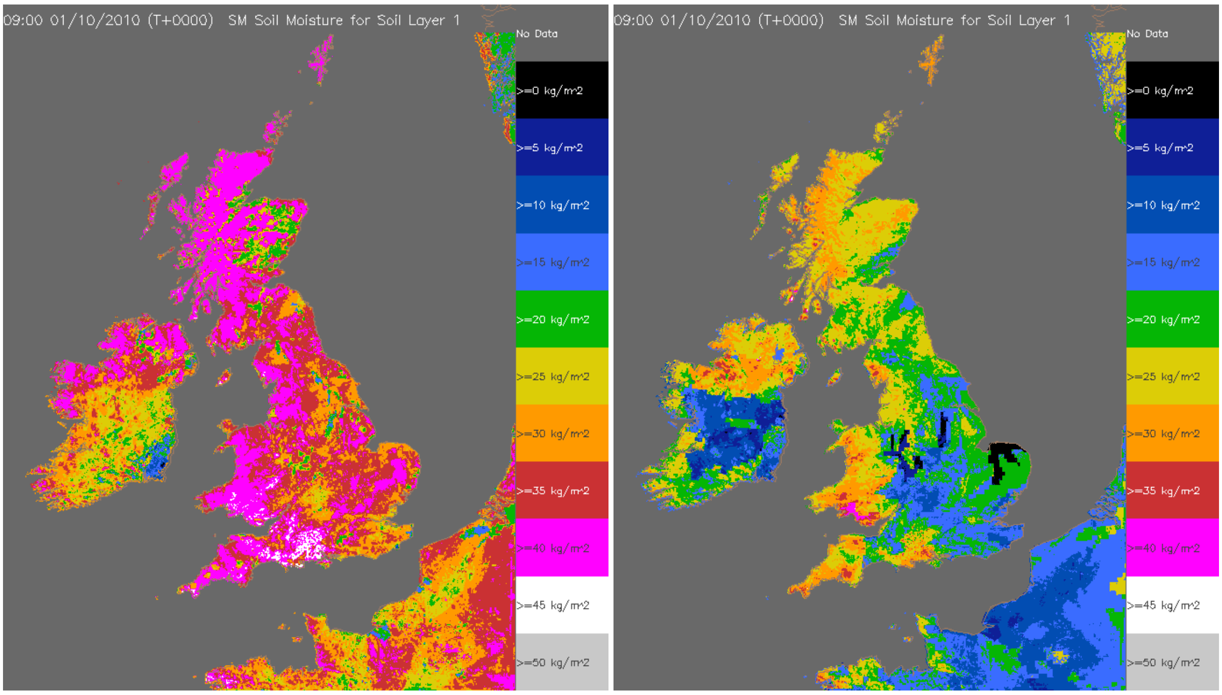


(b) Operational

Figure 6: Surface Runoff 201010010900

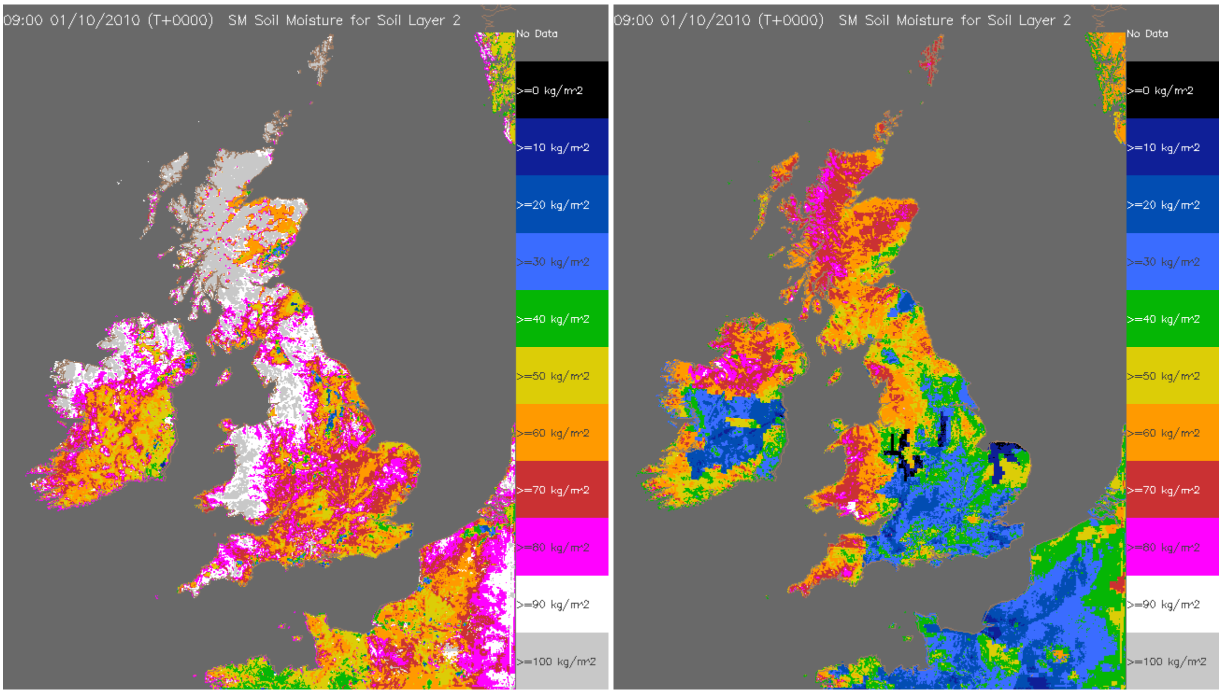
4.2.3 Soil Moisture

Figures 7 to 10 show that soil moisture has increased as a result of the changes in the soil ancillaries. This has been found particularly in layer 4 where soil moisture has increased by up to 50 %. These changes have been caused by the decrease in hydraulic conductivity which has reduced the subsurface runoff considerably and has allowed water to build up in the system. However these changes have had little impact on evaporation as much of this water has been lost to surface runoff. Note that the soil moisture has been compared during October. Comparisons (not shown) during the summer months show a much smaller increase in soil moisture.



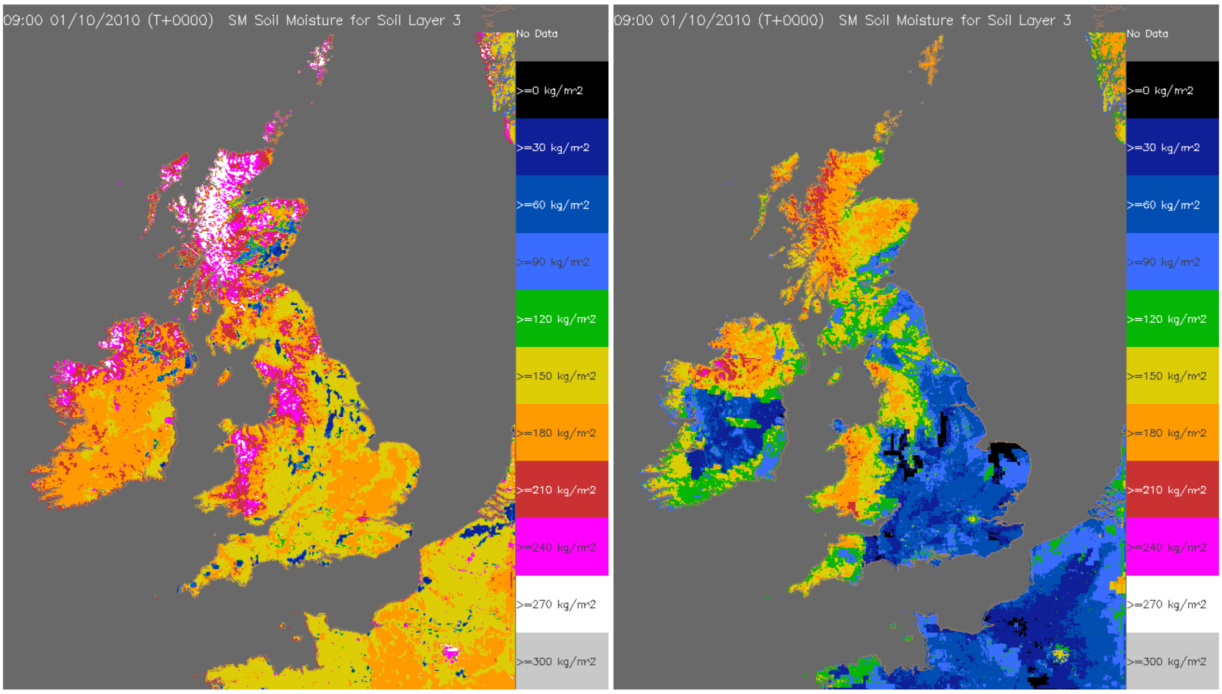
(a) Trial (b) Operational

Figure 7: Soil Moisture Layer 1 201010010900



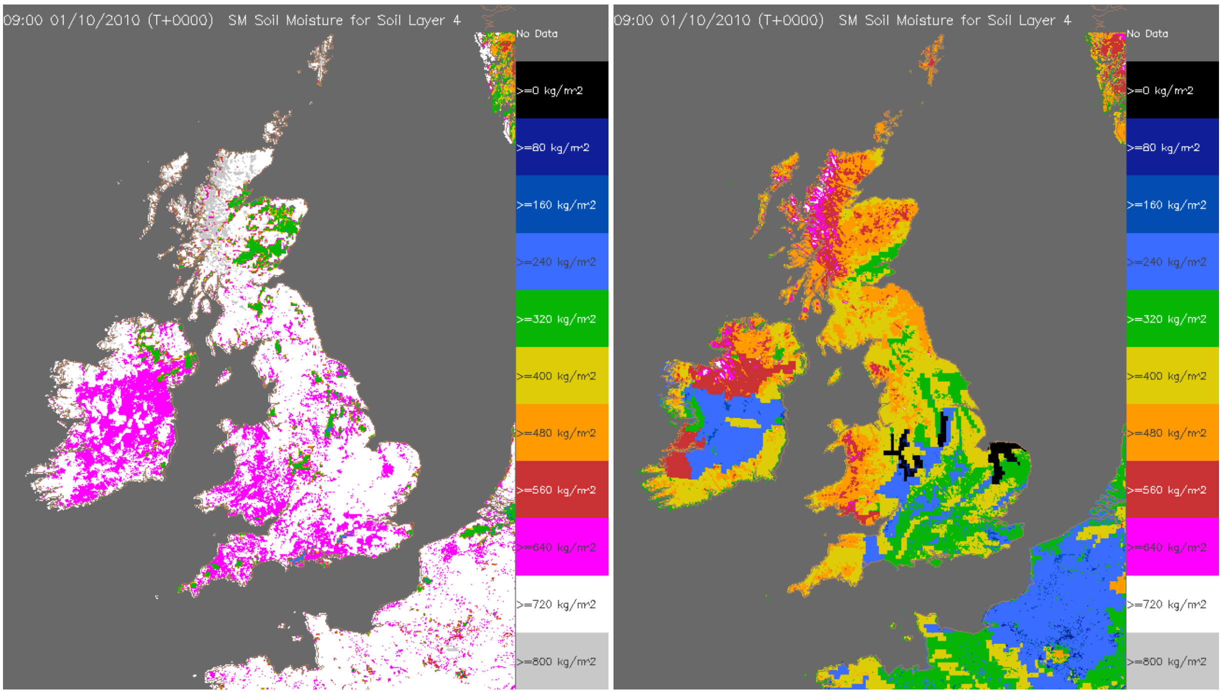
(a) Trial (b) Operational

Figure 8: Soil Moisture Layer 2 201010010900



(a) Trial (b) Operational

Figure 9: Soil Moisture Layer 3 201010010900

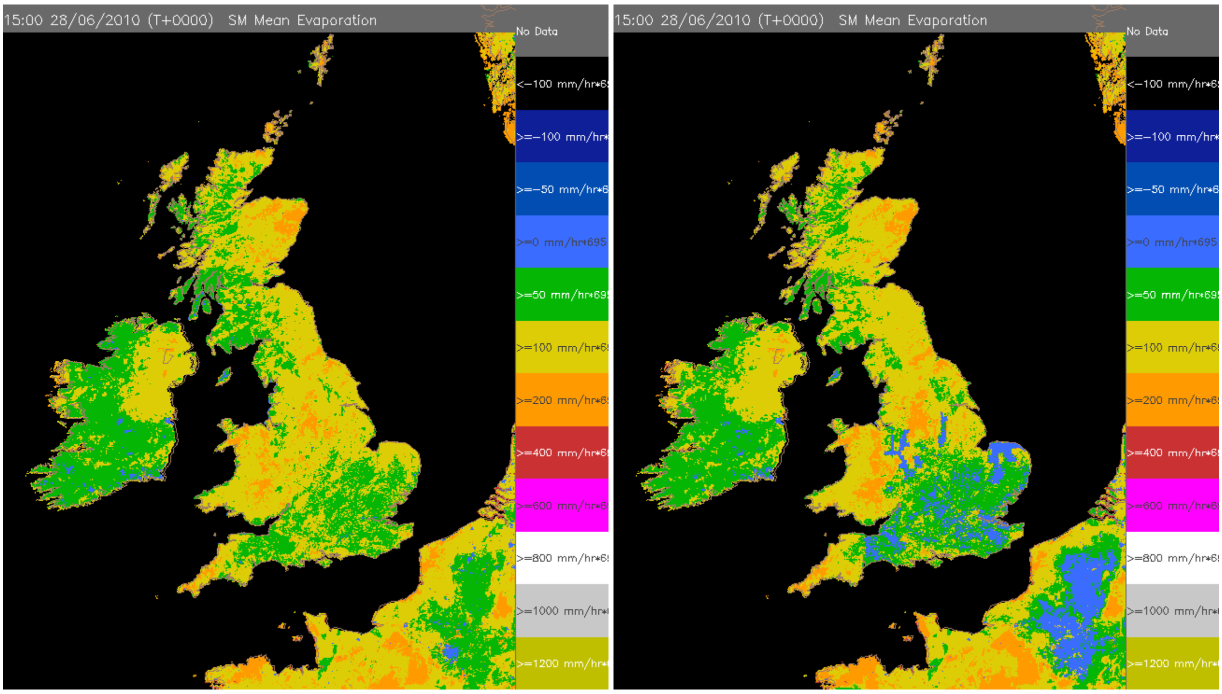


(a) Trial (b) Operational

Figure 10: Soil Moisture Layer 4 201010010900

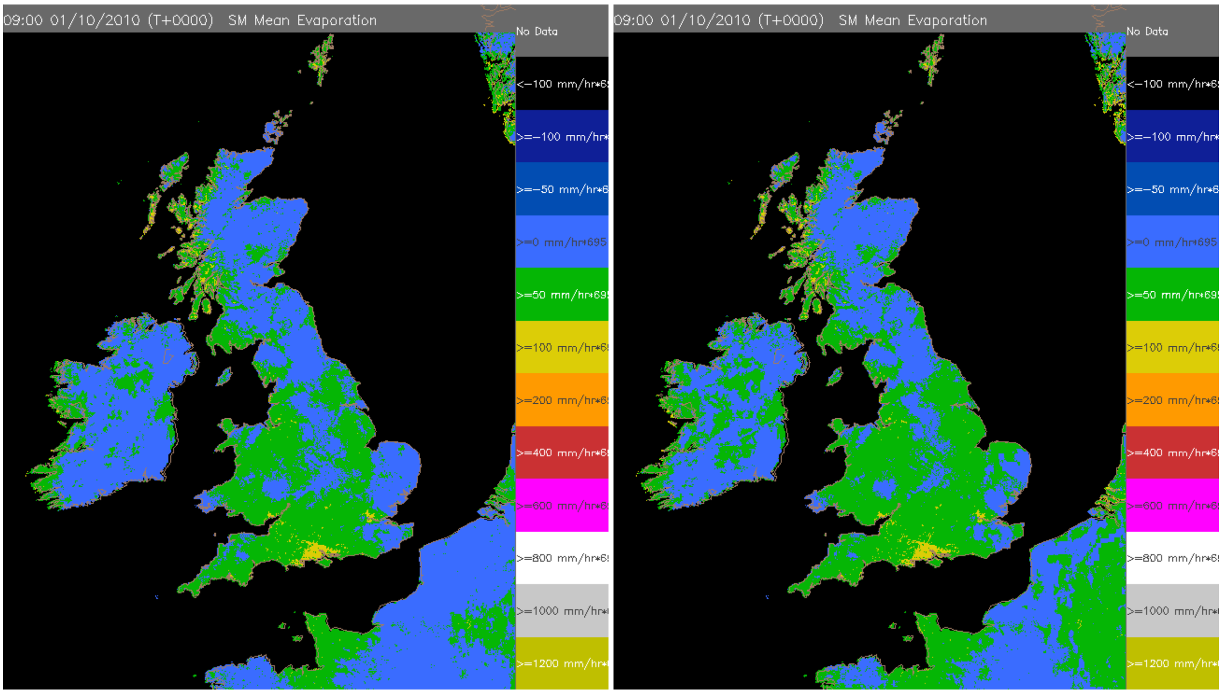
4.2.4 Evapotranspiration

The evaporation has not changed drastically. Figures 11 and 12 (June and October evaporation rates respectively), show a few small local scale changes but this is only where there has been significant changes to soil texture. More available soil moisture during the summer meant there was a small enhancement of evaporation at this time, especially in SE England. The soil moisture in each case is above the critical value and hence evaporation is not sensitive to the changes in soil moisture above this value.



(a) Trial (b) Operational

Figure 11: Evaporation 201006281500

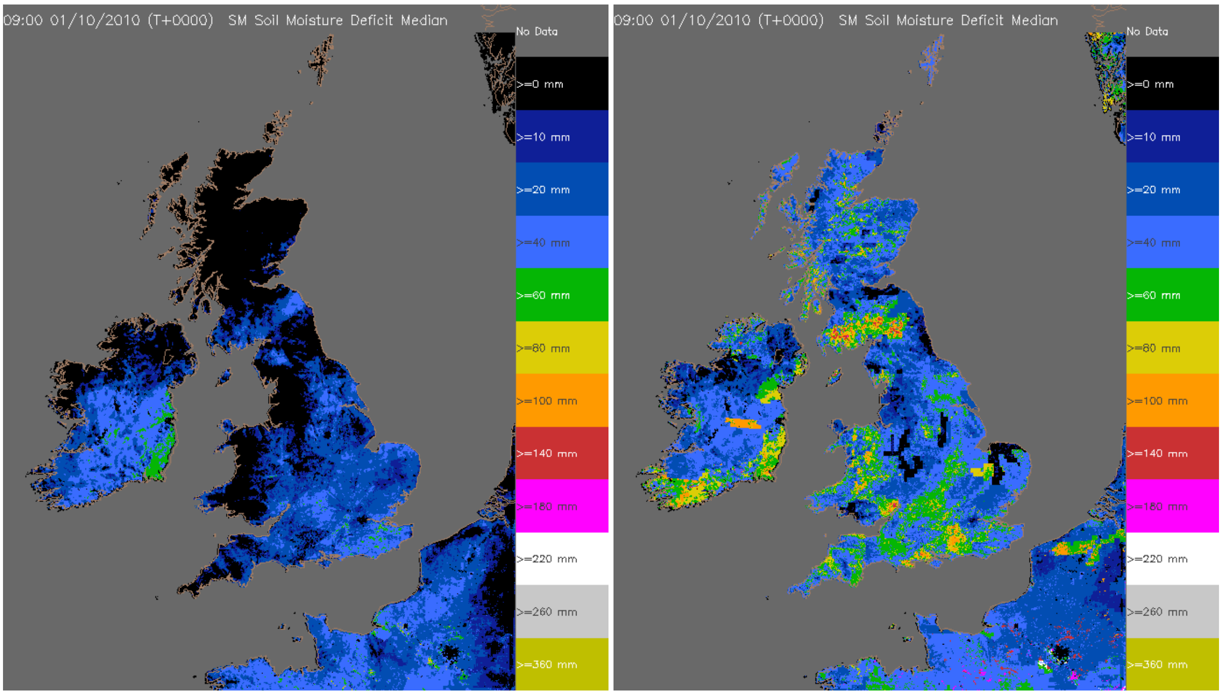


(a) Trial (b) Operational

Figure 12: Evaporation 201010010900

4.2.5 Soil Moisture Deficit

The current formulation of the soil moisture deficit (SMD) gave values which were too small when used with the new soil ancillaries (shown by figure 13. A new method has been implemented for calculating SMDs. Instead of using the soil layer weighting coefficients currently used, it just looks down at the soil moisture to a predefined 'root depth' (0.35m for grass, crops and shrubs; 0.805m for deciduous trees; 0.665 for needleleaf trees).These changes have made SMD magnitudes more in line with those from MORECS. The results from these experiments are show later in the next section.



(a) Trial (b) Operational

Figure 13: Soil Moisture Deficit 201010010900

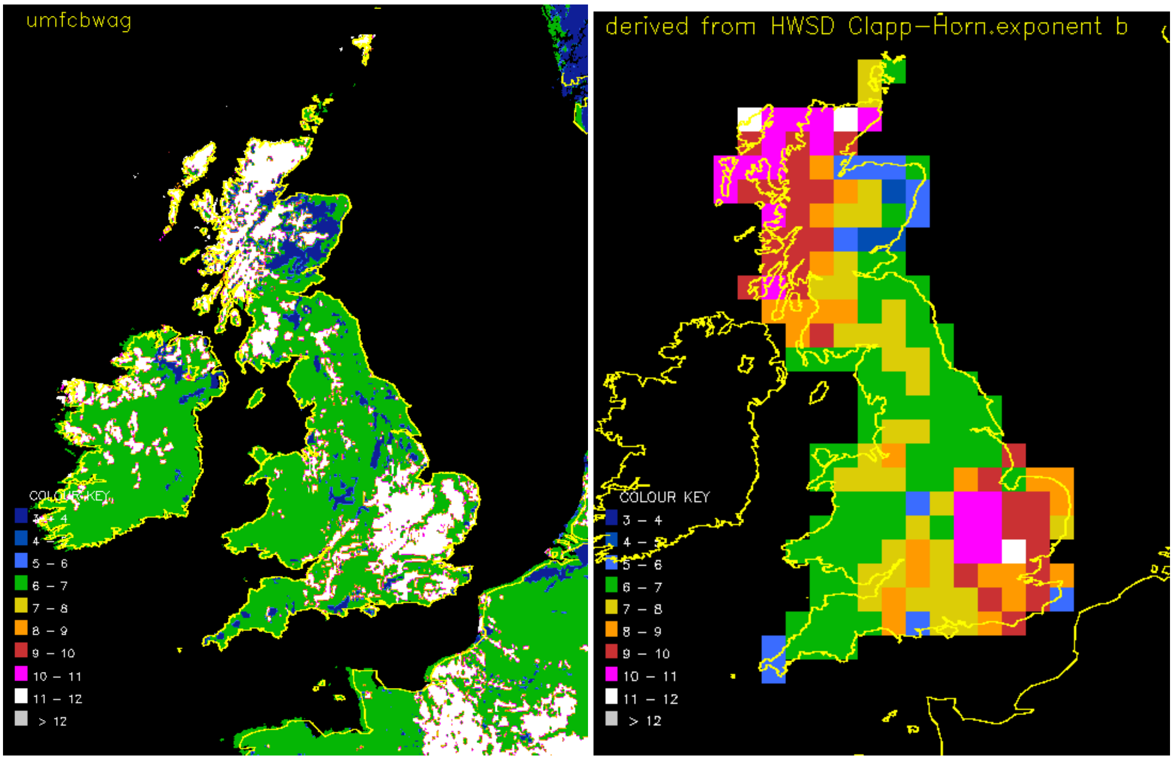
4.3 Aggregating the HWSD-based Soil Hydraulic and Thermodynamic properties onto the MORECS 40km Grid

As an additional tool to assess the impact of the new HWSD-based soil ancillaries it was proposed to do a rerun of the 50-year historical (1961-present) offline-MOSES-PDM. This is run at 40km resolution and therefore requires 40km soil ancillaries. These have been generated by aggregating the new HWSD-based UKPP 2km soil ancillaries.The aggregation for all parameters, except the Saturated Soil Water Suction and Saturated Hydraulic Conductivity, are simple arithmetic means over UKPP land squares within the MORECS squares. Saturated Soil Water Suction and Saturated Hydraulic Conductivity use a aggregation method proposed by Peter Cox (personal communication) which deals with the non linear variation of these parameters with soil moisture.

Figures 14 to 22 show the soil hydraulic parameters before and after aggregation to the MORECS 40km grid. In all cases the domain mean values in the 2km fields are captured by the aggregated 40km ancillaries. However a lot of extreme values are smoothed out and the details gained in the new HWSD-based 2km ancillaries are lost.

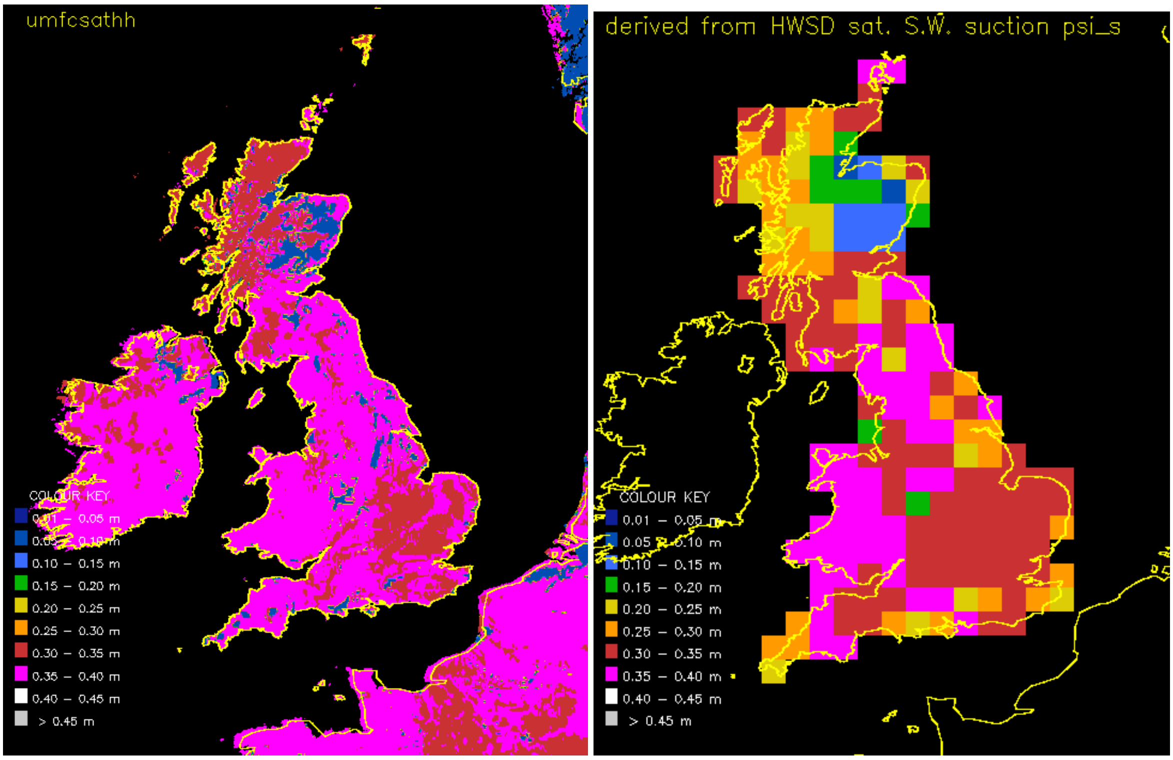
The new method for calculating SMDs has been implemented in this run (as described in the last section). These changes have made SMD magnitudes more comparable with those produced from MORECS.

Timeseries of soil moisture deficit at a selection of the grid squares (figures 23 to 26) show improvements as a result of using the new soil ancillary fields and the new SMD calculations. The figures show the daily median soil moisture deficit for the offline MOSES version 2.1 (old ancillaries and old SMD calculations), offline MOSES version 3.0 (new HWSD-based soil ancillaries and revised SMD calculations) and MORECS for 1976 at grid box numbers 85, 105, 130 and 148. SMD generally peaks higher in summer, better matching that produced in the MORECS dataset and SMD's go to low or near zero values in winter months.



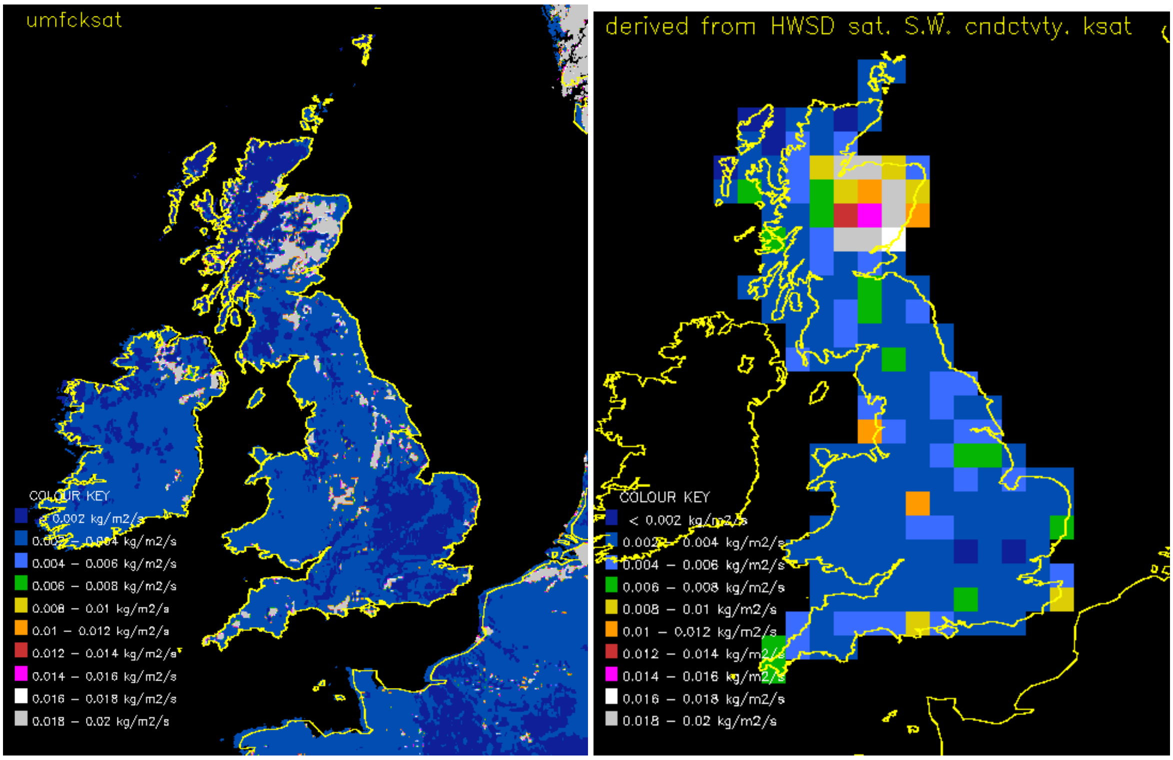
(a) 2km (b) 40km

Figure 14: Clapp & Hornberger b parameter



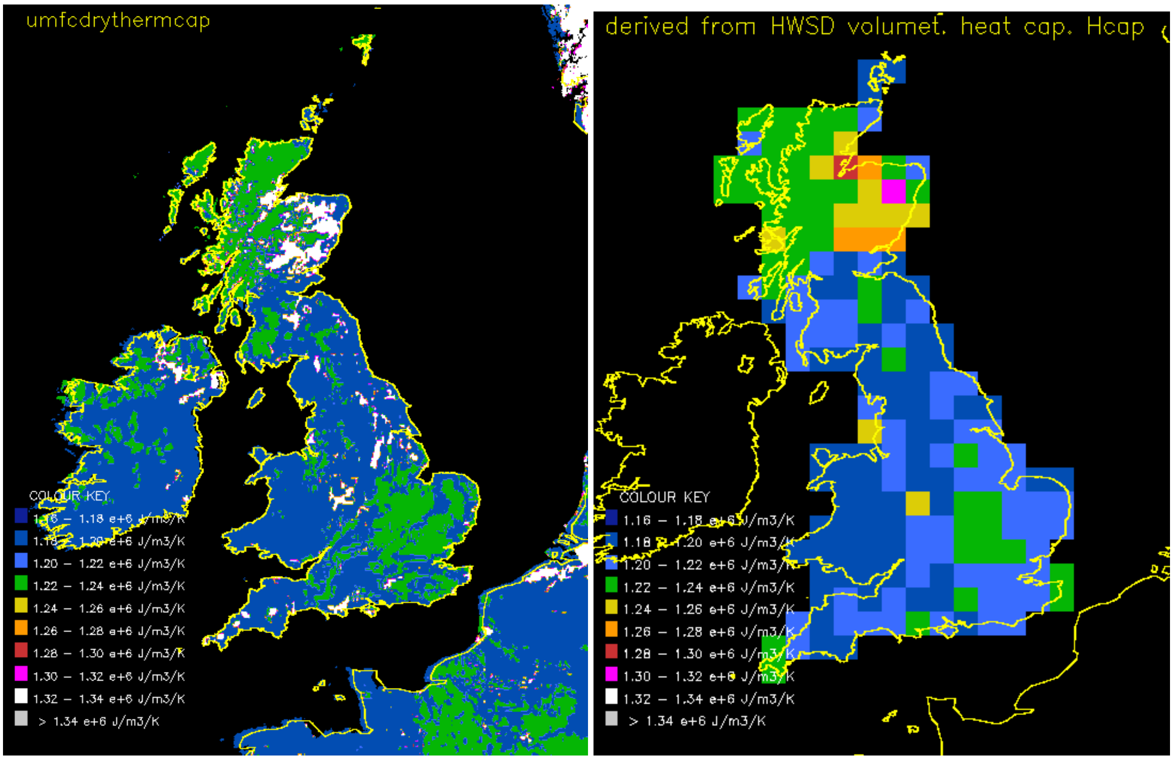
(a) 2km (b) 40km

Figure 15: Saturated Soil Water Suction (m)



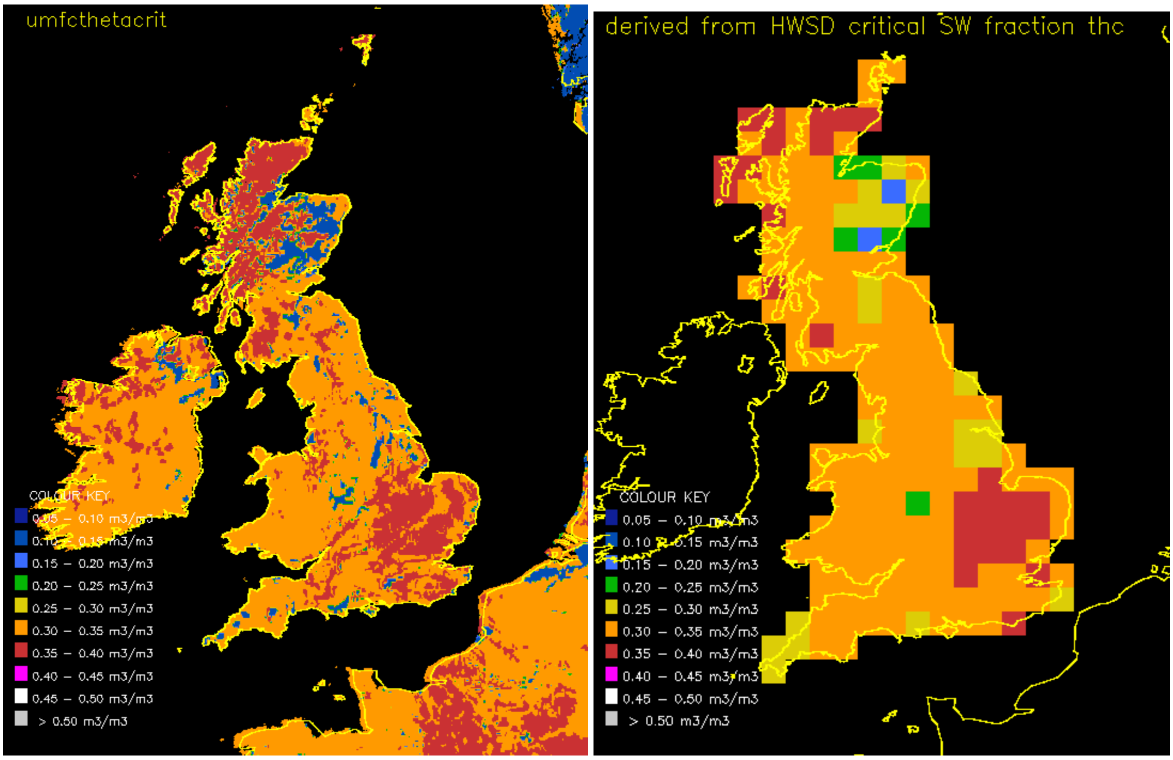
(a) 2km (b) 40km

Figure 16: Saturated Hydraulic Conductivity (kg m^{-2} s^{-1})



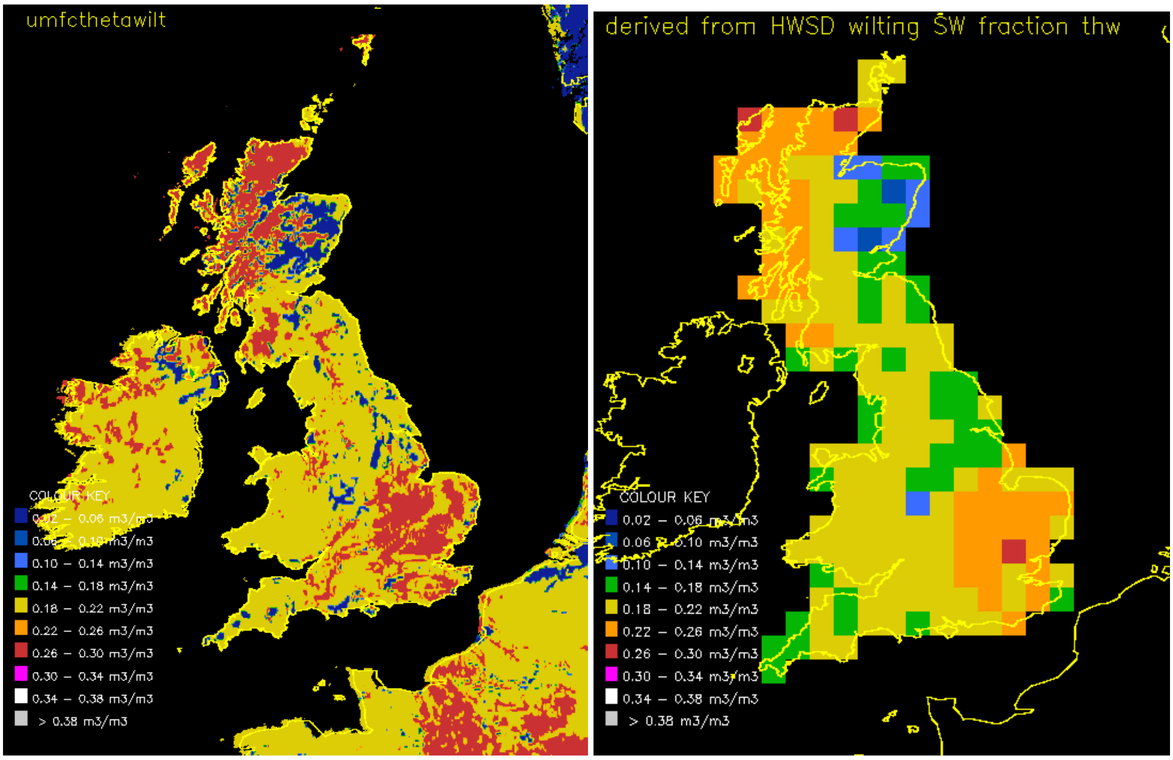
(a) 2km (b) 40km

Figure 17: Dry Soil Volumetric Heat Capacity (J m^{-3}K)



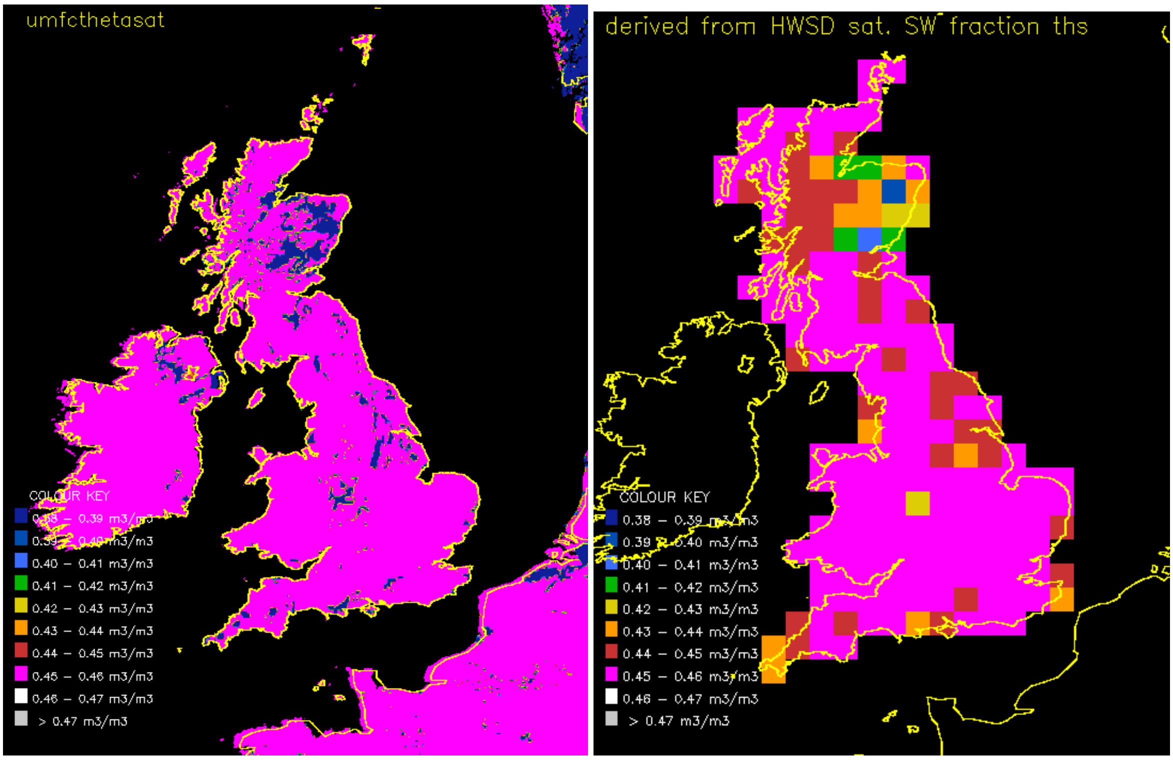
(a) 2km (b) 40km

Figure 18: Volumetric soil water concentration at critical point(m$^3_{water}$m^{-3})



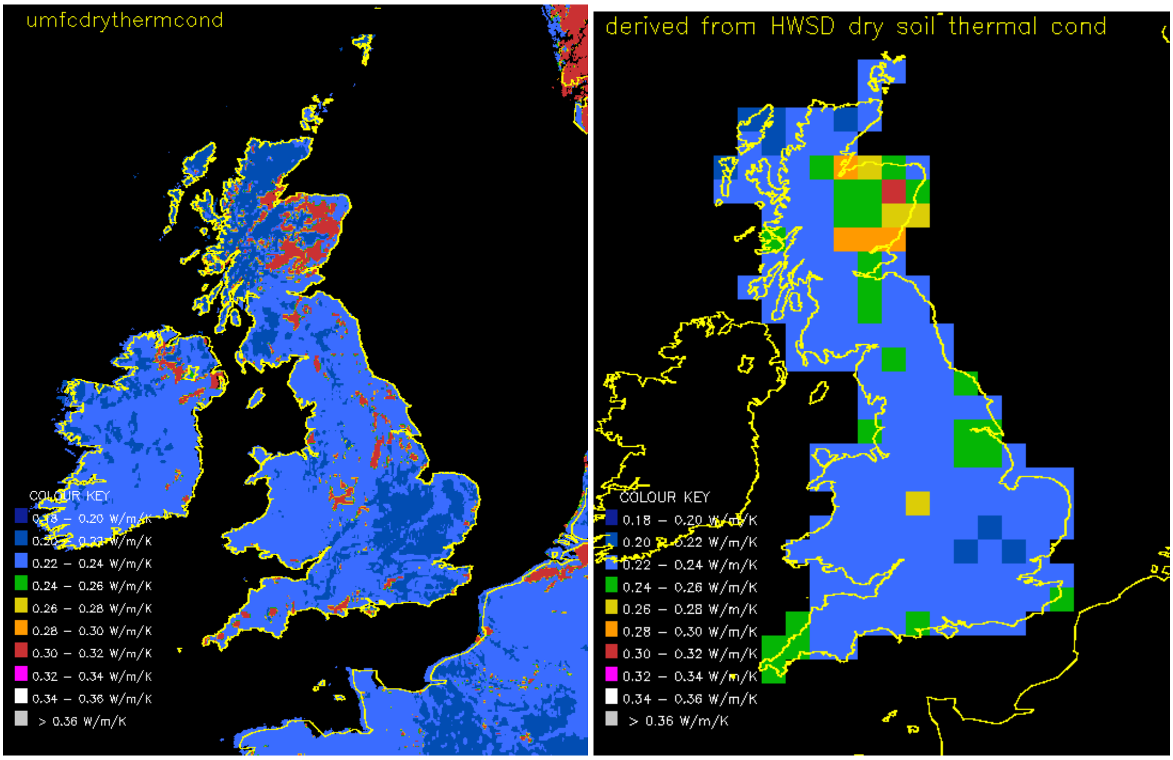
(a) 2km (b) 40km

Figure 19: Volumetric soil water concentration at wilting point(m$^3_{water}$m^{-3})



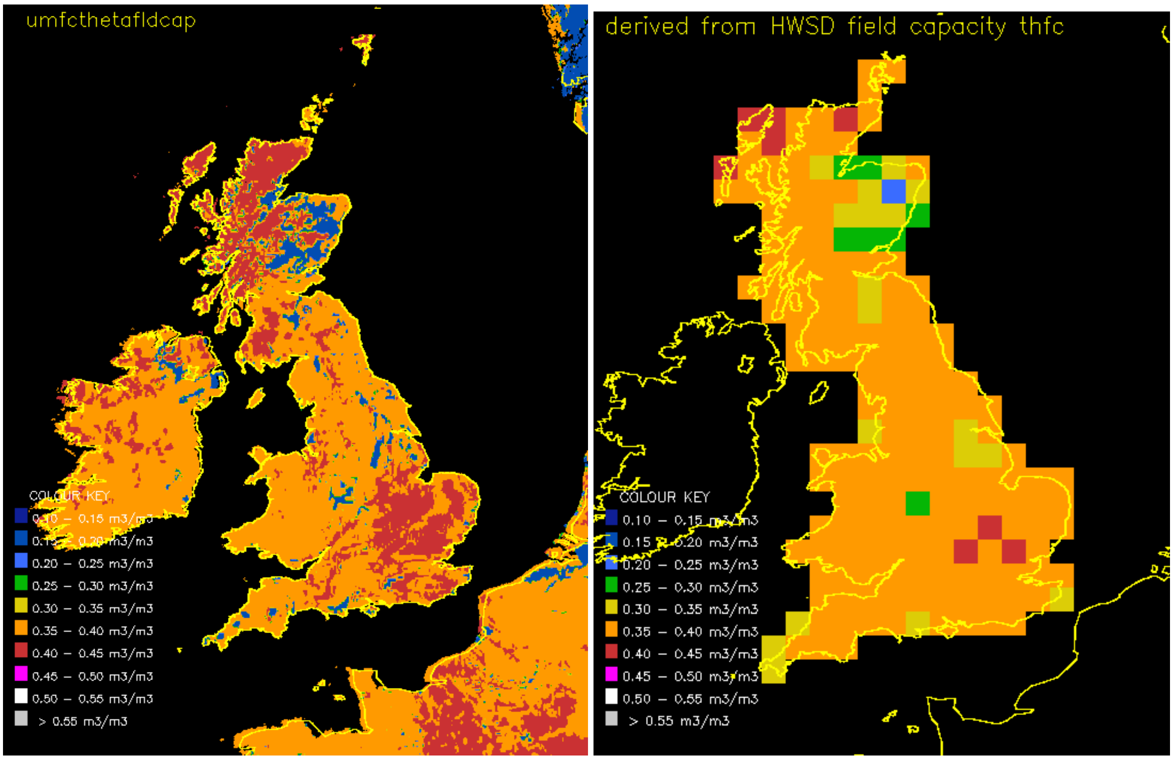
(a) 2km (b) 40km

Figure 20: Volumetric soil water concentration at saturation($m^3_{water}m^{-3}$)



(a) 2km (b) 40km

Figure 21: Dry soil thermal conductivity W^{-1K}



(a) 2km (b) 40km

Figure 22: Volumetric soil water concentration at field capacity (m$^3_{water}$m^{-3})

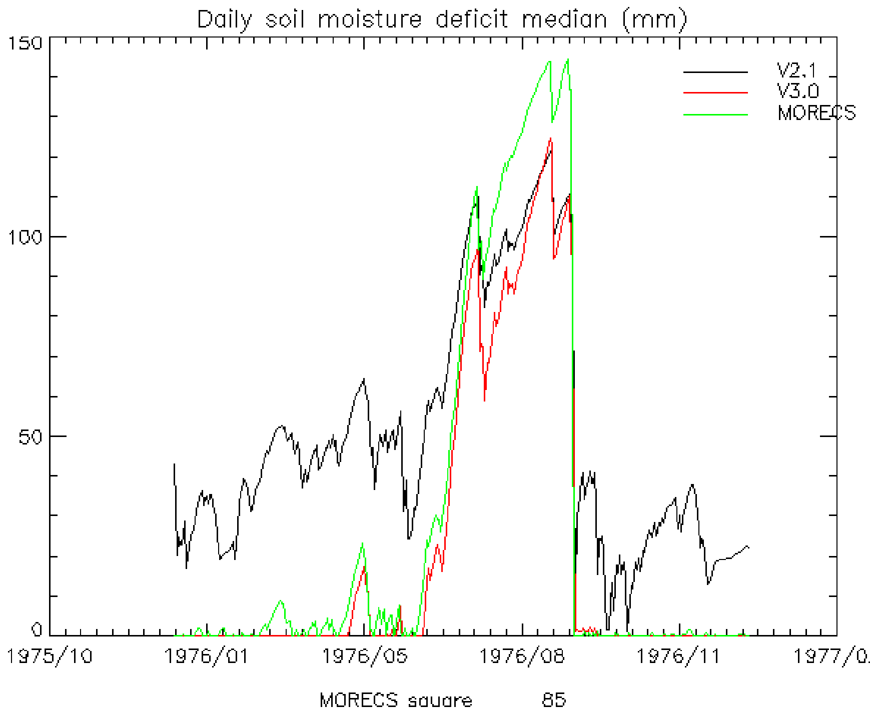


Figure 23: Daily Median Soil Moisture Deficit (mm) for offline MOSES version 2.1 (black), offline MOSES version 3.0 (red) and MORECS (green) for 1976, MORECS square 85

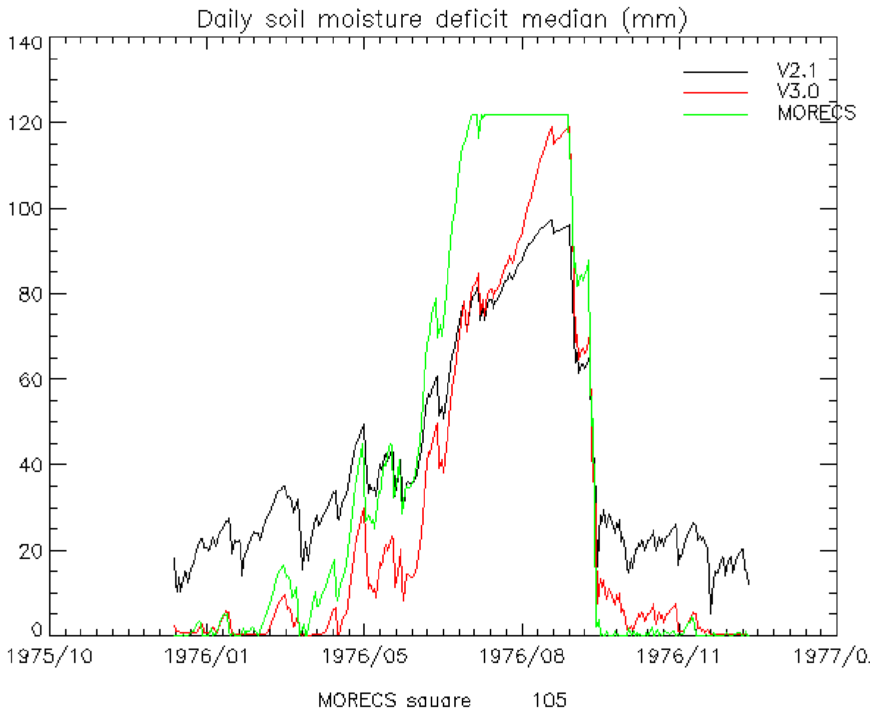


Figure 24: Daily Median Soil Moisture Deficit (mm) for offline MOSES version 2.1 (black), offline MOSES version 3.0 (red) and MORECS (green) for 1976, MORECS square 105

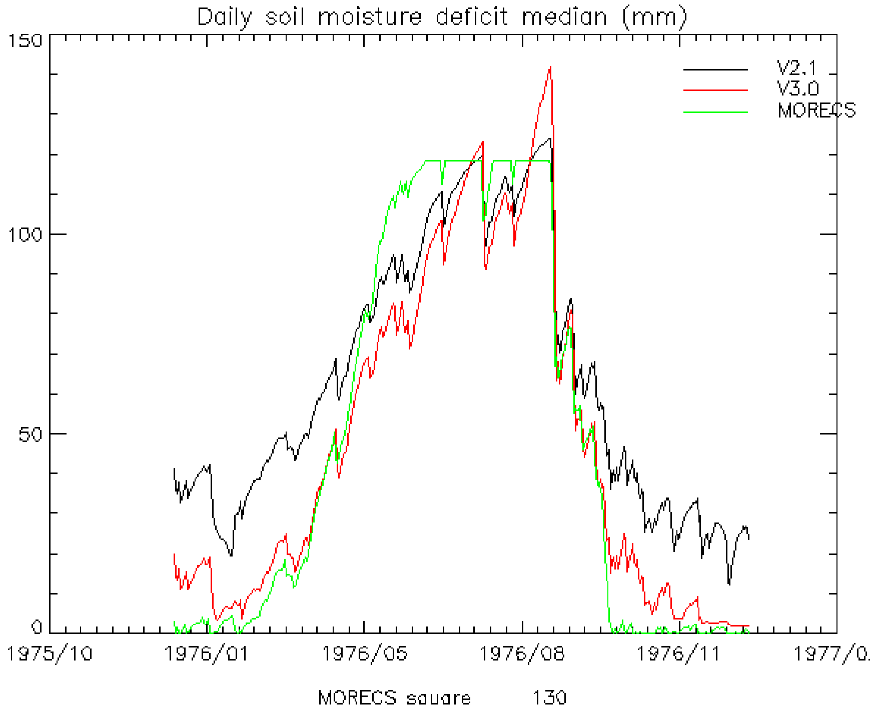


Figure 25: Daily Median Soil Moisture Deficit (mm) for offline MOSES version 2.1 (black), offline MOSES version 3.0 (red) and MORECS (green) for 1976, MORECS square 130

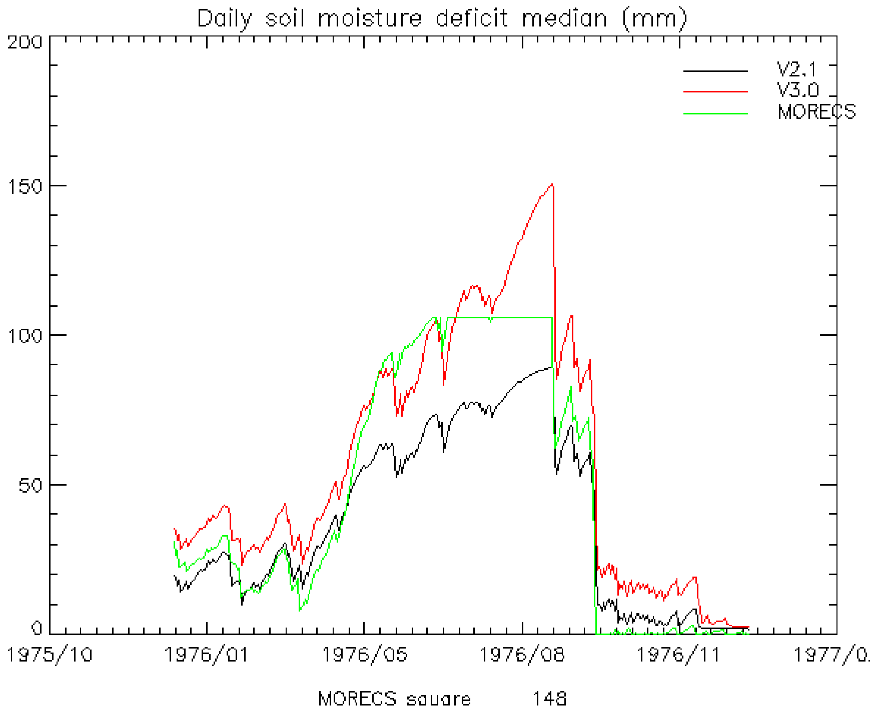


Figure 26: Daily Median Soil Moisture Deficit (mm) for offline MOSES version 2.1 (black), offline MOSES version 3.0 (red) and MORECS (green) for 1976, MORECS square 148

4.4 Conclusions

This study has demonstrated that land surface models can be sensitive to the diagnosis of the soil physical properties. Improvements have been made to the UKPP MOSES-PDM-RFM soil hydraulic parameters, the B-PDM parameter and the parameterisation of the soil moisture deficit.

Overall, the new soil ancillaries have more sensible values and the spatial patterns are realistic. The resolution is greater and they contain a higher degree of geographic detail. In contrast, the current operational fields have wrong details, the range of values is too large and there are many know erroneous values in the fields.

In particular, the HWSD soil properties give much better soil moisture values and show evidence of improvement. Figures 7 to 10 show clear evidence of are the removal of ”anomalously” very low areas of soil moisture in e.g. Norfolk.

My pre-operational trial showed an enhancement of surface runoff over topography and over a 50% reduction in sub-surface runoff. The net decrease in runoff, has meant that less soil water is able to exit the system via the bottom and hence an increase in soil moisture has been observed which is greatest at lower levels. More available soil moisture during the summer meant there was a small enhancement of evaporation, especially in SE England. However this has decreased during Autumn and is now comparable to the current operational field.

The timeseries from a selection of 40km sqaures of the offline-MOSES-PDM for SMD, show that use of the new soil ancillary fields allows SMD to go to low or zero values in winter months and increase to realistic values during the summer.

Overall UKPP MOSES-PDM-RFM is producing results that are consistent with and explainable by the new ancillaries. This change has been implemented successfully into parallel suite 25.

4.5 Acknowledgements

Thanks go to Stephen Moseley for advise and help in converting the soil ancillaries and setting up the UKPP MOSES-PDM-RFM trial. Thanks also go to Imtiaz Dharssi and Keir Bovis for creating the 2km Van Genuchten soil ancillaries over the UKPP domain.

References

P.M. Cox, R.A. Betts, C.B. Bunton, R.L.H. Essery, P.R. Rowntree, and J. Smith. The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dynamics*, 15:183–203, 1999.

I. Dharssi, P.L. Vidale, A. Verhoef, B. Macpherson, C. Jones, and M.J. Best. New soil physical properties implemented in the Unified Model at PS18. Forecasting Research Technical Report, No. 528. *Met Office, Exeter*, 2009.

R.L.H. Essery, M.J. Best, and P.M. Cox. MOSES 2.2 technical documentation. Hadley Centre Technical Note 30. *Met Office, Exeter*, 2001.

FAO/IIASA/ISRIC/ISS-CAS/JRC. Harmonised world soil database, (Version 1.0). Technical report, FAO, Rome,Italy and IIASA, Laxenburg, Austria, 2008.

E. Fischer, S. Senviratne, P. Vidale, D. Luithi, and C. Schar. Soil moisture-atmosphere interactions during the 2003 European sumer heatwave. *Journal of Climate*, 20(20):5081–5099, 2007.

R.M. Fuller, G.B. Groom, and A.R. Jones. The land cover map of Great Britain - An automated classification of LANDSAT Thematics Mapper data. *Photogrammetric Engineering and Remote Sensing*, 60:553–562, 1994.

T.R. Loveland, B.C. Reed, J.F. Brown, D.O. Ohlen, J. Zhu, L. Yang, and J.W. Merchant. Development of a global land cover characteristics database and IGBP - DISCover from 1-km AVHRR data. *International Journal of Remote Sensing*, 21:1303–1330, 2000.

R.J. Moore. The probability distributed principle and runoff production at point and basin scales. *Hydrological Sciences Journal*, 30(2):263–297, 1985.

Global Soil Data Task Group. Global Soil Data Products CD-ROM (IGBP-DIS),[Global Soil Data Products CD-ROM (International Geosphere-Biosphere Programme - Data and Information System)]. CD-ROM available from Oak Ridge Natioanl Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. [http://www.daac.ornl.gov], 2000.

M.Th. van Genuchten. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society Of America Journal*, 44:892–898, 1980.

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