Received: 31 August 2023 | Revised: 23 February 2024 | Accepted: 23 March 2024

DOI: 10.1002/asl.1236

RESEARCH ARTICLE

Atmospheric Science Letters RMetS

# Comparison of Met Office regional model soil moisture with COSMOS-UK field-scale in situ observations

**Elizabeth Cooper**[1] | **Cristina Charlton-Perez**[2] | **Rich Ellis**[1]

[1]UK Centre for Ecology and Hydrology, Wallingford, UK

[2]UK Met Office, MetOffice@Reading, Brian Hoskins, University of Reading, Reading, UK

**Correspondence**
Elizabeth Cooper, UK Centre for Ecology and Hydrology, Wallingford, UK.
Email: elicoo@ceh.ac.uk

**Funding information**
Natural Environment Research Council, Grant/Award Numbers: NE/S017380/1, NE/X019063/1

## Abstract

The UK Met Office state-of-the-art, deterministic, convection-permitting, coupled land-atmosphere, regional weather forecasting system, known as the UKV or UK Variable resolution model (Tang et al. *Meteorological Applications*, 2013; 20:417–426), has been operational since 2015. Science updates are regularly made to the UKV land surface data assimilation scheme when those updates improve predictions of screen temperature and humidity, since these quantities have a direct impact on atmospheric states and weather forecasts. Less attention has been paid to whether UKV soil moisture analyses are close to independent, in-situ soil moisture observations, partly because it is difficult to make meaningful comparisons between 1.5 $km^2$ gridded model outputs and traditional point sensor measurements. Soil moisture is recognized to be important when hydrological forecasts for runoff and rivers are required. This is because soil moisture controls the extent to which rainfall can infiltrate the soil, and the amount of surface runoff affects the timing of peak river flows (Ward & Robinson, *Principles of Hydrology*. McGraw-Hill Publishing Company; 2000; Singh et al. *Water Resources Research*, 2021, 57, e2020WR028827). Gómez et al. (*Remote Sensing*, 2020; 12:3691) report benefits to river flow forecasts when using soil moisture data assimilation in the UKV system instead of a daily downscaled product from the Met Office global model. The Met Office measures soil temperature and soil moisture at Cardington (Osborne & Weedon, *Journal of Hydrometeorology*, 2021, 22:279–295); there is no other UK Met Office site at which soil moisture is measured. In this study, we use field-scale (∼200 m radius) soil moisture measurements from the UK Centre for Ecology and Hydrology's (UKCEH's) COSMOS-UK network to provide independent verification and analysis of UKV soil moisture during summer 2018, an unusually dry period in the United Kingdom. We find that the match to COSMOS-UK soil moisture observations is generally good, and that changes made to the land data assimilation approach during a recent operational upgrade had a generally beneficial impact on UKV soil moisture analyses under very dry conditions.

**KEYWORDS**

land-atmosphere < 13. Geophysical sphere, observations < 10. Tools and methods, regional and mesoscale modelling < 10. Tools and methods, surface-based observations < 10. Tools and methods

## 1 | INTRODUCTION

The summer period of 2018 was exceptionally dry over most of the United Kingdom. A heatwave was officially declared by the Met Office that summer, as defined by the new UK definition of a heatwave, which is "when a location records a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold" (McCarthy, Armstrong, & Armstrong, 2019). The thresholds are determined locally by the UK county and vary between 25 and 28°C. McCarthy, Christidis, et al. (2019) described the meteorological drivers of the 2018 heatwave, starting with an exceptionally dry June due to the blocking high pressure located to the northwest of the United Kingdom. The positive summer North Atlantic Oscillation (SNAO) during that period kept the storm track further north than normal, steering potential precipitating systems away from the United Kingdom. They explained that elevated sea surface temperatures (SSTs) around the United Kingdom contributed to higher air temperatures and suggested that global warming was also a factor. The lack of normal precipitation in this period, coupled with the dry soils already in existence over much of the United Kingdom, contributed to sustained, elevated air temperatures. Note that Turner et al. (2021) described the drier than normal soil moisture conditions in the United Kingdom leading up to the 2018/2019 drought as having roots in autumn 2016. Motivated by this unusual period, we investigated how well the UKV captured these dry soil conditions.

The Met Office uses the UKV system (Tang et al., 2013), a deterministic numerical weather prediction (NWP) model with atmospheric and land data assimilation, as a basis for issuing weather forecasts for the United Kingdom. The UKV is a 1.5-km resolution model that is convection-permitting, which means there are no parameterizations of convective precipitation used (Clark et al., 2016). Land surface data assimilation (LSDA) has been implemented in the UKV system since December 2019. Before then, the UKV soil moisture fields were initialized at 09Z daily using global soil moisture model analyses. At present, both global and UKV systems use the same method and the same observation types for soil moisture DA (Gómez et al., 2020).

In an earlier study, Petch et al. (2020) used the UKV system to determine how much control soil moisture had on the 2018 heatwave in the United Kingdom. They found that while changes to the soil moisture did not affect nightly minimum temperatures over land, the daily maximum air temperatures in certain locations could change by up to 3.5°C when the soil was moistened in the experiment. They reported a mean change in air temperature between 0.6 and 0.8°C when they increased soil moisture and high spatial variability in the response. Therefore, Petch et al. (2020) show that the same modelling system used in this paper is able to simulate the air temperature response to changes in soil moisture in a physically reasonable way.

Here, we compare UKV soil moisture estimates with observations from a selection of sites in the COSMOS-UK network to assess how well the UKV matches this independent observation set. We are motivated by the fact that field-scale COSMOS-UK soil moisture measurements allow for a more meaningful comparison with a UKV grid cell soil moisture value than either point soil moisture sensors or those from satellite retrievals. In situ point measurements of soil moisture over a small measured volume can be easily disturbed or influenced by local flora and fauna, such as plant roots and earthworms. At the other extreme, satellite soil moisture measurements have a large footprint, can suffer from poor temporal coverage and represent moisture only in the surface soil layer, usually the first few cm of soil. Additionally, satellite soil moisture retrieved from ASCAT is already used in the UKV land DA scheme, so it is not an independent source of information.

## 2 | MODEL AND DATA

### 2.1 | Model: UKV system

The control for the UKV (CTL) was created to simulate the operational suite (OS43), the operational weather forecasting system at the time of the new land surface

DA developments. The trial or experimental output (EXP) is from a run of the model using the package of developments that was eventually adopted as the next operational suite (OS44) land surface DA package. The new developments included creating analysis increments for soil temperature of four layers, skin temperature on tiles and snow temperature for tiles and up to three snow layers, where tiles are defined as the fraction of a grid box that is considered to be a type of land (e.g., bare soil or urban) as defined by the modelling system. The use of tiles in a model to compute surface heat and moisture fluxes is described by Essery et al. (2003). These increments were created using the Simplified Extended Kalman Filter (SEKF) (De Rosnay et al., 2013) that has been used for soil moisture since the previous operational suite (OS42). A new optimal interpolation scheme to assimilate both satellite and in situ snow surface observations was implemented. For the UKV domain, this snow depth assimilation scheme is not very active in the summer due to a lack of new snowfall events; therefore, we discount any benefits to improved soil moisture from this particular upgrade to the package of changes. The developments also included a new ASCAT bias correction method with both improved translation of the observations into the model climate space and an error-boosting mechanism when ASCAT observations approach the driest or wettest values.

The UKV uses the Joint UK Land Environment Simulator (JULES) (Best et al., 2011) to simulate land-relevant variables such as soil moisture, soil temperature and snow cover. The land surface data assimilation scheme also makes use of JULES to estimate the sensitivity matrix used in the SEKF DA scheme. JULES has four soil layers of differing thicknesses (10, 25, 65 and 200 cm).

## 2.2 | Data: COSMOS-UK network

The COSMOS-UK network provides near-real-time, field-scale soil moisture and meteorological measurements at 51 sites across the United Kingdom. Data are made publicly available via the UKCEH Environmental Information Data Centre at https://eidc.ac.uk/. Soil moisture is measured at each site using a cosmic-ray neutron sensor (CRNS), which counts epithermal neutrons at the land surface. Neutron count measurements are then used to derive field-scale (~200 m radius) soil water content as described in Cooper, Bennett, et al. (2021). The effective measuring depth of each CRNS instrument varies between approximately 10 and 80 cm, depending on soil moisture as well as the amount of soil organic matter (Cooper, Bennett, et al., 2021; Franz et al., 2013; Zreda et al., 2008, 2012); greater soil water content leads to a smaller CRNS measurement area and a shallower measurement depth. In this study, we account for the variable measuring depth of the COSMOS instrument using the D86 measurement depth provided with the soil moisture dataset and the technique described in Cooper, Blyth, et al. (2021). We do not take account of the variable footprint size of the measurement.

We compared UKV output with observations from 33 of COSMOS-UK's 51 sites, with locations and site characteristics shown in Figure S1 and Table S2. Sites were selected using two criteria. Firstly, we excluded 9 sites that were not operating or had incomplete daily soil moisture data over the period of interest (June/July 2018). Secondly, we chose sites at which the land cover of the COSMOS-UK site and the land cover of the equivalent (nearest neighbouring box to the COSMOS-UK site) UKV grid box are as similar as possible. In effect, these are COSMOS-UK sites at which the land cover is described as arable or grassland (see Table S2) and the corresponding UKV grid cell comprises >65% C3 (temperate) grass (see Figure 1 for the land cover fractions of the model grid cells in which each of our 33 sites are located). We exclude sites at which trees or other vegetation might act to add moisture to the area around the instrument. This is because local sources of moisture not in the soil can make the calibration of the CRNS instrument less reliable (Baatz et al., 2014). Choosing sites at which the land cover of the COSMOS site closely matches that of the larger UKV grid box reduces the representativity error between the two.

We also seek to minimize representativity errors in terms of spatial footprint. An in situ point probe represents soil moisture over an area of at most 1 $m^2$ or 0.0001 hectares. When measuring under very dry conditions, the COSMOS-UK can see up to 12 hectares. Compare these estimates to the UKV, which represents fields at 1.5 km resolution, equating to 2.25 $km^2$ resolution or 225 hectares. This is nearly 19 times larger than the approximately 12 hectares of COSMOS. However, the gap between in situ point probes and Earth Observation satellite products is much larger than the gap between COSMOS and UKV. For example, the high-resolution ASCAT soil wetness index is given at 12.5 km, which equates to 156.25 $km^2$ resolution or 15,625 hectares. In many studies, model output is compared to either in situ probes (order $10^{-4}$ hectares) or satellites (order $10^5$ hectares). By comparing the model (order 10) in this study, the disparity in horizontal scales between the observations and model output has been significantly reduced. That reduction gives us more confidence when comparing a model output to an observation.

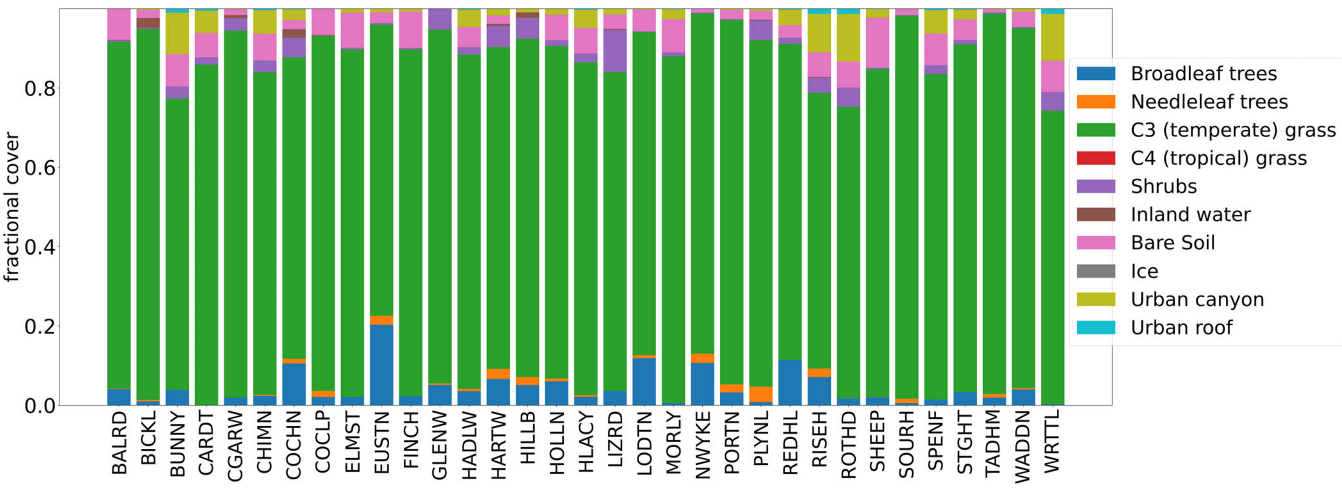


**FIGURE 1** UKV land cover fraction at COSMOS-UK sites. Site locations, details and codes are given in Figure S1 and Table S2. Land types are defined as in JULES (Best et al., 2011). Note that there are two urban-type tiles: canyon and roof (Porson et al., 2010).

## 3 | RESULTS

Figure 2 shows the timeseries (panels a, c and e) and boxplots (panels b, d and f) of soil moisture data for the case study period at three representative sites: Cardington (CARDT), Waddesdon (WADDN) and Rothamsted (ROTHD). The COSMOS-UK data are average daily values; the UKV data are analysis values from the 12Z forecast. The UKV soil moisture is calculated to the observing depth of the COSMOS-UK CRNS instrument for the corresponding day following the method in Cooper, Blyth, et al. (2021). In the three sites shown in Figure 2, the CTL run is biased with respect to the observations to different degrees. Also at each site, both the time series and the boxplots show that the EXP run reduces the soil moisture overall, thus closing the gap between model and observation. In the EXP runs, the time series appears steeper than in the control, meaning that the model experiment dried out the soil faster than the control.

It is evident from the plots (Figure 2c,d) that the Waddesdon site is the one in which the experiment gives the closest match to observations. Rothamsted (Figure 2e,f) also shows improvements, but at Cardington (Figure 2a,b), the EXP run did not show great improvement. Larger differences between UKV and observed soil moisture at some sites, such as Cardington, may reflect mismatches in land cover between the COSMOS-UK footprint and the corresponding UKV grid cell, although we have taken steps to minimize the effect of this by choosing sites where the land surface matches model assumptions of land surface type. Mismatches could also be due to heterogeneity of soil types across UKV grid cells; soil properties, on which UKV soil moisture is strongly dependent via JULES, will be calculated for the whole UKV grid cell and not necessarily reflective of the particular soil type at the COSMOS-UK site. For this reason, Osborne and Weedon (2021) made small adjustments to the UKV configurations for local JULES runs at the Cardington site (these adjustments were not used in this study). We also know that, at Cardington in particular, the very dry conditions during June and July 2018 led to widespread senescence of the grass at the COSMOS-UK site. This senescence was observable at Cardington from local and satellite-derived Normalized Difference Vegetation Index observations (Osborne & Weedon, 2021) and was also visible in phenocam images from the COSMOS site. Either or both of these reasons could account for the mismatch between the model and the observations at Cardington. It should be noted that the UKV LSDA ingests more screen-level observations than soil moisture observations, and the system is designed to prioritize the accurate prediction of screen-level humidity and temperature over soil moisture prediction.

In Figures 3–5, boxplots equivalent to those in Figure 2 are shown for all sites; corresponding time series plots are shown in Figures S3, S4 and S5. Each plot is labelled with the short name of the relevant site; for more site details, see Figure S1 and Table S2. In Figure 3a–u, we show all the sites that we assessed as the EXP, giving a result closer to the COSMOS-UK observations than the CTL. In Figure 4a–g, we show sites that were neutral, and in Figure 5a–e, we show the sites where we assessed that the EXP could not beat the CTL at matching the OBS. At every site but one (Figure 5a, COCHN), the EXP shows some level of drying compared to the CTL, with a downward shift in either the median of the distribution

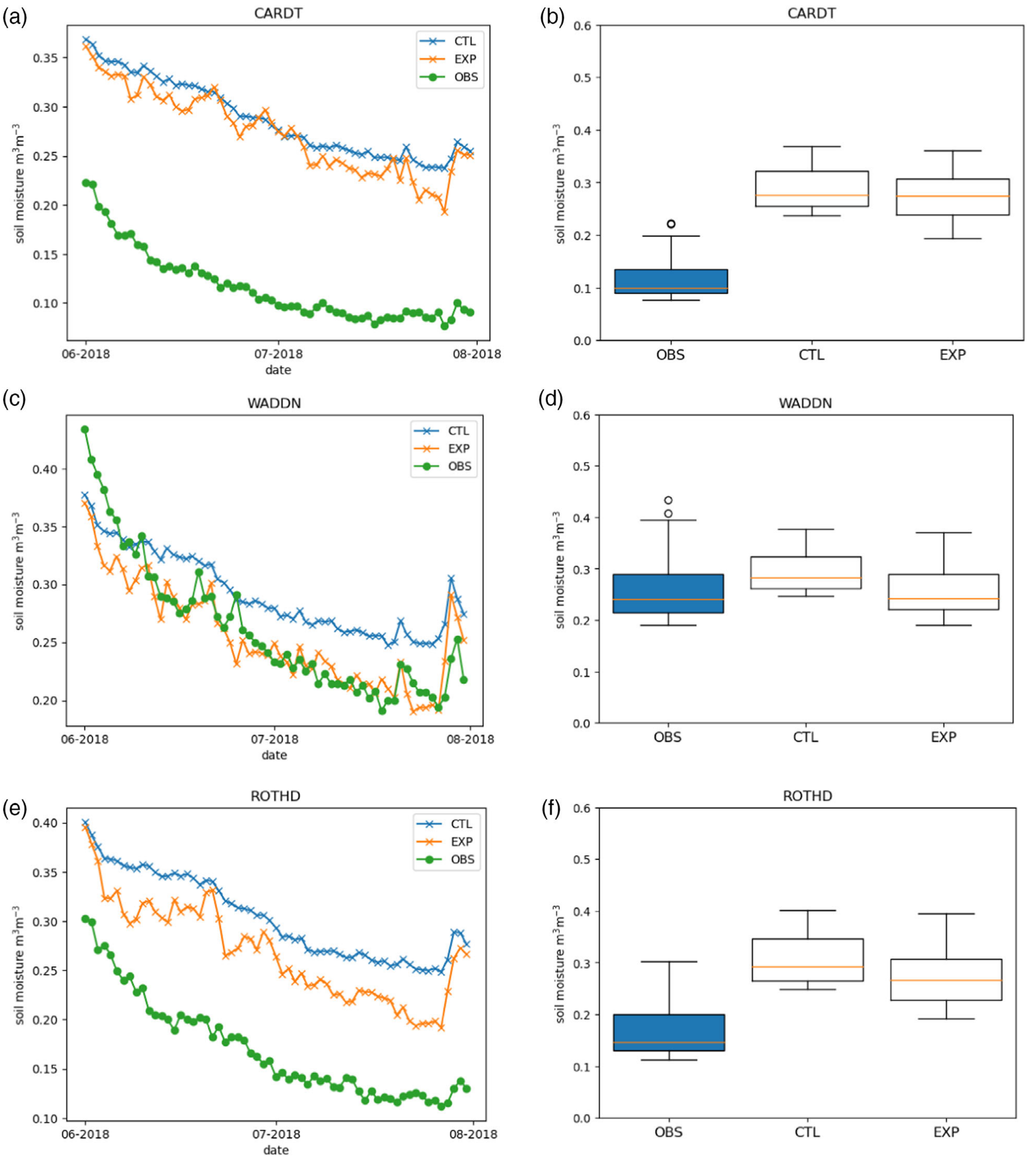


**FIGURE 2** Panels a, c and e show the daily time series during June and July 2018 for a particular site for soil moisture. The observation taken by COSMOS-UK CRNS is in green circles; the UKV is given in crosses, with the control in blue and the experiment in orange. Panels b, d and f show the same data in boxplot form. In each boxplot, the box height represents the interquartile range, or IQR (25–75 percentiles), and the whiskers represent 1.5 times the IQR. Circles give outlying values and the orange line across each box is the median value.

and/or an extension of the lower envelope of the data. This shows that the changes in moving from CTL to EXP had the desired effect, with the UKV able to access lower soil moisture estimations once the improvements were made.

In Figure 3, we show results at 21 of the 33 sites. These are sites at which the experiment changes result in the soil moisture distribution better matching the observed COSMOS equivalent. We define a better match here in that the median of the EXP soil moisture

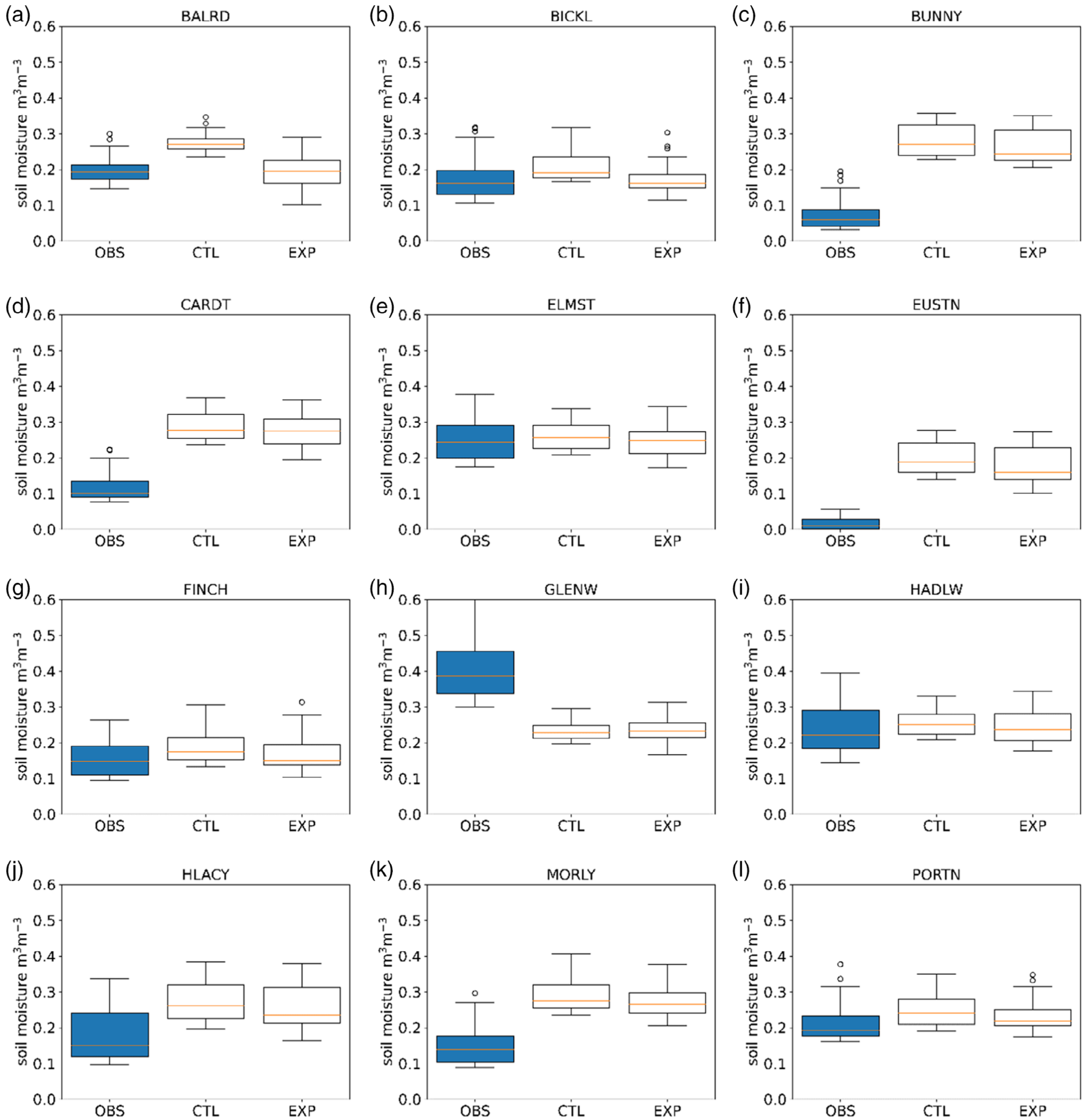


**FIGURE 3** Boxplots created as in Figure 2 for soil moisture values in the OBS, CTL and EXP in June and July 2018 at all sites in our study where the median of the EXP matches the median of the OBS better than the CTL. Site codes can be found in Table S2.

distribution is closer to the OBS distribution median than the CTL. The Inter-Quartile Range (IQR) of the EXP also matches the IQR of the OBS better at ten of these sites, as shown in Figure 3 panels c, h, i, j, l, n, o, p, r and t.

Results for the remaining 12 sites are shown in Figures 4 and 5. At these sites, the EXP does not show improvement over the CTL by comparison of the medians, with the median value of the experiment further from the OBS median than for the CTL. However, we consider the results shown in Figure 4 to be neutral cases; there are only small differences between EXP and CTL distributions at three sites: Chimney Meadows (Figure 4b), Hillsborough (Figure 4d) and North Wyke (Figure 4f). For the remaining 4 sites shown in Figure 4 (Cwm Garw (Figure 4a), Hartwood Home (Figure 4c), Hollin Hill (Figure 4e) and Plynlimon (Figure 4g)), though the median soil moisture is slightly further from the OBS median in the EXP than the CTL, the increased

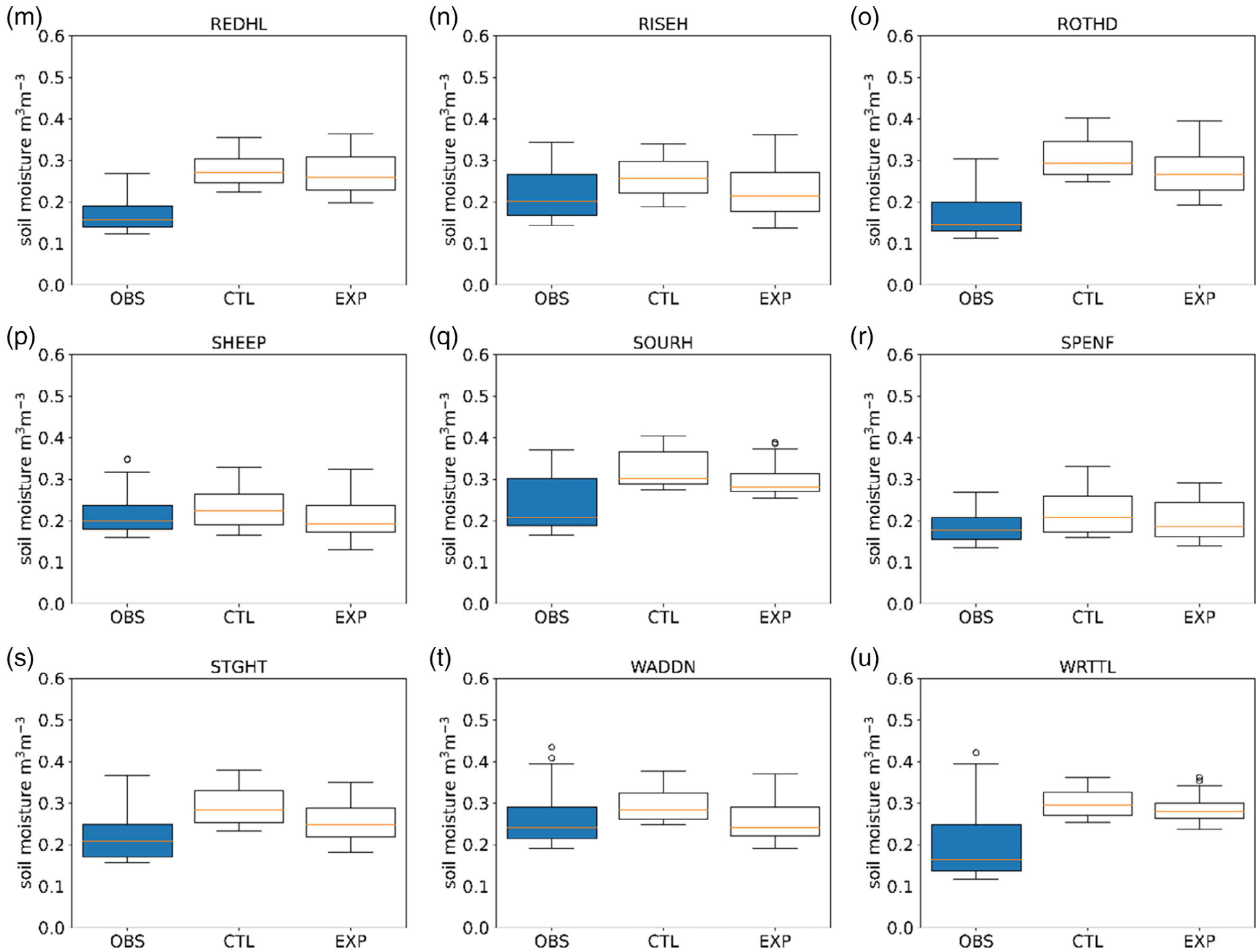


**FIGURE 3** (Continued)

range of the EXP distribution matches the OBS distribution better. Figure 5 shows results at 5 out of 33 sites where the EXP results do not match the OBS better than the CTL.

We can more rigorously analyse the similarity between the model and observations quantitatively using the Kolmogorov-Smirnov ranked significance test. Using this strict test, we can evaluate whether the CTL and EXP sample sets are from a different underlying distribution than the OBS. We chose this test, as implemented in the Python scipy.ks_2samp ("scipy.stats.ks_2samp — SciPy v1.10.0 Manual, 2023"; Virtanen et al., 2020), because it is a non-parametric test and also a rigorous statistical test even when used on a relatively small data set. The null hypothesis is that the two sample sets of data are from identical distributions; thus, if the null hypothesis is rejected, it means that the sets of data are not from identical distributions.

At the two sites, Hillsborough (Figure 4d) and Sheepdrove (Figure 3p), the null hypothesis is not rejected when the CTL is compared to OBS, that is $p > 0.05$ at these two sites; thus, we have some confidence that the CTL and OBS may be from the same distribution. However, at 8 sites, we established with 95% confidence that the null hypothesis could not be rejected for the EXP and the OBS. The 8 sites at which the EXP closely matches the OBS, with corresponding figures are as follows: Balruddery (Figure 3a), Bickley Hall (Figure 3b), Elmsett (Figure 3e), Hillsborough (Figure 4d), Riseholme (Figure 3n), Sheepdrove (Figure 3p), Spen Farm (Figure 3r) and Waddesdon (Figure 3t). The null hypothesis was rejected at the 95% confidence level for all other sites. Using this test suggests that while the CTL at two sites is similar to the observed soil moisture, the EXP model soil moisture data is superior because its distribution is closer to the observed distribution at more sites.

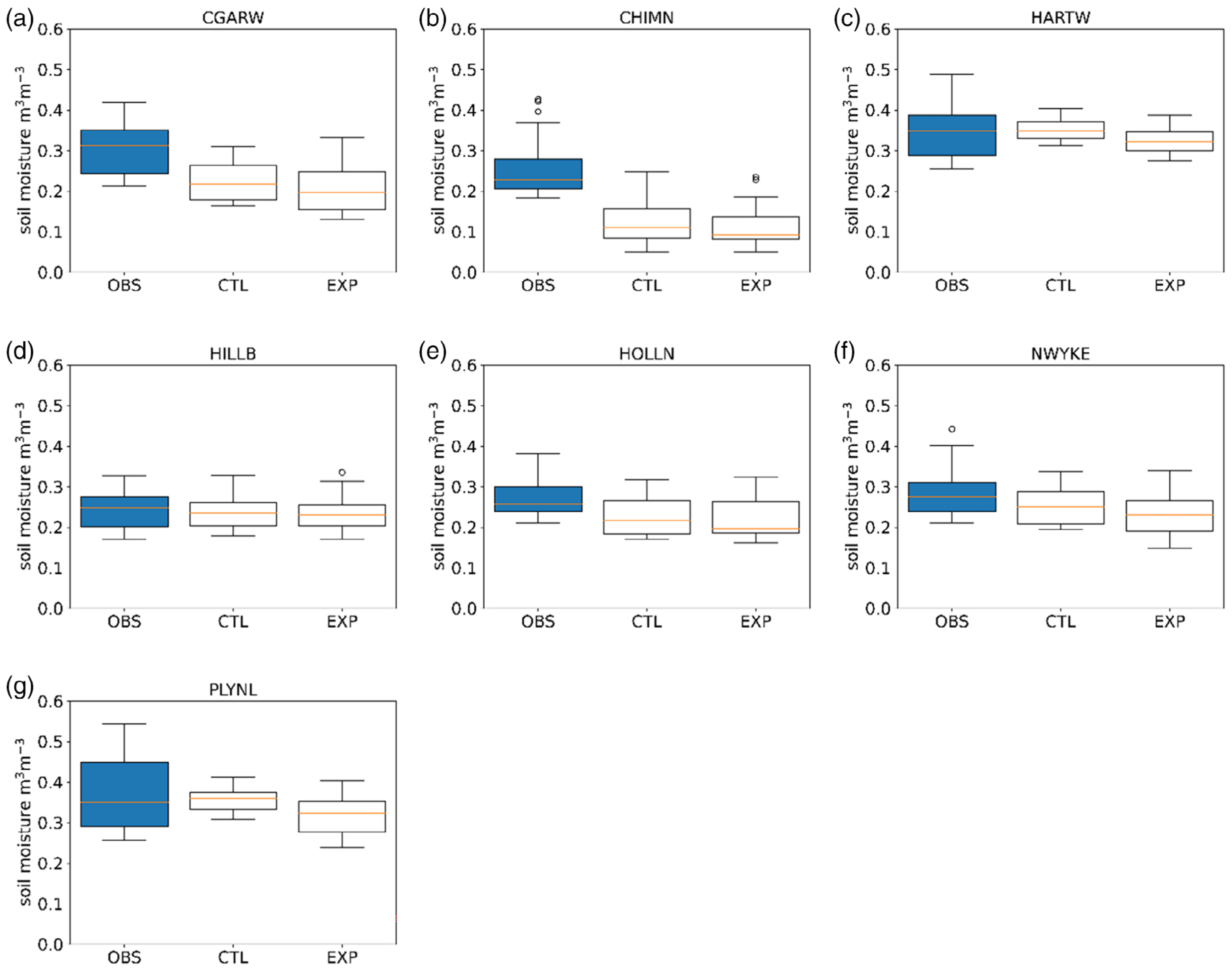


**FIGURE 4** Boxplots created as in Figure 2 for soil moisture values in the OBS, CTL and EXP in June and July 2018 at all sites in our study where the median of the experiment run does not match the median of the OBS better than the CTL, but the IQR or full range (whiskers) of the EXP appears to match the OBS better than the CTL. Site codes can be found in Table S2.

## 4 | DISCUSSION

We have compared UKV soil moisture output with independent in situ field-scale soil moisture observations from UKCEH's COSMOS-UK network, which is, to the authors' knowledge, the first independent validation of UKV soil moisture at sites across the United Kingdom.

This study is a first attempt to compare the soil moisture analyses from a state-of-the-art NWP regional modelling system to independent in situ soil moisture observations in a consistent manner (matching model soil levels to the depth reached by the CRNS sensors). Kumar et al. (2022) state that land surface variables such as soil moisture have not historically been routinely validated against ground truths, with NWP centres around the world focussed much more on the skill of forecasts with respect to atmospheric variables. However, from a flood and drought prediction perspective, the hydrological implications of soil moisture modelling and forecasting are becoming increasingly apparent. It is well known that soil moisture conditions affect infiltration, which in turn controls the magnitude and timing of runoff reaching rivers (Penna et al., 2011; Singh et al., 2021; Ward & Robinson, 2000). In this work, we take a first step towards addressing the dearth of comparisons of NWP model soil moisture to observations. Additionally, the choice of a 1.5 km NWP model and the CRNS instrument closes the gap in representativity between the model and observation footprint. By comparing only at sites where land cover within the CRNS observation footprint closely matches land cover in the corresponding UKV grid cell, we aim to reduce the representativity error between the model and observation.

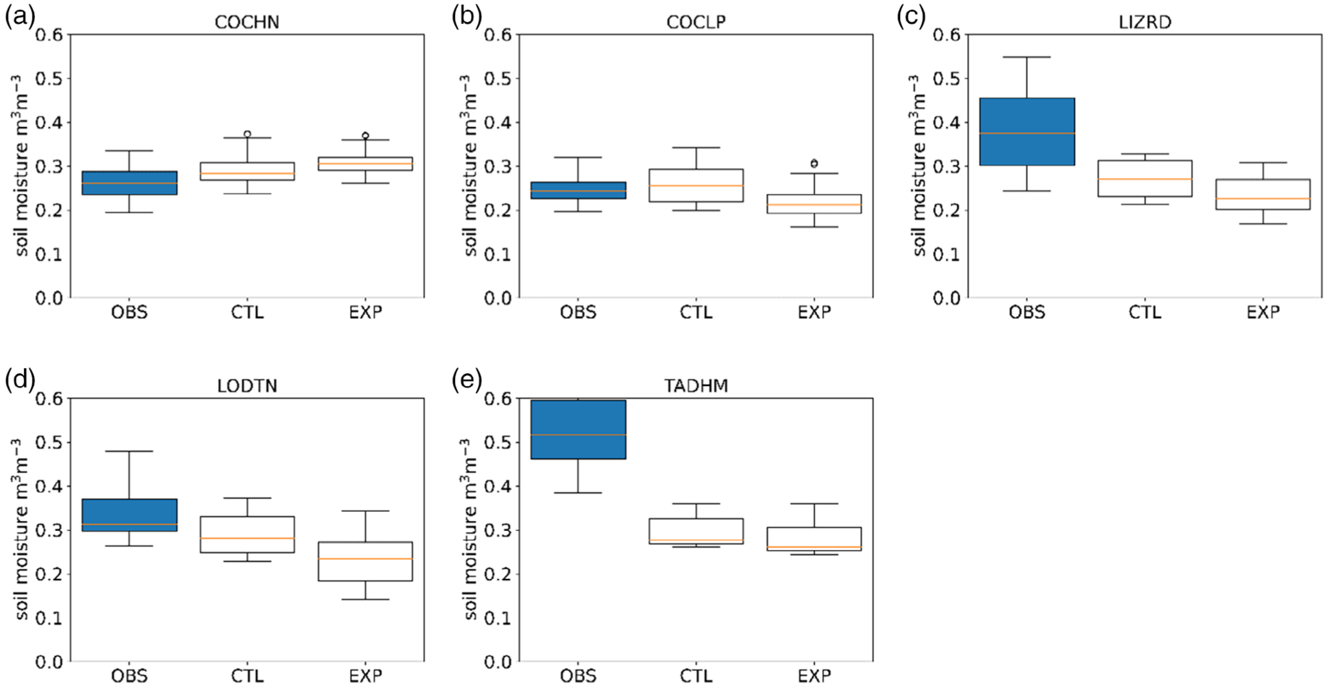


**FIGURE 5** Boxplots created as in Figure 2, for soil moisture values in the OBS, CTL and EXP in June and July 2018 at all sites in our study where the median of the EXP run does not come closer to the OBS than the median of the CTL. Site codes can be found in Table S2.

We found good agreement between the UKV and the COSMOS-UK observations, with changes between the CTL and EXP allowing the UKV modelling system to simulate drier soil conditions during the drought of 2018. We note that such dry summers may become more frequent in a changing climate (e.g. Lowe et al., 2018), and that summer 2022 was also extremely dry.

The EXP changes resulted in a match to COSMOS-UK observations that was better or neutral at 28 of the 33 sites we included in the study. In addition to showing that the model soil moisture in the UKV has been improved to match the independent observations from the COSMOS-UK CRNS network, we have shown that a regional model can simulate soil moisture that tracks a real measurement during a drought in the United Kingdom. Soil moisture should be carefully evaluated in regional NWP systems to ensure that this field is evolving correctly in partnership with the model atmosphere. Due to the increasing chance of hot summers by mid-century (Lowe et al., 2018), dry soils can couple with higher air temperatures to prolong those episodes of hot air temperatures. With heatwaves becoming more frequent, modelling systems will be required to accurately forecast heatwaves with as much lead time as possible to warn the public to take action to protect themselves. Having accurate estimates of soil moisture from these systems will become ever more important to enable realistic simulations of heatwaves.

## AUTHOR CONTRIBUTIONS

**Elizabeth Cooper:** Conceptualization; investigation; methodology; writing – original draft; writing – review and editing. **Cristina Charlton-Perez:** Conceptualization; investigation; methodology; writing – original draft; writing – review and editing. **Rich Ellis:** Conceptualization; investigation; methodology; writing – original draft; writing – review and editing.

## FUNDING INFORMATION

EC and RE acknowledge funding from the Natural Environment Research Council as part of the Hydro-JULES programmes: grant numbers NE/S017380/1 and NE/X019063/1.

## DATA AVAILABILITY STATEMENT

The Met Office UKV model output used in this study has not been made publicly available at this time. COSMOS-UK data, including the soil moisture measurements used here, are published annually and available from the NERC Environmental Information Data Centre (Dataset). https://doi.org/10.5285/5060cc27-0b5b-471b-86eb-71f96da0c80f.

## ORCID

*Elizabeth Cooper* https://orcid.org/0000-0002-1575-4222

## REFERENCES

Baatz, R., Bogena, H.R., Hendricks Franssen, H.-J., Huisman, J.A., Qu, W., Montzka, C. et al. (2014) Calibration of a catchment scale cosmic-ray probe network: a comparison of three parameterization methods. *Journal of Hydrology*, 516, 231–244.

Best, M.J., Pryor, M., Clark, D.B., Rooney, G.G., Essery, R.L.H., Ménard, C.B. et al. (2011) The joint UK land environment simulator (JULES), model description – part 1: energy and water fluxes. *Geoscientific Model Development*, 4, 677–699.

Clark, P., Roberts, N., Lean, H., Ballard, S.P. & Charlton-Perez, C. (2016) Convection-permitting models: a step-change in rainfall forecasting. *Meteorological Applications*, 23, 165–181.

Cooper, E., Blyth, E., Cooper, H., Ellis, R., Pinnington, E. & Dadson, S.J. (2021) Using data assimilation to optimize pedotransfer functions using field-scale in situ soil moisture observations. *Hydrology and Earth System Sciences*, 25, 2445–2458.

Cooper, H.M., Bennett, E., Blake, J., Blyth, E., Boorman, D., Cooper, E. et al. (2021) COSMOS-UK: national soil moisture and hydrometeorology data for environmental science research. *Earth System Science Data*, 13, 1737–1757.

De Rosnay, P., Drusch, M., Vasiljevic, D., Balsamo, G., Albergel, C. & Isaksen, L. (2013) A simplified extended Kalman filter for the global operational soil moisture analysis at ECMWF. *Quarterly Journal of the Royal Meteorological Society*, 139, 1199–1213.

Essery, R.L.H., Best, M.J., Betts, R.A., Cox, P.M. & Taylor, C.M. (2003) Explicit representation of subgrid heterogeneity in a GCM land surface scheme. *Journal of Hydrometeorology*, 4, 530–543.

Franz, T.E., Zreda, M., Rosolem, R. & Ferre, T.P.A. (2013) A universal calibration function for determination of soil moisture with cosmic-ray neutrons. *Hydrology and Earth System Sciences*, 17, 453–460.

Gómez, B., Charlton-Pérez, C.L., Lewis, H. & Candy, B. (2020) The met Office operational soil moisture analysis system. *Remote Sensing (Basel)*, 12, 3691.

Kumar, S., Kolassa, J., Reichle, R., Crow, W., Lannoy, G., Rosnay, P. et al. (2022) An agenda for land data assimilation priorities: realizing the promise of terrestrial water, energy, and vegetation observations from space. *Journal of Advances in Modeling Earth Systems*, 14, e2022MS003259.

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D. et al. (2018) UKCP18 science overview report.

McCarthy, M., Armstrong, L. & Armstrong, N. (2019) A new heatwave definition for the UK. *Weather*, 74, 382–387.

McCarthy, M., Christidis, N., Dunstone, N., Fereday, D., Kay, G., Klein-Tank, A. et al. (2019) Drivers of the UK summer heatwave of 2018. *Weather*, 74, 390–396.

Osborne, S.R. & Weedon, G.P. (2021) Observations and modeling of evapotranspiration and dewfall during the 2018 meteorological drought in southern England. *Journal of Hydrometeorology*, 22, 279–295.

Penna, D., Tromp-van Meerveld, H.J., Gobbi, A., Borga, M. & Dalla, F.G. (2011) The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences*, 15, 689–702.

Petch, J.C., Short, C.J., Best, M.J., McCarthy, M., Lewis, H.W., Vosper, S.B. et al. (2020) Sensitivity of the 2018 UK summer heatwave to local sea temperatures and soil moisture. *Atmospheric Science Letters*, 21, e948.

Porson, A., Clark, P.A., Harman, I.N., Best, M.J. & Belcher, S.E. (2010) Implementation of a new urban energy budget scheme in the MetUM. Part I: description and idealized simulations. *Quarterly Journal of the Royal Meteorological Society*, 136, 1514–1529.

scipy.stats.ks_2samp — SciPy v1.10.0 Manual. 2023. Available from: https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.ks_2samp.html [Accessed 24 January 2023].

Singh, N.K., Emanuel, R.E., Mc Glynn, B.L. & Miniat, C.F. (2021) Soil moisture responses to rainfall: implications for runoff generation. *Water Resources Research*, 57, e2020WR028827.

Tang, Y., Lean, H.W. & Bornemann, J. (2013) The benefits of the met Office variable resolution NWP model for forecasting convection. *Meteorological Applications*, 20, 417–426.

Turner, S., Barker, L.J., Hannaford, J., Muchan, K., Parry, S. & Sefton, C. (2021) The 2018/2019 drought in the UK: a hydrological appraisal. *Weather*, 76, 248–253.

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D. et al. (2020) SciPy 1.0: fundamental algorithms for scientific computing in python. *Nature Methods*, 17, 261–272.

Ward, R.M. & Robinson, M. (2000) *Principles of hydrology*. London: McGraw-Hill Publishing Company.

Zreda, M., Desilets, D., Ferré, T.P.A. & Scott, R.L. (2008) Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters*, 35, L21402. https://agupubs.onlinelibrary.wiley.com/action/showCitFormats?doi=10.1029%2F2008GL035655

Zreda, M., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Franz, T. et al. (2012) COSMOS: the cosmic-ray soil moisture observing system. *Hydrology and Earth System Sciences*, 16, 4079–4099.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Cooper, E., Charlton-Perez, C., & Ellis, R. (2024). Comparison of Met Office regional model soil moisture with COSMOS-UK field-scale in situ observations. *Atmospheric Science Letters*, e1236. https://doi.org/10.1002/asl.1236