Department for Environment Food & Rural Affairs | Department for Business, Energy & Industrial Strategy | Met Office Hadley Centre | Environment Agency

Soil Moisture and the Water Balance

This factsheet summarises the key information currently available from the UK Climate Projections over land for soil moisture as well as other water balance metrics. Read this before using any products as it describes the data availability, the key future climate changes caveats and limitations.

We recommend that users read the UKCP18 Science Overview (Lowe et al., 2018) to understand the different components of the projections and a comprehensive description of the underpinning science, evaluation and results see the UKCP18 Land Science Report (Murphy et al, 2018). References are provided for related hydrology aspects. In UKCP, water balance data are available from two strands of the land projections:

- UKCP Global (60km): a set of 28 plausible climate futures, showing how the 21st Century climate may evolve under a high emission scenario RCP 8.5. It incorporates 15 simulations of the Met Office Hadley Centre model HadGEM3 (PPE-15) and 13 other climate models selected from the CMIP5 ensemble (CMIP5-13);
- UKCP Regional (12km): are a set of 12 high resolution realisations at 12km covering the 21st Century, downscaled from the PPE-15 over the UK and Europe. These are referred to as RCM-12.

We expect water balance data to become available from UKCP Local (Kendon et al, 2019) at a future date, when we will update this factsheet. The probabilistic projections are not considered here because they do not include detailed water balance variables such as soil moisture of evaporation, as discussed in the UKCP18 Land Science Report (Murphy et al, 2018). Of the 28 Global simulations, soil moisture data is available for few of the CMIP5-13. Therefore, this document will focus on the results from the UKCP Global PPE-15 and UKCP Regional RCM-12, and although this means that a smaller range of uncertainty (derived from choice of global climate model) is sampled than for variables such as rainfall or temperature, these data represent the best available understanding of soil moisture and related variables that we currently have.

These datasets are primarily for those interested in understanding how the UKCP set of climate models simulate the hydrological cycle. Users that have used proxy measures for soil moisture (for example, metrics derived from precipitation) may wish to compare their results to this data, bearing in mind the caveats and limitations discussed below, and in the guidance and reports referenced therein.

For many other applications, such as catchment-scale water availability or flood hazard assessments, it is likely that you need to use results from bespoke hydrological models rather than using the direct output from climate models. For example, the Future Flows and Groundwater Levels project, which published a set future rivers flows and groundwater levels for the UK in 2012 using the previous set of UK Climate Projections. Note that the Enhancing the Resilience of the Water Sector to Drought Events project is in the process of updating these using the latest UK Climate Projections.

Key messages

- The Global PPE-15 and Regional RCM-12 projections show reduced soil moisture for the period 2061-2080 under a high emissions scenario (RCP 8.5), compared to 1981-2000. The projected future changes are small in winter and spring, and larger in summer and autumn. The spatial pattern of changes is similar across PPE-15 and RCM-12, with the south-eastern UK showing greater summer drying than the northwest (Figure 1).
- Soil moisture observations suitable for comparison to climate models are few, so we use proxy observations (see 'What do the projections show in recent climate?' for more details). In the recent climate (1980-2000), the Global PPE-15 and Regional RCM-12 models agree well with the proxy observations in terms of duration and magnitude of the summer dry season, but show a delay in season onset and cessation (Figure 2).
- Both sets of models provide useful information regarding the direction of future changes (drier soils). However, given the differences between the models and observations in the recent climate, confidence is lower in the magnitude (by how much soils will dry) and the timing (when drying will occur).
- When analysing soil moisture and related variables in the UKCP suite of products, we advise the use of both sets of models in any analysis and full recognition of the caveats and limitations of the datasets before using the data, for example for impacts modelling.

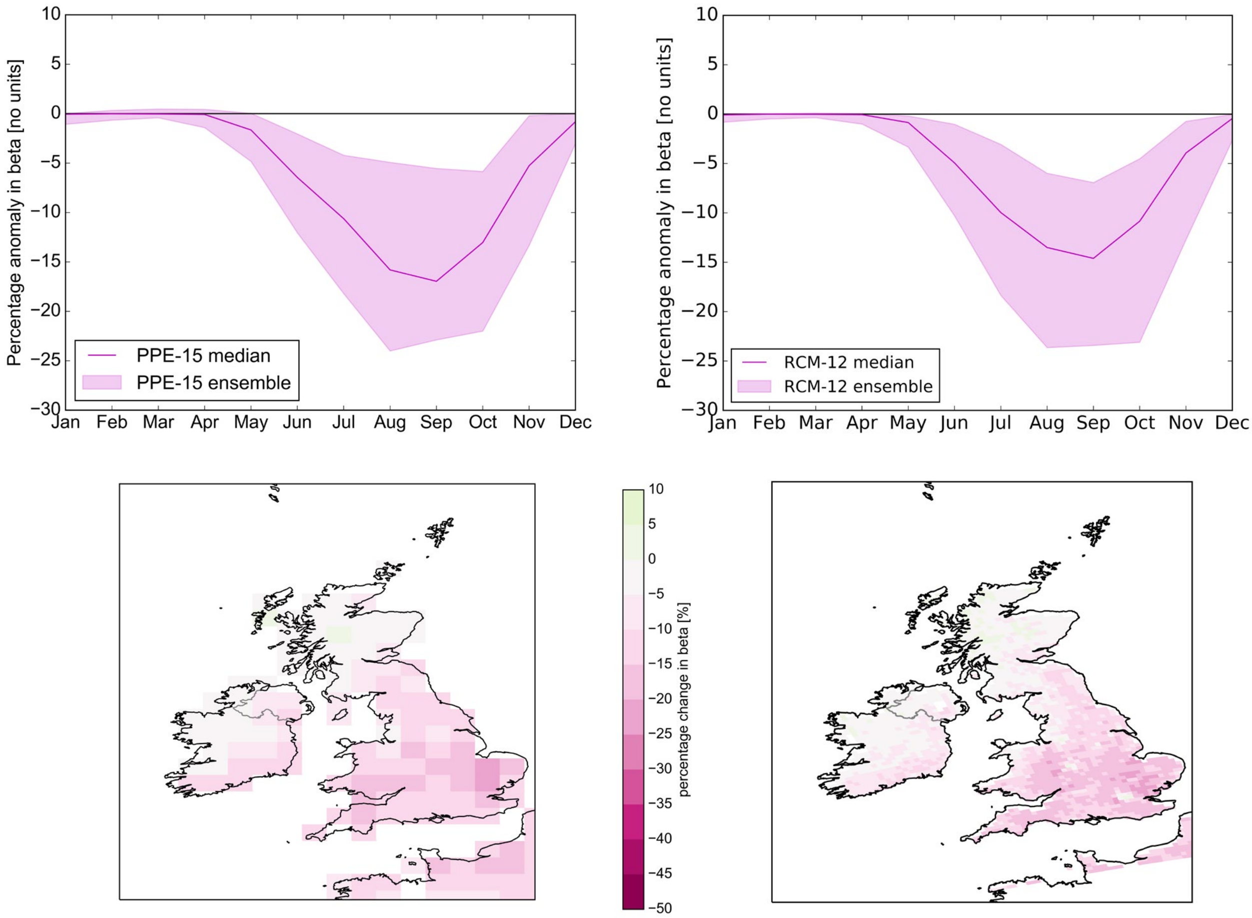


Figure 1 Top: Annual Cycles of UK percentage change in soil moisture availability factor (beta or β) with the ensemble median shown as a line and the ensemble spread shaded for [left] PPE-15 and [right] RCM-12 projections. Bottom: Maps of annual percentage change in the June-July-August median beta(β) in [left] PPE- 15 and [right] RCM-12 projections. The percentage change is the future period (2060-2080) minus the baseline (1980-2000), as a percentage of the values in the baseline.

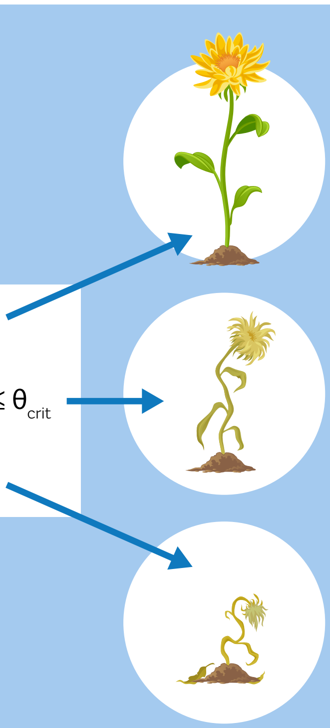
Soil moisture: what is it and why is it important?

Soil moisture is the main pathway for plants to obtain moisture, with the additional water balance variables that are available contributing to or detracting from the storage of water in soil. Soil moisture refers to the amount of moisture held in a given amount of soil, typically with units of kg kg^{-1} or m^3 m^{-3}. Given that a lack of soil moisture constrains plant growth, it can be useful to derive metrics, quantifying the lack of soil moisture relative to the expected level or the level required for optimal plant growth. One such metric is beta (β; Seneviratne et al., 2010):

Soil moisture: Beta [β]

- Compares the soil moisture content to that needed for plants to grow optimally.
- θ is the soil moisture available [m^3 water per m^3 soil]. θ_{crit} and θ_{wilt} are the critical and wilting points.
- Above θ_{crit} ($\beta > 1$), plant growth is not constrained by soil moisture.
- Between θ_{crit} and θ_{wilt} (β between 1 and 0), a plant can recover from the moisture deficit but growth will be constrained by lack of moisture.
- Below θ_{wilt} ($\beta = 0$), the plant has wilted and will not recover.

$$\beta = \begin{cases} 1 & \text{for } \theta > \theta_{crit} \\ \dfrac{\theta - \theta_{wilt}}{\theta_{crit} - \theta_{wilt}} & \text{for } \theta_{wilt} \leq \theta \leq \theta_{crit} \\ 0 & \text{for } \theta > \theta_{wilt} \end{cases}$$



Seneviratne, S. I., et al, 2010: URL https://doi.org/10.1016/j. earscirev.2010.02.004

Therefore, β describes the available soil moisture to the properties of the soil and how much water the soil can contain, therefore allowing comparison of different locations with different soil types. β is known as the soil moisture availability factor or soil moisture stress factor. It relates how much plant growth is restricted by available soil moisture, particularly modelling the extent to which photosynthesis is constrained by available moisture (Best et al., 2011, Section 2.2).

There are many metrics for soil moisture that can be used, for example soil moisture deficit. However, these often make further assumptions around the calculation of evapotranspiration and/or use empirical relationships to compare potential moisture deficits to those observed (e.g. Clarke et al., 2002). Therefore, we focus on a metric derived from the amount of moisture held in the soil, as simulated by the land-surface component of the UKCP models (further details can be found in Pirret et al., 2020). This method focusses solely on soil moisture, but gives results consistent with metrics derived from rainfall, temperature and/or other meteorological parameters.

Soil moisture is closely linked to processes in the water cycle. It has a two-way interaction with precipitation; rainfall can infiltrate and add moisture to the soil, and evaporation from wet soil adds water to the atmosphere (perhaps going through plants between the soil and the atmosphere) and the moisture can develop into clouds and precipitation.

What do the projections show in recent climate?

Observations of soil moisture that covered a large enough area over a long enough period were not available for comparing the climate models to observations. Therefore, we compare with a proxy for observations, whereby we run the land-surface part of the climate model (JULES[1]) driven by observations of the atmosphere like precipitation and temperature (using WFDEI[2] data). This allows us to explore how the land-surface model reacts to observed input compared to input from a climate model, but both will be subject to the limitations and caveats of the land-surface model.

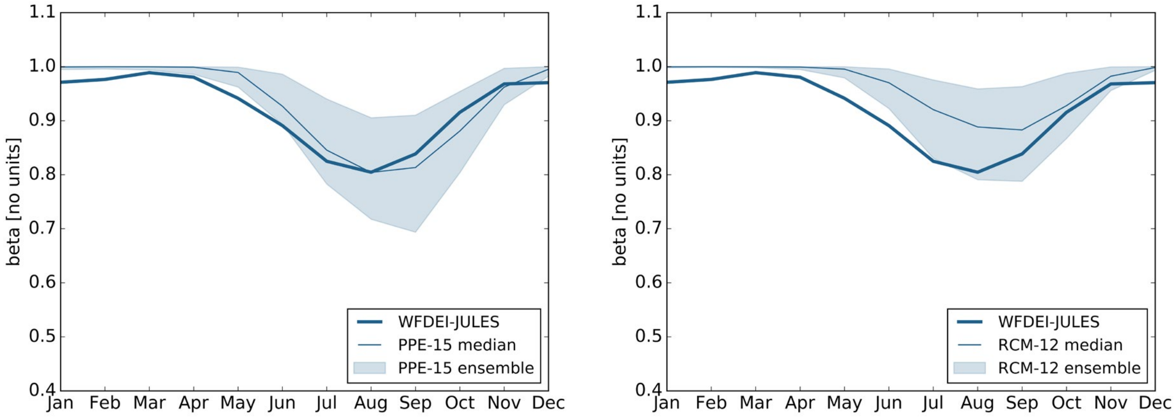


Figure 2 The annual cycles of β for the PPE-15 (left) and RCM-12 (right) models, averaged over the UK and the period 1981-2010. The WFDEI-JULES proxy observations (thick line) are compared with the model ensemble (shaded) including the ensemble median (thin line).

Figure 2 shows the UK average annual cycle of β in the model and in the WFDEI-JULES proxy observations, for the PPE-15 and RCM-12 models. In the PPE-15 models, the ensemble median average is similar in size to the proxy observations, whereas in the RCM-12 models the ensemble average is wetter and the driest members are more similar in size to the proxy observations. In both sets of models, the time when the soil starts to dry in spring and recovers in autumn is later than in WFDEI-JULES.

The timing differences are primarily driven by rainfall where the ensemble average shows too much rainfall in the winter, spring and early summer compared to observations and drier in late summer and autumn (Figure 3.15, Murphy et al., 2018). The latter causing drier soil in the late summer that takes longer to recover its moisture over the autumn. In turn, this affects the timing of surface and subsurface runoff, with the models' annual cycles lagging that of the proxy observations.

Data for evaporation and runoff (surface and subsurface) is provided alongside the soil moisture data. As discussed in Pirret et al. (2020), rainfall is also the likely driver of differences in runoff between the models and proxy observations in recent climate. There is also more rainfall in the RCM-12 compared to the PPE-15, which in turn causes the subsurface runoff to be higher in the RCM-12 than both the PPE-15 and proxy observations. In both PPE-15 and RCM-12, there is lower surface runoff and higher subsurface runoff, which could indicate that the distribution of precipitation tends towards too-low values (that is, the models drizzle too much) and light rain infiltrates more readily than heavy rain. For the two evaporation variables, the differences between models and proxy observations are more strongly linked to temperature, with moisture availability a secondary factor (Pirret et al., 2020).

[1] https://jules.jchmr.org/; Best et al. (2011)

[2] http://www.eu-watch.org/data_availability; Weedon, G. P., G. Balsamo, N. Bellouin, S. Gomes, M. J. Best, and P. Viterbo, 2014: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. Water Resources Research, 50, 7505–7514, https://doi.org/10.1002/2014WR015638

How does future climate compare to recent climate?

For soil moisture, the PPE-15 and RCM-12 models show similar magnitude changes, both projecting lower soil moisture in the summer and early autumn (Figure 1). The dry season is projected to be 'longer and deeper', as can be seen by comparing Figure 3 to Figure 2, meaning soil moisture spends a longer time below levels optimal for plant growth. This is consistent with the projected changes to precipitation, with on average drier summers causing soil moisture to become drier for longer. There are differences in the regions with largest changes in future soil moisture between the PPE-15 and RCM-12 projections, and between the different members within the two sets of projections. However, all are plausible representations of soil moisture in the future climate.

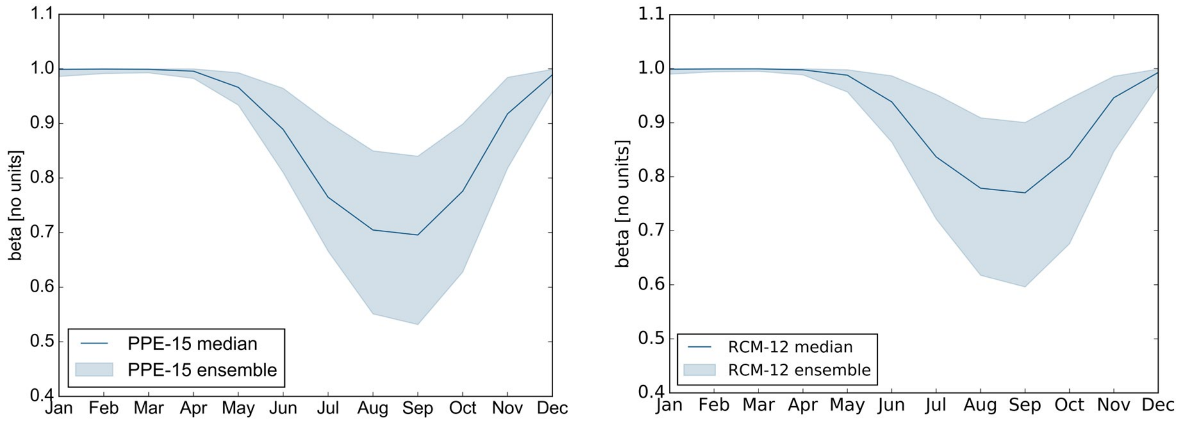


Figure 3 The annual cycles of beta (β) for the PPE-15 (left) and RCM-12 (right) models, averaged over the UK and the period 2061-2080, with model ensemble (shaded) and the ensemble median (thin line).

Evaporation is projected to increase through much of the year, related to increased temperatures under climate change. However, in the summer and early autumn, evaporation is projected to decrease due to reduced moisture availability. Evaporation from canopy changes from projected increases to decreases earlier in the year than evapotranspiration from soil, related to the latter's access to the soil moisture store. Projected changes in surface runoff show a pattern similar to rainfall, with lower values in summer and higher in winter. The subsurface runoff is projected to decrease for much of the year with slight increases in winter. Pirret et al. (2020) further discuss projected changes in these four variables.

How confident are we in the results?

Confidence in climate projections comes from: comparing the results from different climate models; comparing the climate model to observations; and understanding processes and their representation within the models. On the first count, the Global and Regional models show a consistent reduction in soil moisture for the future when averaged across the UK but, differences arise between the two sets of models in the regions that experience the greatest changes. The Global PPE-15 and Regional RCM-12 models are both driven by HadGEM3-GC3.05, and a greater breadth of uncertainty would be sampled by using data from different underlying climate models. Furthermore, these data are only available for a high emissions scenario (RCP 8.5), so emissions uncertainty is not sampled. Availability of data for soil moisture and related variables constrains the range of uncertainty that can be sampled, and the Global and Regional represent our best current insights into soil moisture.

The details of future change are uncertain as illustrated by the differences seen when comparing the models' baseline period to proxy observations, i.e. the "bias". Furthermore, the bias can be affected by model uncertainties in a broad range of processes, of which the relative importance can change over time. This means that while historical biases indicate future plausibility, they cannot guarantee credibility of future projections.

Comparing Figure 3 to Figure 2 reveals that the size of future changes in β are greater than the size of the bias. However, the bias is a significant proportion of the future changes. Therefore, confidence is high in the direction of future change (i.e. that the soil will dry) but confidence is low in the magnitude of this change (i.e. how much the soil will dry). This is particularly true when the timing of the soil moisture's drying in spring and recovery in autumn is considered; we have high confidence that the season with drier soils will be longer under a future climate, but low confidence in how the season's start and end dates are projected to change. Therefore, if metrics such as season start or end are required for impacts studies, careful consideration must be given to comparing the baseline period model simulations to observations, as well as to future projections.

This uncertainty in timing also occurs in the two evaporation variables, particularly in evapotranspiration from soil moisture store where different ensemble models respond differently due to different amounts of available soil moisture. The uncertainty in projected changes to both surface and subsurface runoff is high, due to the large ensemble spread in future climate and differences between the models and proxy observations in recent climate (Pirret et al., 2020).

What do you need to be aware of?

Whilst the projections represent the latest scientific understanding and the results have been peerreviewed by independent experts, keep in mind the caveats and limitations of the projections. Whilst our understanding and ability to simulate the climate is advancing all the time, our models are not able to represent all of the features seen in the present-day climate. This means that when including the climate projections in decision-making, consider how best to factor the capabilities and limitations of UKCP. This should be informed by a thorough understanding of the consequences of different climate outcomes – perhaps including those beyond the ranges of uncertainty presented in UKCP, for example from other modelling centres because these results may be specific to the one climate model used to generate the ensemble. See the UKCP18 Guidance: How to Use the Land Projections and the UKCP Guidance on Caveats and Limitations for further information.

Further to the caveats and limitations that apply to all UKCP data discussed above, there are some aspects of the model simulations that particularly caveat the data for soil moisture, evaporation and runoff. The models use prescribed vegetation, which means that the model does not represent how increasing atmospheric carbon or reduced soil moisture would affect vegetation, or any feedbacks that this may have on the atmosphere or land surface. For further details, see Pirret et al (2020).

Where can I find more information?

More detailed evaluation of soil moisture, evaporation and run-off can be found in Pirret et al. (2020). For further information on the latest UK Climate Projections:

- Find a summary of the key results from the UKCP website.
- Download data from the UKCP User Interface and the CEDA Data Catalogue.
- Find out more on the underpinning science from the UKCP18 Land Projections Report (Murphy et al, 2018) and Convection Permitting Report (Kendon et al., 2019).

What data are available and where can you find them?

The data availability is summarised in Table 1. You can access the datasets via the CEDA Data Catalogue but note that this requires the technical skill to analyse large datasets. The reason for this is the anticipated user of these data would be used to working with large datasets, including use of these data for comparison with offline models rather than for direct use.

	UKCP Global realisations	UKCP Regional realisations
Soil Moisture Availability Factor	β [no units]	β [no units]
Evaporation variables	Evaporation from canopy [in mm per day]	Evaporation from canopy [in mm per day]
	Evapotranspiration from soil moisture store [mm per day]	Evapotranspiration from soil moisture store [mm per day]
Runoff variables	Surface runoff [mm per day]	Surface runoff [mm per day]
	Subsurface runoff [mm per day]	Subsurface runoff [mm per day]
Geographical extent	UK, Global	UK, Europe
Co-ordinate Systems	Regular lat/lon	Rotated lat/lon
Spatial resolution	60 km	12 km
Temporal resolution	Daily, Monthly	Daily, Monthly
Period of data	1900-2100	1980-2080
Emissions scenarios	RCP8.5†	RCP8.5†

Table 1 Summary of available water balance variables for UKCP. †Further information on emissions scenarios can be found in UKCP18 Guidance: Representative concentration pathways.

This document can be cited as:

Pirret, J.S.R., Fung, F., Lowe, J.A., McInnes, R.N., Mitchell, J.F.B. and Murphy, J.M. (2020). UKCP Factsheet: Soil Moisture. Met Office.

References

Best, M.J, Pryor, M., Clark, D.B., Rooney, G.G., Essery, R.L.H., Ménard, C.B., Edwards, J.M., Hendry, M.A., Porson, A., Gedney, N., Mercado, L.M., Sitch, S., Blyth, E., Boucher, O., Cox, P.M., Grimmond, C.S.B. and Harding, R.J. (2011): The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geoscientific Model Development, 4, 677–699, https://doi.org/10.5194/gmd-4-677-2011

Clark, C. (2002). Measured and estimated evaporation and soil moisture deficit for growers and the water industry. Meteorological Applications 9, 85–93 URL https://doi.org/10.1017/S1350482702001093

Kendon, E.J., Fosser, G., Murphy, J.M., Chan, S., Clark, R.T., Harris, G.R., Lock, A., Lowe, J.A., Martin, G., Pirret, J.S.R., Roberts, N., Sanderson, M. and Tucker, S. (2019). UKCP Convection-permitting model projections: Science report. Met Office. Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP-Convection-permittingmodel-projections-report.pdf

Lowe, J.A., Bernie, D., Bett, P.E., Bricheno, L., Brown, S., Calvert, D., Clark, R.T., Eagle, K.E., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G.R., Howard, T., Kaye, N., Kendon, E.J., Krijnen, J., Maisey, P., McDonald, R.E., McInnes, R.N., McSweeney, C.F., Mitchell, J.F.B., Murphy, J.M., Palmer, M., Roberts, C., Rostron, J.W., Sexton, D.M.H., Thornton, H.E., Tinker, J., Tucker, S., Yamazaki, K. and Belcher, S. (2018). UKCP18 Science Overview report. Met Office. Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E.J., Bett, P.E., Clark, R.T., Eagle, K.E., Fosser, G., Fung, F., Lowe, J., McDonald, R.E., McInnes, R.N., McSweeney, C.F., Mitchell, J.F.B., Rostron, J.W., Thornton, H.E., Tucker, S. and Yamazaki, K. (2018). UKCP18 Land Projections: Science Report. Met Office. Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf

Pirret, J.S.R., Fung, F., Mitchell, J.F.B. and McInnes, R.N. (2020): Soil Moisture and the Hydrological Cycle in the UKCP Global and Regional Models. In review.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews, 99, 125–161, URL https://doi.org/10.1016/j.earscirev.2010.02.004

