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Grid-based simulation of soil moisture in the UK: future changes in extremes and wetting and drying dates

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Abstract

Soil moisture, typically defined as the amount of water in the unsaturated soil layer, is a central component of the hydrological cycle. The potential impacts of climate change on soil moisture have been less specifically studied than those on river flows, despite soil moisture deficits/excesses being a factor in a range of natural hazards, as well as having obvious importance for agriculture. Here, 1 km grids of monthly mean soil moisture content are simulated using a national-scale grid-based hydrological model, more typically applied to look at changes in river flows across Britain. A comparison of the soil moisture estimates from an observation-based simulation, with soil moisture deficit data from an operational system developed by the UK Met Office (Meteorological Office Rainfall and Evaporation Calculation System; MORECS), shows relatively good correspondence in soil drying and wetting dates, and in the month when soils are driest. The UK Climate Projections 2018 Regional projections are then used to drive the hydrological model, to investigate changes in occurrence of indicative soil moisture extremes and changes in typical wetting and drying dates of soils across the country. Analyses comparing baseline (December 1981–November 2011) and future (December 2050–November 2080) time-slices suggest large increases in the spatial occurrence of low soil moisture levels, along with later soil wetting dates, although changes to soil drying dates are less clear. Such information on potential future changes in soil moisture is important to enable the development of appropriate adaptation strategies for a range of sectors vulnerable to soil moisture levels.

1. Introduction

Soil moisture is an integral part of the hydrological cycle, controlling the division of precipitation into runoff, evapotranspiration and recharge (Holsten *et al* 2009, Hughes *et al* 2021). It is typically defined as the amount of water in the unsaturated soil layer (Seneviratne *et al* 2010). Levels of soil moisture are important for various reasons, and both deficits and excesses can cause issues. Soil moisture influences natural hazards like subsidence/heave (Pritchard *et al* 2015), landslides (Ray and Jacobs 2007), and flood occurrence (Ledingham *et al* 2019), as well as fire risk in peat soils (Turetsky *et al* 2015, Soulsby *et al* 2021). It also has obvious importance for regulating plant growth and nutrient uptake (Grillakis 2019), where soil moisture deficits can cause plant stress and reduce plant growth, while excesses can restrict the availability of oxygen to plant roots and so also reduce plant growth (Piniewski *et al* 2020). Soil moisture levels are also important for crop sowing, tillage, harvest, and irrigation demand, so the timing of any deficits or excesses can affect different crops differently (Piniewski *et al* 2020). As such, soil moisture is the key factor affecting crop yield in rain-fed agriculture (Piniewski *et al* 2020), which accounts for about 75% of the total agricultural area worldwide (Portmann *et al* 2010).

There has been a significant amount of research on the potential impacts of climate change on river flows, but less specifically on soil moisture. Global studies include that of Gerten *et al* (2007), who suggest decreases in soil moisture in many regions by 2071–2100, with regional patterns varying between global climate models (GCMs). For Europe, Samaniego *et al* (2018) analyse the soil moisture index

(SMI) and show that a 3 K increase in global mean surface temperature above pre-industrial levels leads to a 40% increase in drought area compared to the impacts under a 1.5 K increase. Similarly, Grillakis (2019) shows that SMI worsens across Europe, in terms of occurrence, extent and duration, with greater changes in eastern Europe and the Mediterranean.

Studies for smaller regions include Mimeau *et al* (2021), who use a sensitivity-based approach for ten sites in southern France and show that scenarios consistent with climate models lead to decreased soil moisture and an increase in the days per year with dry soils. Holsten *et al* (2009) use a semi-distributed eco-hydrological model to simulate soil moisture in part of Germany, and show a decreasing historical trend (1951–2003), with mid-century GCM projections suggesting further decreases. Similarly, Jasper *et al* (2006) use a distributed hydrological model and two GCMs to simulate soil moisture for a river-basin in Switzerland, and show decreases in many areas by 2081–2100, with the magnitude related to land use, soil type and slope. Piniewski *et al* (2020) use Euro-Cordex Regional Climate Model (RCM) projections and the Soil & Water Assessment Tool (SWAT) to assess the effect of soil moisture deficits and excesses on yields for four crops in Poland, at the times of year critical for each. For three crops they show a general increase in the severity of SMDs and the total area affected.

For the UK, Arnell and Freeman (2021) look at agro-climatic indicators including 'potential soil moisture deficit' (PSMD) and 'number of days with wet soils'. They show that PSMD increases substantially in future, and wet soil days decreases, with greater decreases for clay-loam than sandy or shallow soils. Rudd *et al* (2019) use a grid-based hydrological model to look at soil moisture droughts across Great Britain (GB) using large climate ensembles, and show future increases in drought severity everywhere, with large increases in drought intensity in the south-east. Naden and Watts (2001) use a simple hydrological model to simulate soil moisture at five sites across GB for two future time-slices, and show a small increase at the most northern site and marked reductions for the three southerly sites. The largest soil moisture changes were on clay soils, with slope also a factor. Changes in moisture levels in clay soils are particularly important for subsidence/heave, and Pritchard *et al* (2015) suggest that future increases in clay-related subsidence hazards are likely to be greatest in south-east England.

This study looks at potential future changes in soil moisture across the UK, using a national-scale grid-based hydrological model that simulates soil moisture across a wide area in a consistent way. The latest UK Climate Projections are applied (UKCP18; Lowe *et al* 2018), and the 1 km grids of model-simulated monthly mean soil moisture are used to investigate changes in occurrence of indicative soil moisture extremes, along with changes in typical wetting and drying dates of soils across the country.

2. Methods

2.1. Hydrological model

The Grid-to-Grid (G2G) is a national-scale hydrological model that usually runs on a 1 km grid at a 15 min time-step, and is parameterized using digital datasets (e.g. soil types, land-cover) (Bell *et al* 2009). The model was originally developed for GB, but a version was recently established for Northern Ireland (NI) and the parts of the Republic of Ireland that drain into NI (Kay *et al* 2021a). The GB and NI versions are applied here (each aligned with the GB national grid), including a snow module (Bell *et al* 2016).

G2G assumes that soil properties vary spatially. Soil depth can vary from a few centimetres to several metres, and G2G soil moisture estimates should be interpreted as depth-integrated values for the whole soil column. The soil moisture is output as a fractional volumetric water content θ (m water/m soil). See supp. section 1.1 for further detail. Output gridded time-series of monthly mean θ, derived as monthly averages of simulated 15 min θ, are investigated here.

Hydrological model evaluation typically focuses on simulated flows, as (a) long-term observed flows are usually available, (b) flow is the accumulation from upstream so assesses a wider area, and (c) flow is usually the variable of most interest (Grillakis 2019). G2G has been shown to perform well in terms of river flows for a wide range of catchments across Britain (Bell *et al* 2009, 2016, Rudd *et al* 2017), particularly those with reasonably natural regimes as it does not typically include artificial influences (Rameshwaran *et al* 2022). Direct evaluation of simulated soil moisture is more difficult, as there is usually a lack of long-term spatial observed data (Grillakis 2019) and remotely sensed data are typically limited to the top few centimetres of soil (Al-Sharafany 2021). There can also be conceptual differences between the model variables and properties that can be measured (Dankers and Kundzewicz 2020).

2.2. Observation-based simulation

The model requires gridded time-series of precipitation, potential evaporation (PE), and temperature (T). An observation-based simulation (hereafter 'SIMOBS'; Kay *et al* 2021b) is performed for GB and NI for December 1980–November 2011, using the following datasets derived from meteorological station data:

- Daily 1 km grids of precipitation (CEH Gridded Estimates of Areal Rainfall, CEH-GEAR; Tanguy *et al* 2016), divided equally over each model time-step within a day.

- Monthly 40 km grids of short grass PE (Meteorological Office Rainfall and Evaporation Calculation System, MORECS; Hough and Jones 1997), copied down to the 1 km grid and extended where necessary by copying from the nearest 1 km box with data, then divided equally over each model time-step within a month.
- Daily 1 km grids of min and max T (HadUK-Grid; Met Office *et al* 2019), interpolated through the day using a sine curve.

For NI some adjustments are required (see supp. section 1.2). The GB and NI simulations are initialised using a states file saved at the end of a prior observation-based run (January 1970–November 1980).

2.3. Climate change simulations

Daily precipitation, PE, and min and max T data derived from the UKCP18 Regional projections (Met Office Hadley Centre 2018) are used to drive the G2G hydrological model for December 1980–November 2080. The same state initialisation file is used for each RCM-based simulation (hereafter 'SIMRCM'; Kay *et al* 2022) as for SIMOBS. The SIMRCM baseline period is December 1981–November 2011 (with a year excluded as spin-up), and the SIMRCM future period is December 2050–November 2080.

The climate projections comprise a 12-member perturbed parameter ensemble (PPE) of the Hadley Centre RCM for December 1980–November 2080, with 2006 onwards using RCP8.5 emissions (Riahi *et al* 2011). The RCM PPE is nested in an equivalent GCM PPE, and ensemble members are numbered 01–15, with 01 the standard parameterisation. The alternative parameter sets were designed using both plausibility and diversity principles, but there are no RCM equivalents for GCM PPE members 02, 03 and 14 (Murphy *et al* 2018; section 4.3). The data are available on the native ∼12 km rotated lat–lon climate model grid and re-projected onto a 12 km grid aligned with the GB national grid—the latter are used here. The 12 km RCM precipitation are bias-adjusted to match CEH-GEAR using monthly correction factor grids (Kay 2021, Kay *et al* 2021a), then downscaled to 1 km using average annual rainfall patterns (Bell *et al* 2007) and temporally downscaled as for observed data. The 12 km RCM T are downscaled to 1 km using a lapse rate with elevation, and temporally downscaled as for observed data. The 12 km RCM PE is estimated from daily climate variables using a formulation closely replicating MORECS (as Robinson *et al* 2021 but using the bias-adjusted precipitation for the interception component) and including potential future increases in stomatal resistance (Rudd and Kay 2016), then spatially and temporally downscaled as for observed data.

2.4. Analysis of simulated soil moisture

The simulated 1 km gridded time-series of monthly mean θ are first turned into grids of time-slice mean θ for each month. That is, for each 1 km box and each month, the mean of the 30 θ in a time-slice is calculated, for the SIMOBS baseline and for the SIMRCM baseline and future for each ensemble member. Three features of the monthly time-slice mean θ are then examined, for each 1 km box:

(a) Whether the maximum monthly time-slice mean θ (θ_{max}) exceeds an estimate of field capacity (θ_{fc});
(b) Whether the minimum monthly time-slice mean θ (θ_{min}) goes below an estimate of residual soil moisture (θ_r); and
(c) The drying and wetting dates for time-slice mean θ, relative to a baseline threshold (θ_{thresh}) which defines a value 'near field capacity'.

The estimates of θ_{fc} and θ_r for each 1 km box are as in G2G (supp. section 1.1). These values should be considered indicative only, but are useful as fixed thresholds for analysing the occurrence of more extreme soil moisture levels. The threshold for soil drying and wetting dates (θ_{thresh}) is set using the simulated baseline θ (section 2.4.1).

The performance of SIMOBS is assessed against MORECS (section 2.4.1). Then baseline SIMRCM is assessed against SIMOBS, and potential future changes are investigated by comparing baseline and future SIMRCM. This is done for the occurrence of soil moisture extremes (section 2.4.2) and for drying and wetting dates (section 2.4.3).

2.4.1. Performance of observation-based simulation

To assess G2G performance for soil moisture, the SIMOBS θ are compared to MORECS soil moisture deficit (SMD) data. SMD represents the effective rainfall needed to bring soil moisture back to field capacity (supp. section 1.1). MORECS is an operational system developed by the UK Met Office to provide weekly and monthly model-based estimates of evaporation and SMD on a 40 km grid (Hough and Jones 1997), using meteorological data from a set of stations across the country, together with Penman–Monteith PE estimates and a set of crop models (Hough *et al* 1997). Here, MORECS 40 km estimates of month-end SMD are available across GB (190 boxes; GB national grid) and NI (11 boxes; Irish national grid), for a short grass land-cover and soils with the median available water content (AWC) within each grid box (AWC considers plant rooting depths and the suction with which water is held within a soil, so depends on land-cover and soil texture). The comparison looks at the typical drying and wetting dates (derived as below), and the month when soils are driest (minimum θ, maximum SMD).

Bayliss and Jones (1993) use MORECS 1961–1990 time-slice mean month-end SMD to map typical wetting dates for GB, showing that soils return to near field capacity earlier in the north/west than in the south/east. They use an SMD threshold of 10 mm to represent 'near field capacity' (0 mm is field capacity, but that threshold cannot be used since time-slice mean SMDs are generally non-zero). Here, a similar method derives both drying and wetting dates for 1981–2010. To ensure that dates can be derived for every 40 km box, the threshold is set according to the max and min time-slice mean values; $SMD_{thresh} = 0.9^{*}SMD_{min} + 0.1^{*}SMD_{max}$ (i.e. lying between the min and max, close to the min—'near field capacity'). The month-end SMD are linearly interpolated between months, and the approximate drying (wetting) dates are extracted according to when the interpolated values cross SMD_{thresh} from below to above (above to below).

Similarly, for analysis of SIMOBS θ a threshold is set according to the max and min of the monthly time-slice mean values; $\theta_{thresh} = 0.2^{*}\theta_{min} + 0.8^{*}\theta_{max}$ (i.e. lying between the min and max, close to the max). The monthly θ are linearly interpolated between months (assuming they apply mid-month), and the approximate drying (wetting) dates are extracted according to when the interpolated values cross θ_{thresh} from above to below (below to above). The weights on min and max for SIMOBS θ and MORECS SMD are different because SMD cannot go below zero (field capacity), whereas θ can go above field capacity. Different weights were tested, and the above gave the best overall match for drying and wetting dates. The SIMOBS θ analysis is performed at 1 km and after averaging θ to 40 km, to improve comparability with 40 km MORECS data. Figure 1 shows examples of the derivation of drying and wetting dates for a sample of locations across GB, for both MORECS SMD and SIMOBS θ (see supp. figure 1 for NI examples).

2.4.2. Analysis of soil moisture extremes

The assessment of performance for occurrence of soil moisture extremes compares maps of where SIMOBS time-slice mean $\theta_{max} > \theta_{fc}$ or $\theta_{min} < \theta_{r}$ to maps of the number of baseline SIMRCM ensemble members where $\theta_{max} > \theta_{fc}$ or $\theta_{min} > \theta_{r}$. To assess potential future changes in occurrence of soil moisture extremes, the baseline SIMRCM counts are compared to future SIMRCM counts.

2.4.3. Analysis of soil drying and wetting dates

For each baseline SIMRCM, θ_{thresh} is derived from θ_{min} and θ_{max} in the same way as for SIMOBS (section 2.4.1), to ensure that drying and wetting dates can be derived for all 1 km boxes and all baseline SIMRCM (although θ_{max} is limited to August–March to avoid anomalous values in late spring/early summer in some ensemble members for a very limited number of higher altitude locations, which are possibly related to snowmelt). Distributions of drying and wetting dates from the SIMRCM ensemble and SIMOBS are compared.

To assess potential future changes in drying and wetting dates, the θ_{thresh} derived for each baseline SIMRCM are applied for the corresponding future SIMRCM. Figure 2 shows examples of baseline and future drying and wetting dates for locations across GB, for member 01 (figure 2(a)) and the ensemble range (figure 2(b)) (see supp. figure 2 for NI examples). Distributions of dates from the baseline and future SIMRCM ensembles are then compared. Note that, for some 1 km boxes, future dates cannot be derived as the future time-slice mean θ is always below θ_{thresh} (e.g. point 8 in figure 2(a)).

3. Results

3.1. Performance of observation-based simulation

SIMOBS gives relatively similar drying and wetting dates to MORECS for GB (figures 3(a) and (b)); the mean difference across GB is approximately −11 d for the drying date and −4 d for the wetting date, with SIMOBS tending to give slightly earlier dates in each case. The spatial patterns of wetting dates are very similar, with dates as early as September/October in the north/west and as late as December/January in the east. There is a bit more difference in the drying dates, with MORECS dates predominantly in April, but SIMOBS giving more in March. The month when soils are driest shows good correspondence between SIMOBS and MORECS, and is typically August in the south-east and June in the north-west (figure 3(c)). The spatial patterns in the drying/wetting dates and the driest month are related to the spatial distributions of precipitation (generally higher in the north/west) and soil types (more variable, and often deeper, in the south/east). See supp. section 2.1 and supp. figure 3 for NI performance, which is similar to that for GB.

Note that the MORECS data are for median AWC soils; the AWC range in each 40 km box was derived from a 1 km soil database, from which the median was used (Hough and Jones 1997). The 1 km SIMOBS data will obviously show more spatial variation than the 40 km MORECS data, but even averaging the SIMOBS θ to 40 km before analysis may not be equivalent to the median AWC soil used by MORECS.

3.2. Analysis of soil moisture extremes

Maps of the number of SIMRCM baseline ensemble members where $\theta_{max} > \theta_{fc}$ or $\theta_{min} < \theta_{r}$ show relatively good correspondence with this occurrence for SIMOBS (figure 4(a)). Bar charts of the percentage of 1 km boxes (across GB and NI) in each case show that SIMRCM tends to give a slightly larger percentage area for $\theta_{max} > \theta_{fc}$ than SIMOBS, but a closer match

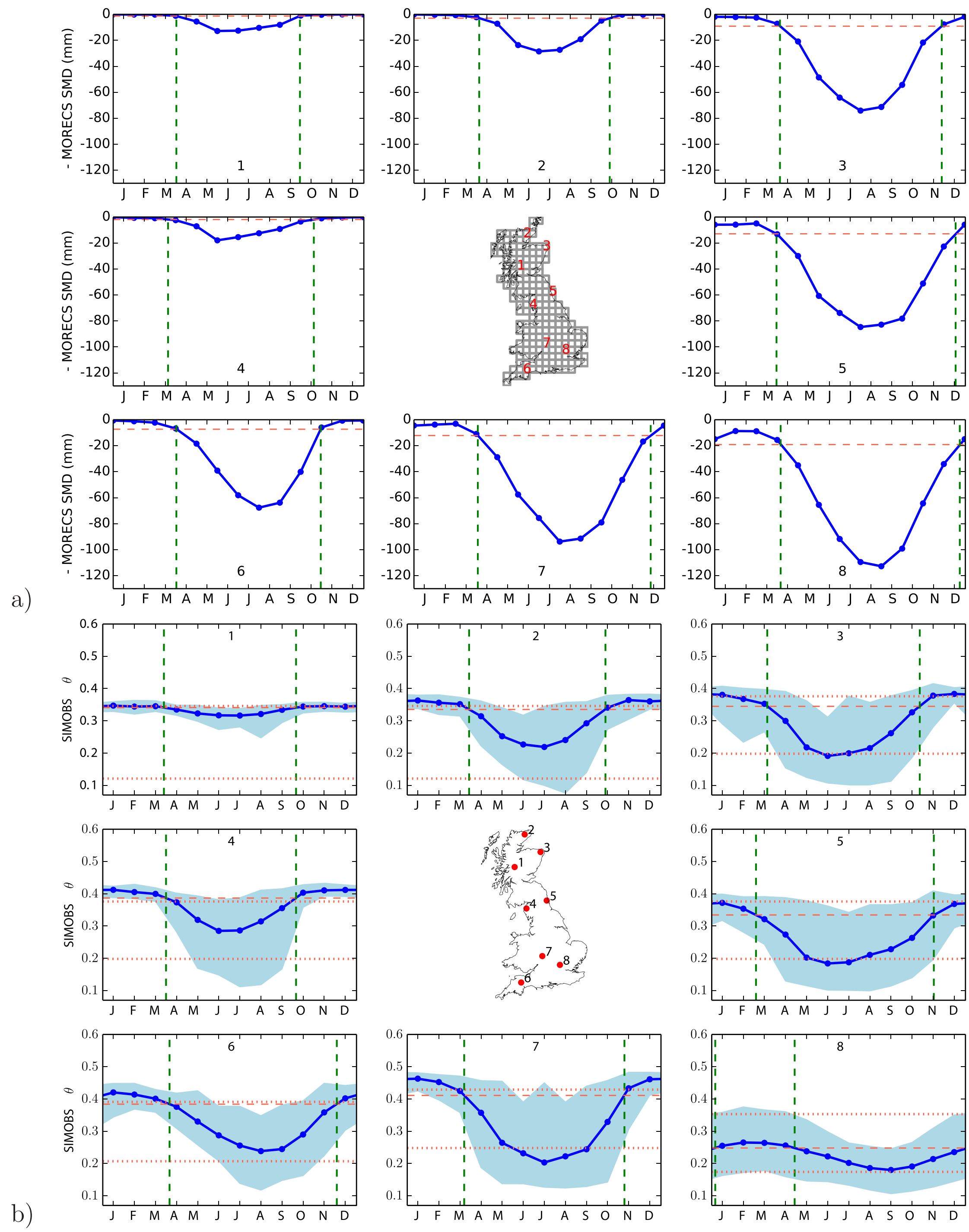

Figure 1. Example monthly soil moisture profiles and drying and wetting dates for locations across GB for (a) MORECS SMD (mm) and (b) SIMOBS θ (m water/m soil). Each plot shows the monthly time-slice mean SMD or θ (blue solid line/dots), the threshold used for deriving the drying and wetting dates (red dashed horizontal line) and the derived dates (green dashed vertical lines). Note that the MORECS SMDs are plotted as negative values, for easier comparison with θ, and (b) also shows the time-slice min-max range of monthly θ (blue shading), and the θ_{fc} and θ_r values (red dotted horizontal lines).

for the percentage area where $\theta_{min} < \theta_r$, although with a wider range of variation across the SIMRCM ensemble (figure 4(b)).

For SIMRCM future, there is little change in the locations where $\theta_{max} > \theta_{fc}$, but a substantial increase in the locations where $\theta_{min} < \theta_r$, when compared to SIMRCM baseline (figure 4). Coverage in the latter case more than doubles, from 31% to 66% of the country (figure 4(b)), spreading from south/east England to include much more of England, Wales and NI (figure 4(a)). The future increased spread of locations where $\theta_{min} < \theta_r$ is illustrated by points 3, 4 and 6 in figure 2(b), which also suggests that the simulated future soil moisture decreases are significant, as the baseline and future SIMRCM ranges often do not overlap.

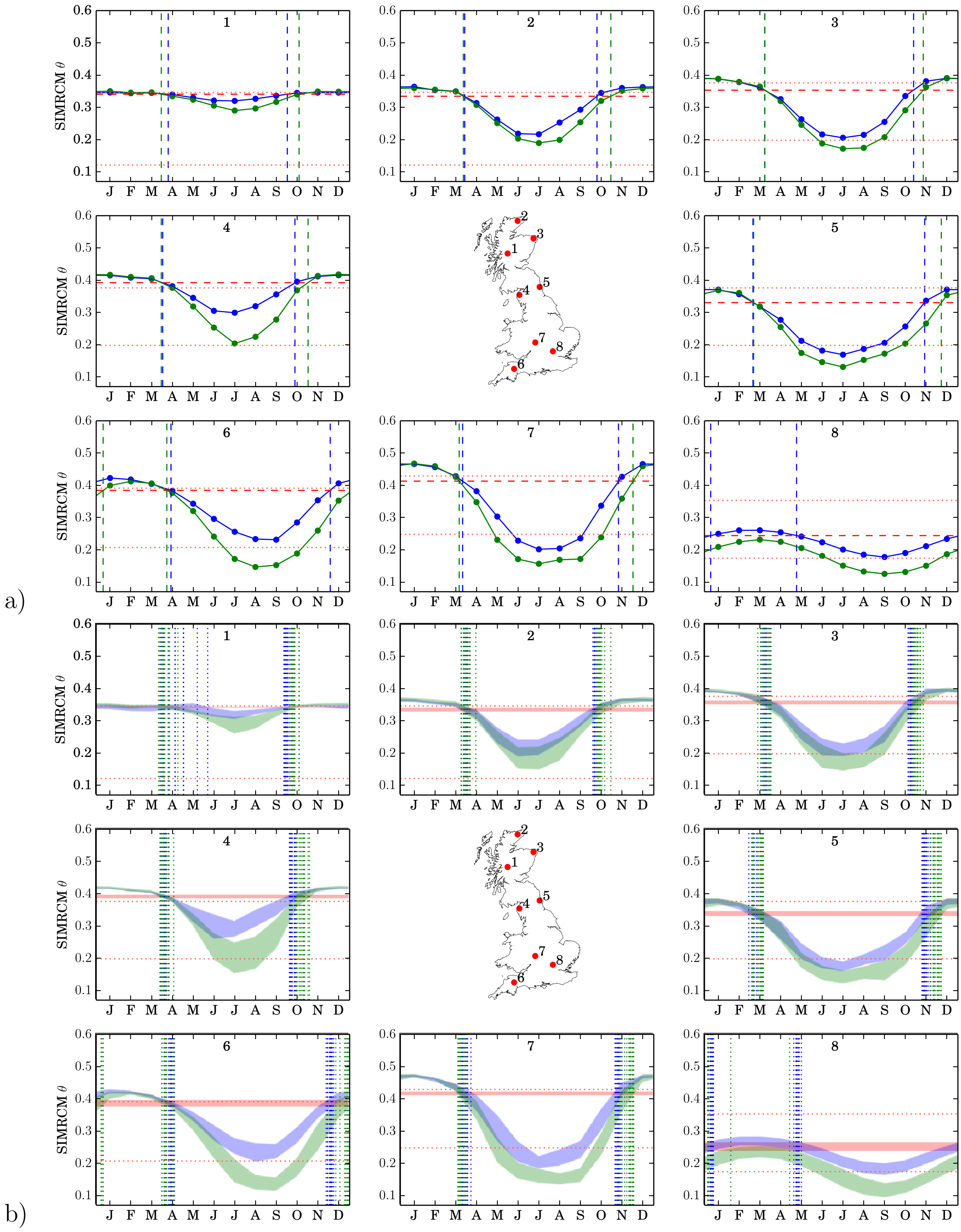

Figure 2. Example monthly soil moisture profiles and drying and wetting dates for locations across GB, for baseline (blue) and future (green) time-slices from (a) SIMRCM 01, and (b) the SIMRCM ensemble range. Each plot shows the monthly time-slice mean θ (solid lines/dots or shading), the threshold used for deriving the drying and wetting dates (red dashed horizontal line or shading), and the derived dates (dashed vertical lines). The θ_{fc} and θ_{r} values are also shown (red dotted horizontal lines).

3.3. Analysis of soil wetting and drying dates

Since θ_{thresh}, the threshold used for the drying and wetting date analysis (section 2.4), is derived separately for SIMOBS and each SIMRCM, these are first compared (supp. section 2.1). Maps show substantial similarity between θ_{thresh} for all SIMRCM members and SIMOBS (supp. figure 4). Figure 2(b) shows relatively small variations in θ_{thresh} between ensemble members (red shading) for example locations across GB, although it varies by location.

Histograms showing the distribution of drying and wetting dates through the year, for 1 km boxes across the UK, show good correspondence between SIMOBS and baseline SIMRCM for the wetting date, but the baseline SIMRCM drying dates are often a little later in the year than for SIMOBS (figure 5). This can be seen in maps of the dates (supp. figures

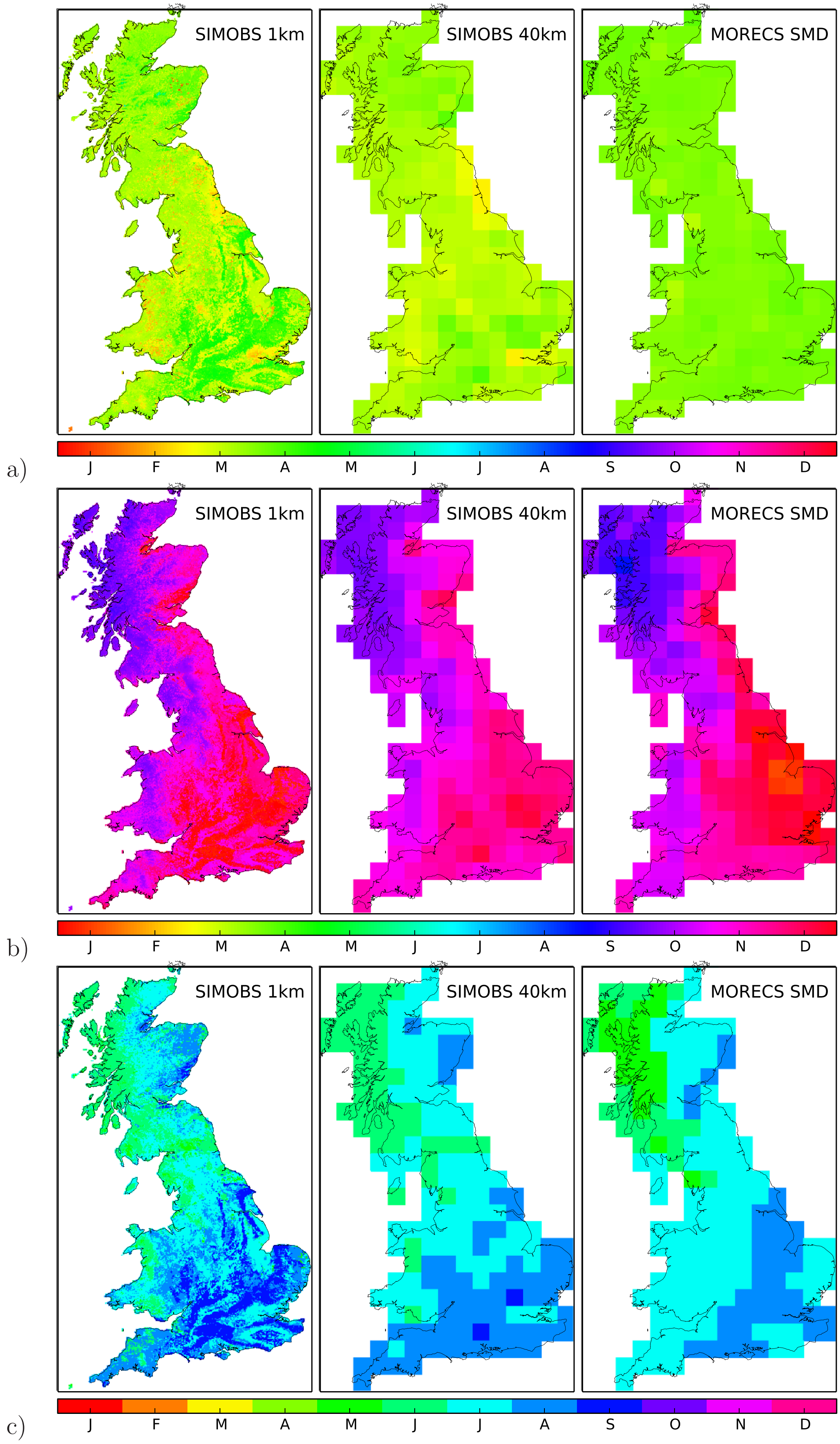

Figure 3. Comparison of GB (a) drying dates, (b) wetting dates, and (c) driest month, for SIMOBS θ at 1 km (left) and 40 km (middle), and for MORECS SMDs (right).

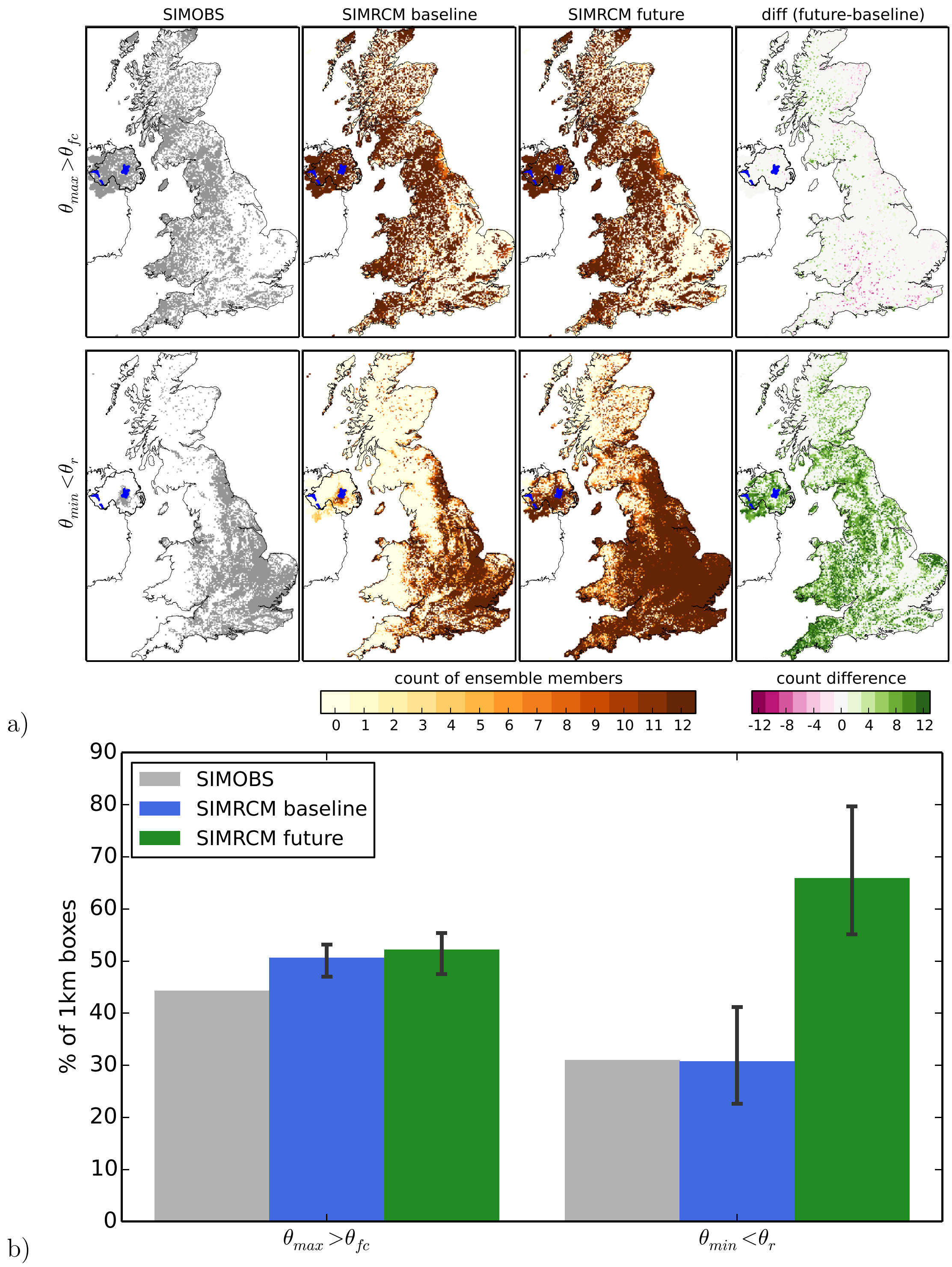

Figure 4. (a) Maps showing where $\theta_{max} > \theta_{fc}$ and $\theta_{min} < \theta_r$ for SIMOBS (left column). For comparison, counts of the baseline and future SIMRCM ensemble members where $\theta_{max} > \theta_{fc}$ and $\theta_{min} < \theta_r$ are shown (second and third columns), along with the count difference (future minus baseline; right column). (b) Bar chart of the percentage of 1 km boxes where $\theta_{max} > \theta_{fc}$ or $\theta_{min} < \theta_r$, for SIMOBS (grey), SIMRCM baseline (blue) and SIMRCM future (green). The SIMRCM bars show the ensemble median, with the grey lines on each bar showing the min-max range across the ensemble.

5(a) and 6(a)). These also show earlier drying dates in parts of Scotland in some ensemble members (supp. figure 5(a)), possibly related to snowfall/melt simulation in these higher altitude areas.

Figure 2(b) shows that the clear decreases in future soil moisture typically lead to later wetting dates but no clear change in drying dates, for example locations across GB. The full analysis shows a slight shift to earlier drying dates in the future SIMRCM (figure 5 and supp. figure 5), and a shift to later wetting dates (figure 5 and supp. figure 6). Maps of the change in wetting dates show later dates in future across most of the UK in all ensemble members; the ensemble range of the UK-mean change in date is

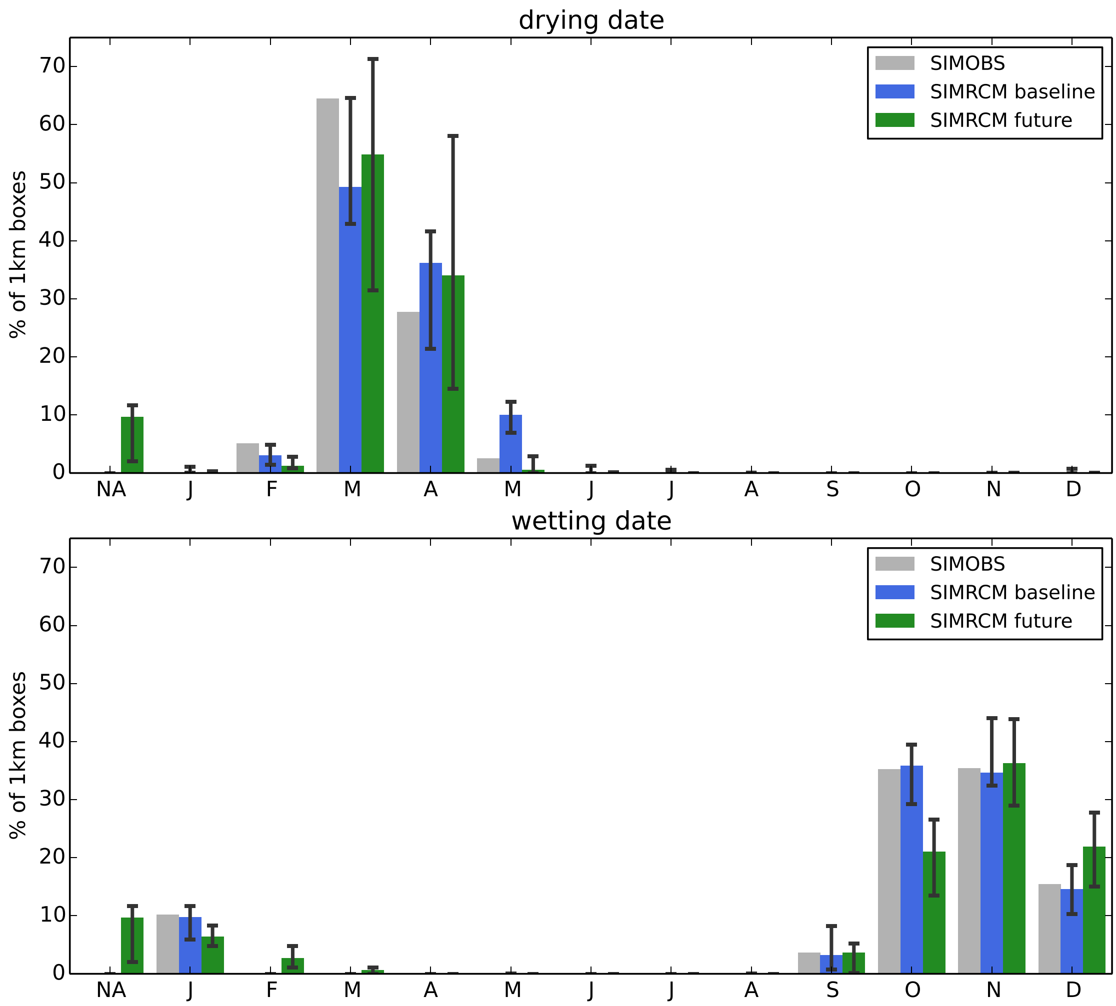

Figure 5. Histograms showing the distribution of drying dates (top) and wetting dates (bottom) through the year, for SIMOBS (grey), SIMRCM baseline (blue) and SIMRCM future (green). The SIMRCM bars show the ensemble median, with the grey lines on each bar showing the min-max range across the ensemble. For SIMRCM future, any boxes where drying and wetting dates cannot be derived are plotted as 'NA' on the left.

6.6–17.5 d (figure 6(b)). The exception is some boxes, mainly in western Scotland, which show slightly earlier wetting dates in some ensemble members (e.g. 08, 15). Maps of the change in drying dates generally show earlier dates in some locations and later dates in others, although some ensemble members show mainly later dates (e.g. 15) and some mainly earlier dates (e.g. 13) (figure 6(a)). The ensemble range of the UK-mean change in drying date is −6.0–5.8 d. The fine-scale spatial variability in projected changes in drying/wetting dates in the south/east in particular (figure 6) is related to distributions of soils types (cf figure 3). The comparison of baseline and future dates is complicated because the latter cannot be derived for a small number of 1 km cells, where the future θ lies below the baseline-derived θ_{thresh} throughout the year (supp. section 2.2).

4. Discussion

Analysis of the possible future impacts of climate change on soil moisture across the UK, using a national-scale grid-based hydrological model and the UKCP18 Regional projections, suggests potentially substantial increases in the spatial occurrence of low soil moisture levels. It also suggests that soil wetting dates will shift to later in the year, particularly in the south and east. For ensemble members where this combines with near-stationary or earlier drying dates, this will mean an increase in the proportion of the year with drier soils, and a decrease in the period with wetter soils (when groundwater recharge can occur). A direct analysis of the 'soil moisture availability factor' from the UKCP18 GCM and RCM ensembles also shows lower soil moisture in summer and early autumn (Pirret et al 2020).

The simulated soil moisture changes are consistent with the precipitation projections for wetter winters and drier summers (Murphy et al 2018; figures 4.8(c) and (d)), and more variable patterns of change in spring and autumn precipitation (Arnell et al 2021 figure 5). In particular, autumn precipitation tends to decrease in most regions but increases in western Scotland, hence the future wetting date being later

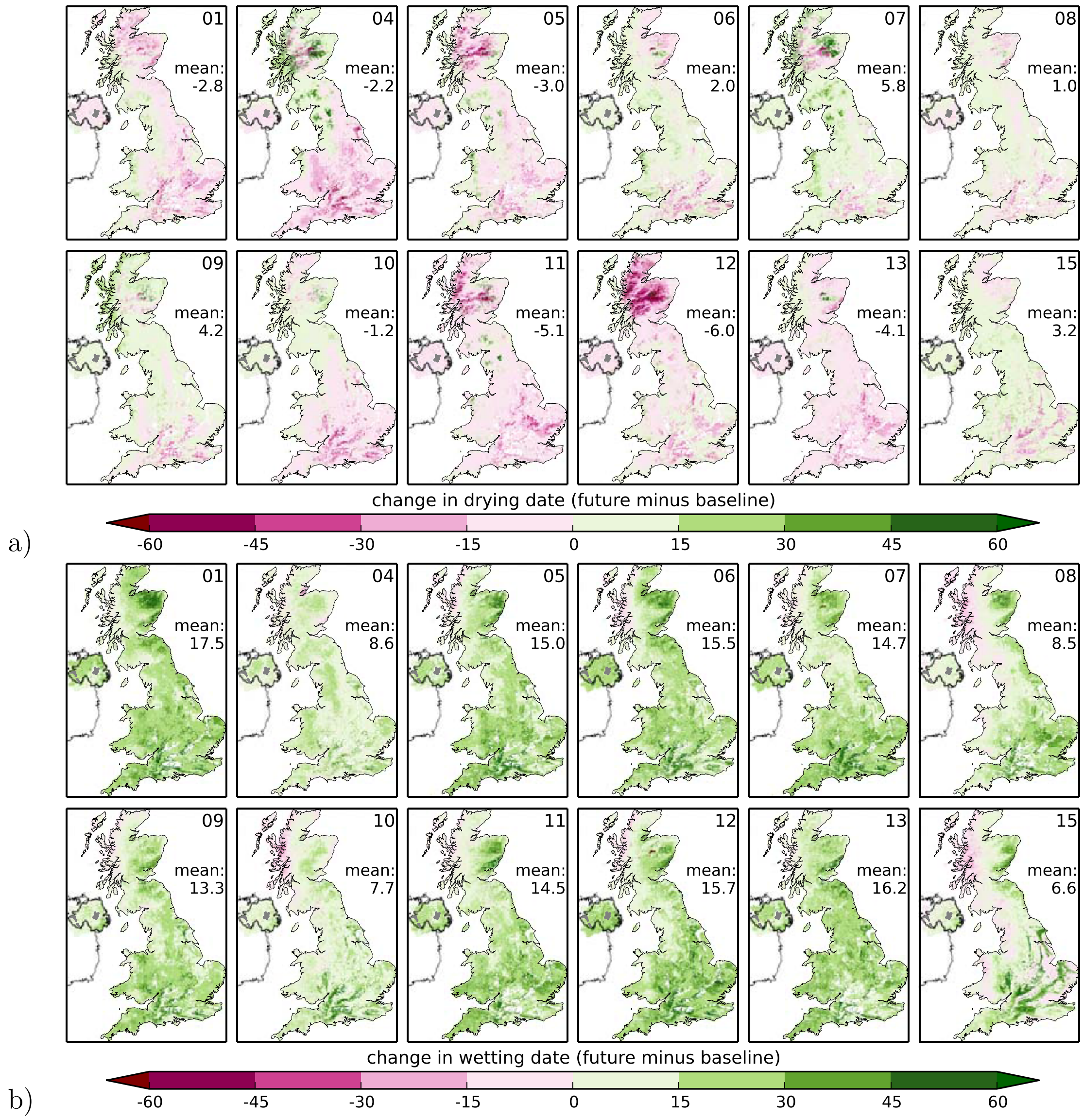

Figure 6. Maps showing the change (number of days) in (a) drying dates and (b) wetting dates for each SIMRCM ensemble member (number top-right), calculated as future (2050–2080) minus baseline (1981–2011). Note that cells where future drying/wetting dates cannot be derived are left white.

in most regions but earlier in western Scotland. In contrast, spring precipitation shows less consistency in direction of change across the ensemble, for most regions, hence the change in drying date being less consistent by ensemble member and location. Projected increases in PE will also contribute to soil moisture changes, although the effect will be moderated in the south/east where actual evaporation already tends to be water-limited (Kay *et al* 2013).

The projections of future decreases in soil moisture, and lengthening duration of dry soil conditions, are consistent with other modelling results (Arnell and Freeman 2021, Hughes *et al* 2021). In particular, Hughes *et al* (2021) show a shortening of the recharge season across GB, related to a delay in the reduction of SMDs to zero in the autumn, although they show an overall increase in annual recharge due to winter increases. The results are also consistent with a study of potential future changes in the magnitude and timing of extreme river flows, which shows worsening and delayed low flows across GB, and often delayed annual maxima across England and Wales (Lane and Kay 2021).

Information on potential future changes in soil moisture could be important to enable appropriate adaptation planning for a range of sectors vulnerable to soil moisture levels. Vulnerability could relate to absolute soil moisture levels, or the duration or timing of lower/higher soil moisture levels. For example, it may be necessary to adjust crop sowing/planting times or plant alternative crops/cultivars that are less susceptible to soil moisture variations (Arnell and Freeman 2021). The greater reliance on recharge occurring in fewer months may mean that, even if overall recharge typically increases, water resource systems that rely on groundwater could be more vulnerable to year-to-year variability (Hughes *et al* 2021). The drying of peat soils may necessitate more careful approaches to managed burning of moorland (Soulsby *et al* 2021). The potential increased future occurrence of subsidence/heave in clay soils may have implications for insurers of residential properties, and for infrastructure design and maintenance (Clarke and Smethurst 2010).

The main limitation of the analyses is that only one GCM/RCM is applied; the climate model is generally considered to be the largest source of uncertainty in hydrological impacts modelling (e.g. Krysanova *et al* 2017). The Hadley Centre GCM gives greater reductions in summer precipitation and greater increases in summer T across England than other CMIP5 models (Murphy *et al* 2018; figure 5.2), so it is likely to give greater reductions in summer soil moisture. An additional limitation is the use of only RCP8.5, which is considered a high emissions scenario. Further sources of uncertainty include the use of interpolated monthly soil moisture, and the estimation of PE, but the important effect of higher carbon dioxide concentrations on plant stomatal closure (Berg and Sheffield 2018) is included. Land-cover change, which could have greater effects than climate change (Wang *et al* 2018), is not included. Only a single hydrological model is applied; the way that soil moisture is conceptualised and parameterised could affect the simulated impacts under climate change, and it is not easy to separately evaluate the performance of interacting components (Dankers and Kundzewicz 2020).

5. Conclusions

A national-scale grid-based hydrological model, frequently used previously to investigate the potential impacts of climate change on river flows across GB, has been used to investigate potential future changes in soil moisture across the UK. The model produces 1 km grids of monthly mean soil moisture content, as a fractional content of water per unit depth of soil, integrated over the depth of the soil. The model outputs when driven with observation-based data are compared with SMD data from the MORECS operational system. This shows relatively good correspondence in soil drying and wetting dates, and in the month when soils are driest.

The UKCP18 Regional projections (for December 1980–November 2080 under RCP8.5 emissions) are then used to drive the hydrological model, to investigate changes in occurrence of indicative soil moisture extremes, and changes in typical soil drying and wetting dates. Analyses comparing baseline (December 1981–November 2011) and future (December 2050–November 2080) periods suggest large increases in the spatial occurrence of low soil moisture levels, along with later soil wetting dates. Changes to soil drying dates are less clear.

There has been relatively little specific modelling of the potential impacts of climate change on UK soil moisture, and studies often use simple water balance models and/or covered limited areas (e.g. Naden and Watts 2001, Arnell and Freeman 2021). This study adds spatial and temporal detail using a national-scale hydrological model that simulates soil moisture across a wide area in a consistent way. It covers NI as well as GB, and uses the latest climate projections for the UK. The application of only one GCM/RCM under a high emissions scenario could be considered a limitation for adaptation planning, but could be taken as a 'reasonable worst-case' scenario appropriate for some decision-making applications (Arnell *et al* 2021). Future work could extend the application to other climate models and compare results between hydrological models.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5285/f7142ced-f6ff-486b-af33-44fb8f763cde, 10.5285/c9a85f7c-45e2-4201-af82-4c833b3f2c5f. Data will be available from 01 November 2023.

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