Sensitivity of the 2018 UK summer heatwave to local sea temperatures and soil moisture

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Abstract
The impact of local climate conditions on air temperatures during a hot summer period over the United Kingdom in 2018 is studied using simple sensitivity experiments with a state-of-the-art regional numerical weather prediction system. The experiments are designed to investigate the influence of sea surface temperature (SST) and soil moisture on the air temperatures over land. They involved applying changes to the analysed SST and soil moisture patterns with magnitudes consistent with the differences between forecast analysis and climatology. The results from daily 5-day forecasts over an 11-day period show that a 3°C reduction in SSTs reduces the simulated air temperatures averaged over all land points by just over 1°C. Moistening the soil while using the control SSTs reduces the temperatures by a little less than 1°C on average although this can be larger than 3°C locally. While the reduction in SST impacts the daily maximum and minimum temperatures to a similar extent, the increase in soil moisture had little impact on the daily minimum temperatures.

KEYWORDS
heatwave, kilometre grid-scale, regional modelling, soil moisture, SSTs, weather forecasting

1 INTRODUCTION

The UK mean temperature for summer 2018 (June, July, August) was the equal highest on record (in a series from 1884, Kendon et al., 2019). High maximum temperatures affected northern and western areas in late June, with local records being set including the warmest day in Glasgow, reaching 31.9°C. Later in July the highest temperatures were being recorded in South East England reaching 35.6°C on 27 July. The dominance of high pressure over or close to the United Kingdom resulted in it being one of the top five sunniest summers and large parts of central England received less than 50% of average summer rainfall. Some locations in Southern England had over 50 consecutive dry days between late May and early July, and Southern England overall had its driest June since 1925.

Large-scale weather patterns are key to driving heatwaves over the United Kingdom. Folland et al. (2009) define the summer North Atlantic Oscillation (SNAO) as having a strong influence on European summer climate as it indicates the positioning of the mid-latitude jet stream and North Atlantic storm track. The SNAO in turn is subject to decadal scale variability such as the Atlantic Multidecadal Oscillation (AMO). These links have been further identified by others (for example...
Sutton and Dong, 2012). During summer 2018 the SNAO was in a positive phase, with the North Atlantic storm track displaced to the north of the United Kingdom, resulting in a predominance of high pressure over the United Kingdom and Europe. Local conditions such as the state of the land also play a role in the manifestation of heatwaves and high temperatures at a regional scale (e.g., Fischer et al., 2007).

Two features of the hotter periods of the 2018 UK summer were the warmer than average SSTs and drier than average soils. In July 2018 the monthly mean SST anomalies close to the United Kingdom were the second highest for a summer month in the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003), behind only August 2003. The UK land temperature and coastal SST are of course highly correlated, but July 2018 SST anomalies were higher than in some other notable heatwave events such as summer 1976. Both the SSTs and the soil moisture are likely to influence the magnitude and extent of high temperatures over land. As an island nation, the impact of SSTs on the temperature of the air advected over the United Kingdom can be quite significant, even during periods when large-scale flows are limited, such as blocking conditions. For example, local sea breeze circulations can have far-reaching impacts on the UK climate (e.g., Simpson et al., 1977; Galvin, 1997). Furthermore, even in blocking conditions there is generally some large-scale flow from ocean to land.

The restriction of soil moisture under drought conditions associated with heatwaves will also impact air temperatures over land. This is because less moisture is available for transpiration, which changes the Bowen ratio and results in greater heating of the atmosphere. Grasses are affected more by the reduction in soil moisture because the root distribution does not go as deep into the soil as for trees, hence grasses have a smaller water reservoir from which they can extract moisture for transpiration. Teuling et al. (2010) showed that the mean differences in land surface temperature (LST) between land covered by grass and trees during normal heatwaves over Europe is of the order of 1.7°C, but this average difference can be more than 3.5°C for an extreme heatwave such as August 2003. Locally these temperature differences can be almost 20°C. Miralles et al. (2014) investigated the sensitivity of air temperatures to relative soil moisture in a mega-heatwave over Europe and found that reducing it from 30% down to 5% could increase temperatures by 2–4°C, depending on other conditions.

In this short paper we utilize the regional forecast system used over the United Kingdom for weather prediction to carry out sensitivity studies to help quantify the role of local SSTs and soil moisture on air temperatures. We focus our attention on maximum and minimum temperatures as both are important when considering the impacts of heatwaves in the United Kingdom (e.g., Rooney et al., 1998). To do this, forecasts are repeated for a period during the summer of 2018 with (1) adjusted SSTs and (2) adjusted soil moisture contents and compared against a control which is the standard forecast at the time. The changes made to SSTs and soil moisture are designed to be more representative of a climatological value for that time of the year. Section 2 describes the modelling system used and the experimental set up. Section 3 describes results of the SST and soil moisture experiments and a summary is given in Section 4.

2 | METHODOLOGY

2.1 | Selection of case study period

In 2018, during the last week of June and through nearly all of July, temperatures over the United Kingdom were particularly high compared to climatology. This is illustrated in Figure 1 which compares observed daily maximum/minimum screen temperatures with their climatological values, highlighting the unusually warm conditions prevailing over the United Kingdom during summer 2018. An 11-day period from 16th to 26th July 2018 has been selected for this study (indicated by the shaded rectangle in Figure 1), during which time temperatures were warming. This period is representative of the heatwave as a whole, with broad blocking conditions and relatively high temperatures. Although clearly not the warmest period during the heatwave, it has been chosen since SSTs and soils were also particularly warm and dry (not shown), allowing us to establish an approximate upper bound on the impacts of SSTs and soil moisture on air temperature. Eleven days was considered long enough to average out local scale weather variability within the larger scale blocking conditions associated with this period of the heatwave.

The rainfall over the United Kingdom during the 11-day period was 13 mm, which is a notable but not exceptional dry spell for a UK summer, equivalent to the 18th percentile of the distribution of all 11-day periods ending in July in observational records from 1960 to present. For the whole summer period there was 73% rainfall compared to climatology, making it the 12th driest summer in a series from 1910.

2.2 | The modelling system

The UKV is the Met Office deterministic regional numerical weather prediction (NWP) system for the United Kingdom. It is a limited-area configuration of the Met
Office Unified Model (UM; Cullen 2003), coupled to the Joint UK Land Environment Simulator (JULES) model (Best et al., 2011; Clark et al., 2011) for the land surface. Both the UM and JULES contain a comprehensive set of parametrization schemes for key physical processes; the particular science configuration of these used in this study is known collectively as Regional Atmosphere and Land – Version 1 (RAL1; Bush et al., 2019). RAL1 is an updated version of the operational forecast model used at the time and has improved representation of the diurnal cycle of temperatures.

The UKV is one-way nested inside the Met Office deterministic global forecast model (Walters et al., 2017), covering the area shown in Figure 2. The inner part of the domain has a fixed grid length of 1.5 km in both directions providing a good representation of UKs

**FIGURE 1** Timeseries of observed daily maximum (solid red line) and minimum (solid blue line) temperatures over the United Kingdom. Climatological (1981–2010 average) daily maximum (dashed red line) and minimum (dashed blue line) temperatures are shown for comparison. The shaded rectangle highlights the chosen period and within this period the control forecast maximum and minimum temperatures are shown at 2-day (solid black) and 3-day (dashed black) lead times.

**FIGURE 2** The UKV model domain and orography. The inner region (labelled 1.5 x 1.5) has a fixed grid length of 1.5 km in both directions. The grid length is smoothly increased to 4 km in the hatched region around the inner domain. Outside this transition zone, grid cells are either 1.5 x 4 km (north and south of the inner region), 4 x 1.5 km (east and west of the inner region), or 4 x 4 km (domain corners).
orography. Surrounding this is a narrow transition zone (hatched area in Figure 2), where the grid length is smoothly stretched from 1.5 km to 4 km. In the vertical there are 70 quadratically spaced levels, terrain-following near the surface and relaxing to horizontal at the model top at 40 km. In operations, it is run every hour to a range of different lead times with initial conditions (analyses) for each cycle generated using a four-dimensional variational data assimilation (4D-Var) system. However, for the work presented here it has been re-run from archived UKV analyses once per day for the period of interest (a total of 11 forecasts). The initialisation time for each forecast is 03Z, chosen since (a) LBCs are available to run out to \( T + 120 \) on this cycle, and (b) to give the model chance to spin-up before the peak of diurnal heating in runs where the initial SST and soil moisture fields are adjusted; see the following sections.

SSTs are derived by interpolating the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA, Donlon et al., 2012) product to the UKV grid. In common with most operational regional NWP systems, SSTs are held fixed throughout each forecast. Soil moisture is initialised by interpolating fields provided by a global-scale analysis, attempting to account for the change in soil properties between the global and regional model grids (Lewis et al., 2018). Included in Figure 1 are the Day 2 (\( T + 48 \)) and Day 3 (\( T + 72 \)) forecasts from the control experiments which highlight that the model predicted temperatures match the observations well in this period although there is an underestimation of the maximum temperature by a degree or so.

### 2.3 Sea surface temperature experiments

The purpose of this experiment is to understand the extent to which local SSTs influence maximum and minimum air temperatures over land during a heatwave. To assess this, several options were considered: (a) replace the SSTs in the control runs with their climatological values, (b) replace the SSTs with those from another year that was more similar to climatology, or (c) subtract uniform perturbations from the SSTs to make them more consistent with climatology in the broad sense. The first option was discarded since it was desirable to preserve small-scale structure in the SSTs that would be lost by relaxing to a relatively smooth climatology. The third option was favoured over the second because the spatial structure of the SSTs is not altered and is thus likely to give a simpler response.

Figure 3 shows the spatial distribution of SST anomalies inside the inner region of the UKV domain, averaged over all 11 days in the case study period. In regions close to the UK coast the SSTs are typically between 1 and 4°C warmer than the climatology other than in the north-west. To span this range, two experiments were conducted with SSTs reduced by 1.5 and 3°C, respectively.

![Figure 3](image)

**Figure 3** OSTIA SST anomalies relative to the daily AVHRR pathfinder climatology (v5.0; Casey et al., 2010), averaged over all 11 days in the case study period. The boundary of the inner region of the UKV domain is shown for reference (see Figure 2).
2.4 Soil moisture experiments

As with the SSTs, the basic aim of the soil moisture experiments is to understand how the unusually dry soils influence the magnitude and distribution of the higher than average air temperatures.

In the United Kingdom (and many other regions), soil moisture influences evaporation mainly through transpiration from vegetation and there is an active range, between the wilting point and the critical point, where the transpiration is directly influenced by water availability. Below the wilting point there is no transpiration, whilst above the critical point the transpiration is only influenced by other environmental factors because there is sufficient water in the soil. Therefore, for our sensitivity studies we ensure that changes to the soil moisture remain within this active range by applying changes to the initial conditions of each run based upon the following:

\[
\Delta \theta = \begin{cases} 
  f(\theta_c - \theta) & \text{if } \theta < \theta_c \\
  0 & \text{otherwise}
\end{cases}
\]

**FIGURE 4** Total column (to a depth of 1 m) soil moisture at the critical point (top left). Other panels show differences in total column soil moisture relative to this, at the wilting point (top right), in the control simulations (bottom left), and in the SMC0.75 experiment with increased soil moisture (bottom right). In the latter two cases, the maps represent an average over all 11-days in the case study period. Only land points in the United Kingdom are shown.
where $\theta$ is the soil moisture content, $\theta_C$ is the value at the critical point and $f$ is a relaxation parameter for the sensitivity experiments. Here, values of $f = 0.5$ and $f = 0.75$ are considered, labelled as SMC0.5 and SMC0.75, respectively.

Figure 4 shows the spatial distribution of the critical soil moisture content across the domain, along with differences in soil moisture relative to the critical point for the wilting point and initial values for both the analysis and SMC0.75 sensitivity experiment. As the majority of land cover over the United Kingdom is classified as grass within the model, only the soil moisture in the top 1 m of soil is considered here because this depth contains 86% of the modelled root distribution for this surface type (Best et al., 2011), hence it is most indicative of the soil moisture limitation for the vegetation cover. This figure shows that the initial soil moisture for the analysis was generally below the critical point over much of the domain, with the main exception being over the western part of Scotland. The soil moisture was not as low as the wilting point, so could be considered as Stage (II) drying as defined by Teuling et al. (2010), i.e., evapotranspiration being self-limiting, but not negligible (Stage [III]) or independent of soil moisture (Stage [I]). Figure 4 also shows that the relaxation methodology enables the soil moisture to approach the critical point whilst maintaining the spatial distribution of the anomalies in the analysis.

**FIGURE 5** Maximum screen temperatures on Day 4 of a forecast initialised at 03Z on 16th July 2018. Shown are maximum temperatures in the control (top left), the experiment with SSTs reduced by 3°C (top right), and the difference between the 3°C SST experiment and control (bottom left). Only the inner region of the UKV domain (see Figure 2) is shown.
3 | RESULTS

3.1 Sea surface temperature experiments

Our analysis focuses on the forecast maximum and minimum air temperatures as a function of lead time. A close look at any given day and at any given lead time reveals many interesting responses that highlight the small-scale changes that can occur due to changing the SSTs. As an example, Figure 5 shows maximum temperatures on Day 4 of a forecast initialised on 16th July. It shows a particularly strong impact of the reduced SSTs on the maximum daily screen temperatures with lots of structure on the smaller scales. Regions such as East Anglia are 10°C colder than the control with a 3°C SST reduction. Furthermore, there are regions that are over 3°C warmer than the control despite the reduction in the SSTs. There are many reasons why such responses will occur (such as changes in sea breeze penetration) but ensembles would be needed to understand if such changes are a robust feature of the experiment on this day. In the work presented here we focus on the mean response to the changes made as a function of forecast lead time averaged over the whole period, assuming this will average out small-scale local effects.

Figure 6 shows differences in daily maximum temperatures between the experiment with 3°C cooler SSTs and control, averaged over the whole 11-day period, at lead times of 1 and 3 days. The lower SSTs have a larger impact on temperatures over the ocean than land and the impacts are larger 3 days into a forecast when compared to the first day (Day 5 differences from control are very similar to Day 3 and are not shown here). The other key feature to note is that after averaging over the 11-day period there is much less spatial structure in response to changing the SSTs, suggesting smaller-scale responses are indeed averaged out when we look over 11 days. Focusing on Day 3 we can see all land areas are between 0.5 and 1.5°C cooler in the 3°C experiment than the control. This relatively uniform spatial response in maximum temperatures is replicated in the minimum temperatures (not shown).

Figure 7 shows area-mean maximum and minimum temperature differences over the 11-day period separated by land and sea points for the two SST experiments (SST reductions of 1.5 and 3°C), relative to the control. The impact of changing the SSTs grows with forecast lead time for the first 2–3 days and then becomes steady. Focusing on the longer lead times (>3 days) it can be seen that the 3°C SST reduction leads to just over 1°C reduction in maximum and minimum temperatures over land. The impact of the 1.5°C experiment is about half that suggesting a relatively linear response. Over the sea there is a reduction in maximum and minimum temperatures of approximately 2.5°C in the SST3 experiment; again this is halved when the SSTs are reduced by 1.5°C.

3.2 Soil moisture experiments

Figure 8 shows the sensitivity of maximum temperatures to changes in the soil moisture in the SMC0.75 experiment at lead times of 1 and 3 days, averaged over the

![Figure 6](image1.png)  
**Figure 6** Maps of maximum screen temperature differences (experiment – Control) at lead times of 1 day (left) and 3 days (right) for the 3°C SST experiments averaged over the 11-day period. Only the inner region of the UKV domain (see Figure 2) is shown.
There are larger spatial differences than seen in the SST experiments, with the spatial pattern following that of the soil moisture differences from the critical point seen in Figure 4. Areas in the analysis where the soil moisture is close to the critical point show little change in temperature in the sensitivity experiment as would be expected. However, areas where the initial soil moisture is furthest from the critical point have differences in temperature of up to 2°C by $T + 24$, growing to almost 3.5°C by $T + 72$ in the SMC0.75 experiment. The magnitude of these differences is similar to those found by Teuling et al. (2010) for difference in land surface temperatures (LST) between grass and tree cover types over Europe during heatwave conditions (note that differences in LST will be larger than at screen level due to super adiabatic layers very close to the surface), where the trees will be less affected by the water limitation than the grasses due to their deeper root distribution profiles (and hence closer to our sensitivity experiments).

When averaged over the UK land area, the impact of the soil moisture changes on the maximum temperatures through the 11-day period (Figure 9) are between 0.6 and 0.8°C for the two experiments; this is a little smaller than...
seen in the 3°C SST experiments. The effect on the maximum temperature is greater for larger values of $f$, but differences are not that large due to the nonlinear interactions between soil moisture and the surface heat and moisture fluxes through energy balance constraints. As with the SST experiments the impact grows over first 2–3 days of the forecast. Changes to the soil moisture have little impact on the night time minimum temperatures. As there is no transpiration at night (e.g., De Dios et al., 2015), the small differences (of the opposite sign to other changes) are likely to be due to the changes in downward longwave radiation resulting from differing atmospheric moisture profiles caused by changes to the day time evaporation.

An additional experiment was carried out where the changes to soil moisture and SSTs were made together. Detailed results are not shown here as the response of the maximum and minimum temperatures to the combined changes was very close to the sum of the responses from the two individual experiments.

**4 | SUMMARY**

The UK summer of 2018 was the joint hottest on record (in a series from 1910). During this heatwave there were times when SSTs were considerably warmer and the land was drier than climatology. This paper presents some simple sensitivity experiments using the Met Office’s UK forecasting system (UKV model) to quantify the influence of these local sea and soil moisture conditions on the maximum and minimum air temperatures. In the experiments, 11 days are simulated in a daily forecast cycle that runs out to a 5-day lead time. Sensitivity experiments reduce the SSTs by 1.5 and 3°C everywhere, and in separate experiments soil moisture is increased in the active range between the wilting and critical point.

The experiments with reduced SSTs showed that while day-to-day there could be large local impacts on maximum and minimum temperature from the SST changes in individual forecasts, the mean impact over the 11-day period was relatively uniform over land ranging between 0.5 and 1.5°C. This was not the case for the soil moisture experiments where the spatial distribution of the temperature changes over land follows that of the pattern of dry soils and locally was up to 3.5°C. In both SST and soil moisture experiments it was found that the impact grew from the start of the forecast but was steady after 2–3 days into the forecast. This growth is at least in part because forecasts were initialised from the control’s analysis.

Cooling the SSTs by 3°C led to a mean reduction of the air temperature over the ocean and land of approximately 2.6 and 1.2°C, respectively, at later forecast times. The magnitude of the change was the same in both maximum and minimum temperatures. The impact of halving the SST adjustment (cooling by 1.5°C) roughly halved the impacts on maximum and minimum temperatures. Changes to the soil moisture in the two experiments had a more similar impact to each other. The average maximum temperature over land was 0.6 and 0.8°C cooler in the two experiments. Soil moisture changes had little impact on minimum temperatures.

The experiments described here highlight a novel use of a regional operational forecasting system to investigate sensitivities to local conditions. As the model is regional, local feedbacks are isolated from larger scale feedbacks on the synoptic scale and beyond and with a grid-length of 1.5 km much smaller scale processes such as sea breezes are more explicitly represented. These processes.

**FIGURE 9** Area-averaged differences in daily maximum and minimum temperatures over land between the experiments with increased soil moisture and control, as a function of forecast lead time. Results are an average over the full 11-day case study period.
are likely to be important in these experiments and further would could begin to explore the role of these processes in some detail.

ACKNOWLEDGEMENTS
The authors would like to thank three anonymous reviewers who valuable comments improved the quality of this manuscript.

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How to cite this article: Petch JC, Short CJ, Best MJ, et al. Sensitivity of the 2018 UK summer heatwave to local sea temperatures and soil moisture. Atmos Sci Lett. 2020;21:e948. https://doi.org/10.1002/asl.948