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Impacts of climate change on wheat in England and Wales

Mikhail A. Semenov*

Department of Biomathematics and Bioinformatics, Centre for Mathematical and Computational Biology, Rothamsted Research, Harpenden, Herts AL5 2JQ, UK

The frequency and magnitude of extreme weather events are likely to increase with global warming. However, it is not clear how these events might affect agricultural crops and whether yield losses resulting from severe droughts or heat stress will increase in the future. The aim of this paper is to analyse changes in the magnitude and spatial patterns of two impact indices for wheat: the probability of heat stress around flowering and the severity of drought stress. To compute these indices, we used a wheat simulation model combined with high-resolution climate scenarios based on the output from the Hadley Centre regional climate model at 18 sites in England and Wales. Despite higher temperature and lower summer precipitation predicted in the UK for the 2050s, the impact of drought stress on simulated wheat yield is predicted to be smaller than that at present, because wheat will mature earlier in a warmer climate and avoid severe summer drought. However, the probability of heat stress around flowering that might result in considerable yield losses is predicted to increase significantly. Breeding strategies for the future climate might need to focus on wheat varieties tolerant to high temperature rather than to drought.

Keywords: drought and heat stress; wheat simulation model; stochastic weather generator; UKCIP02; LARS-WG; Sirius

1. INTRODUCTION

The frequency and magnitude of extreme weather events are predicted to increase under climate change (Solomon *et al.* 2007). In a warmer future climate, most global climate models (GCM) simulate increased summer dryness and winter wetness in most parts of the northern middle and high latitudes. There is an increased chance of intense precipitation and flooding due to the greater water-holding capacity of a warmer atmosphere (Barnett *et al.* 2006). Weisheimer & Palmer (2005) examined changes in extreme seasonal temperatures using multi-model multi-scenario ensembles. They showed that by the end of the century, the probability of extreme warm seasons is projected to rise over many areas. This increase in extreme warm seasons arises from the combined effect of a shift in the temperature mean and an increase in the temperature variability. Isolated incidents of extreme high temperatures could seriously damage agricultural crops; a continuous period of extreme high temperature could be deadly. Using UKCIP02-based climate projections for the UK (Hulme *et al.* 2002), it has been demonstrated that by the end of the century, not only will the frequency of heat waves increase substantially (by an order of magnitude), but also their length and severity with higher peak temperatures during a heat wave (Semenov 2007).

Changes in climate and extreme weather events are likely to impact agricultural crops, but it is not clear whether yield losses resulting from severe droughts or heat stress will increase in the future. Owing to the complex nonlinear interactions between a plant and its environment, the assessment of impacts is not trivial and requires the use of process-based crop simulation models. The aim of this paper is to analyse the impact of climate change on the magnitude and spatial patterns of two indices for wheat: the probability of heat stress around flowering and the severity of drought stress.

2. METHODS

We used a crop simulation model to predict the impact of climate change on wheat. Eighteen sites in England and Wales were selected for in-depth analysis (the site locations with soil available water capacity (AWC) are given in figure 1 of the electronic supplementary material). Daily site-specific climate change scenarios were generated at each site, using the LARS-WG stochastic weather generator (WG; Semenov 2007) and the output from HadRM3 regional climate model (Hulme *et al.* 2002). Impact indices, the probability of heat stress around flowering and the severity of drought stress, were computed for each site using the Sirius wheat simulation model (Jamieson *et al.* 2000; Lawless *et al.* 2005). These indices were spatially interpolated

*mikhail.semenov@bbsrc.ac.uk

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over England and Wales and the results are presented as risk maps. Note that these maps display accurate information only at the selected 18 sites, especially for the drought stress index (DSI), which depends on the soil properties that have significant spatial variability.

2.1. Impact indices

In this study, we examine two conditions that might cause substantial losses in wheat yields. Large yield losses can result from a short duration of extreme weather, e.g. high temperature at a particular growth stage. It is known, for example, that a short episode of high temperature around flowering can substantially reduce the grain yield (Wheeler *et al.* 2000). In an experiment on the effects of CO_2 and temperature on the grain yield, Mitchell *et al.* (1993) observed that halfway through anthesis, when 50 per cent of the ears in a population have flowered, a temperature of 27°C or higher can result in a high number of sterile grains. Although the effect of reduced grain numbers on the final yield could be compensated for during grain filling by the production of larger grains, the yield losses could be still high. Wheeler *et al.* (1996), using temperature gradient tunnel systems, demonstrated that a temperature of 31°C or higher, prior to anthesis, can considerably reduce the number of grains per ear, reducing significantly the grain yield (Wheeler *et al.* 1996; Ferris *et al.* 1998). We estimated the probability of heat stress around flowering, $P^{\mathrm{T27}}_{\mathrm{ant}+10}$, that the maximum temperature exceeded 27°C at least once during 10 days after anthesis began. The probability, $P^{\mathrm{T31}}_{\mathrm{ant}-5}$, that maximum temperature exceeds 31°C at least once during 5 days prior to anthesis has also been computed, but has not been reported in this paper, because it was negligibly small for the present and future climate scenarios in the UK.

Considerable yield losses can be the outcome of the cumulative effect of weather conditions over the growing season, e.g. losses due to prolonged drought. We calculate a DSI, defined as a measure of the reduction in the grain yield due to water stress, as

$$\mathrm{DSI} = 1 - \frac{Y_{\mathrm{WL}}}{Y_{\mathrm{pot}}}, \qquad (2.1)$$

where Y_{WL} and Y_{pot} are water-limited and potential grain yields. A potential yield is calculated using the Sirius crop simulation model for the crop with satisfied daily water demands. In this study, we calculated the 95 percentile for the DSI, Q^{95}_{DSI}, the level of yield losses due to water stress that can be expected on average once every 20 years.

2.2. Climate change scenarios with high temporal and spatial resolution

Process-based models, such as crop simulation models, require daily site-specific weather as one of their inputs. To be able to use these models in climate change studies, it is vital to provide future climate scenarios with appropriate temporal and spatial resolutions, taking into account the model sensitivity to variations in climatic variables. Crop simulation models incorporate a mixture of nonlinear responses of the crop to climatic and environmental variations (Semenov *et al.* 1993; Porter & Semenov 2005). Nonlinear models can potentially produce large differences in predictions in response to small variations in initial conditions or their inputs (Strogatz 2001). It was demonstrated in Porter & Semenov (1999) that climate change scenarios derived from the GCM, which incorporated changes in climatic variability, significantly increased the risk of crop failure compared with scenarios based only on changes in the mean values.

In this study, we used the UKCIP02 climate predictions based on a series of climate modelling experiments completed by the Hadley Centre, using the HadCM3 and HadRM3 climate models (Hulme *et al.* 2002). These climate predictions are based on global emission scenarios published in 2000 by the Intergovernmental Panel on Climate Change (IPCC; Nakicenovic & Swart 2000) and are available for three time periods: the 2020s; the 2050s; and the 2080s. The HadCM3 global climate model is a complex computer model used to simulate the evolution of global climate. It is based on physical principles, describing the transport of mass and energy at a coarse spatial resolution of approximately 300 km. The regional climate model HadRM3 has a finer horizontal resolution of 50 km and taking boundary conditions from the HadCM3 simulations provides a higher spatial resolution of the local topography and more realistic simulations of fine-scale weather features. For each 50 km grid cell, UKCIP02 predictions are provided as changes between 'control' and changed climates for the monthly mean of climatic variables, such as monthly precipitation, minimum and maximum temperature and radiation. The coarse spatial resolution of the global and regional climate models, large uncertainty in their output at a daily scale (particularly for precipitation) and an inaccurate reproduction of weather statistics including extreme events mean that the daily output from these models is not appropriate for use with crop simulation models (Mearns *et al.* 1995; Fowler *et al.* 2005).

We used the LARS-WG stochastic WG (see www.rothamsted.bbsrc.ac.uk/mas-models/larswg.php) to generate daily site-specific climate scenarios (Semenov *et al.* 1998; Semenov & Brooks 1999). WGs are capable of generating daily weather time series statistically similar to the observed weather as required by crop simulation models (Wilks & Wilby 1999). WGs have been adopted in climate change studies as a computationally inexpensive tool to generate climate change scenarios with high temporal and spatial resolutions based on the output from the GCM (Wilks 1992; Barrow & Semenov 1995). Calibrated with observed weather data at a site, the WG parameters are adjusted with the predicted changes in climatic mean and variability, derived from the GCM output (Semenov 2007). This new parameter set is used by the WG to generate future climate scenarios.

Using LARS-WG and the output from the UKCIP02 projections, we generated 150 years of daily weather for three time periods: the baseline representing 1961–1990, the 2020s and the 2050s for 18 sites in England and Wales. Future climate scenarios were generated for the high-emission IPCC scenarios (HI) with the CO_2 concentration ($[CO_2]$) of 334 ppm for the baseline, 437 ppm for the 2020s and 593 ppm for the 2050s. We refer to the climate scenarios as the baseline, 2020HI and 2050HI, respectively. The construction of daily climate change scenarios is a two-step procedure (Semenov 2007). First, for a selected site, we calculate the LARS-WG parameters by analysing 30 years of observed daily weather. Using this set of parameters, LARS-WG is able to generate daily weather specifics to this site for the baseline scenario. The second step is to derive changes in the mean and variability of climate variables from the UKCIP02 predictions for this site. The mean changes in total monthly precipitation, monthly mean maximum and minimum temperature and monthly mean radiation are available directly from UKCIP02 at 50 km grid cells. Changes in the duration of monthly means in dry and wet series, required by LARS-WG, were calculated using daily precipitation from HadRM3, which are available for the period 2065–2095 (the 2080s). Changes in the wet and dry series for the 2020s and the 2050s were calculated by scaling down the changes for the 2080s.

2.3. Crop simulation model

The Sirius crop simulation model was used to calculate grain yield (Jamieson *et al.* 1998*b*; Brooks *et al.* 2001). The model requires daily weather data, a soil physical description and management information (e.g. sowing date, nitrogen application) to calculate biomass accumulation from intercepted photosynthetically active radiation day by day. Grain growth is calculated from the biomass using simple partitioning rules. Leaf area index (LAI) is calculated using a simple canopy model (Lawless *et al.* 2005). Phenological development is linked to the mainstem leaf appearance rate (determined by temperature) and the final leaf number, determined by the responses to day length and vernalization (Jamieson *et al.* 1998*a*). Soil is used as a reservoir for water and nitrogen, and as these are used up, the effects of deficits are calculated through their influences on LAI expansion (Jamieson & Semenov 2000). The model has been calibrated for several modern wheat cultivars and is able to simulate accurately the behaviour of crops exposed to a wide range of conditions, including those in Europe, New Zealand, USA and Australia and under the conditions of climate change (Semenov *et al.* 1996; Jamieson *et al.* 1999, 2000; Ewert *et al.* 2002; Martre *et al.* 2006). Results of the Sirius validation against field experiments are given in figure 2 of the electronic supplementary material.

We used Sirius v. 2005 (www.rothamsted.bbsrc.ac.uk/mas-models/sirius.php). The model accepts parameters for previously calibrated varieties (Sirius v. 2000) as input with additional calibration for the maximum leaf area. We selected two winter wheat cultivars, cv. Avalon and cv. Mercia, both obligate winter wheat cultivars with moderate-to-weak day length response, which have been calibrated previously using field experiments in the UK (Wolf *et al.* 1996; Ewert *et al.* 2002; Lawless *et al.* 2005). Mercia is a late-flowering cultivar maturing on average two weeks later than cv. Avalon. The sowing date was set at 10 October, which is typical for England and Wales. According to the long-term classical experiment at Rothamsted, the sowing date for wheat has not changed for the last 70 years and varies between the end of September and the beginning of November (Anon. 2006).

For each of 18 sites, parameters of the dominant soil were derived using digital National Soil Map (NATMAP) available as a vector (1 : 250 000) or gridded (1 km grid) maps for England and Wales (Hallett *et al.* 1996; figure 1, electronic supplementary material). Each soil series is supplied with detailed (by horizon) information on the soil texture, content of sand, silt and clay, and also on the hydrology of the soils, including volumetric water content at various pressure suctions. The following soil parameters are required as input to Sirius: the maximum root depth; saturation water content; drained upper and lower limits; and a percolation coefficient. All simulations were carried out by Sirius without nitrogen (N) limitation; so soil parameters related to the N distribution in the soil, e.g. organic N content or mineralization rate, did not need to be specified. Most of the required parameters were available directly from the NATMAP. The percolation coefficient was estimated from the clay content, using the nonlinear regression relationship for British soils derived in Addiscott & Whitmore (1991).

3. RESULTS AND DISCUSSION

Predicted relative changes in mean yields between the baseline and 2020HI or 2050HI climate scenarios are presented in figure 1 for cv. Mercia and cv. Avalon. For all scenarios and both wheat cultivars, average yields are predicted to increase mainly owing to yield stimulation with rising $[CO_2]$. It was shown that elevated $[CO_2]$ increases the photosynthetic rate in wheat (C3 plant) over a wide range of radiation (Lawlor & Mitchell 1991; Long *et al.* 2006). In Sirius, radiation-use efficiency is proportional to $[CO_2]$ and increases by 30 per cent for a doubling in $[CO_2]$ (Jamieson *et al.* 2000; Ewert *et al.* 2002). The magnitude and the spatial pattern of changes for the 2020HI scenario are similar for both cultivars (an increase up to 10%). However, for 2050, early flowering cv. Avalon produced a larger increase in the yield compared with cv. Mercia. For example, in the southeast, the increase in the mean of the grain yield for Mercia was 7.5–10 per cent, whereas for Avalon the mean yield increased by 17.5–20 per cent. Note that the coefficient of variation of the grain yield (standard deviation divided by mean, %) for the baseline scenario varied between 6 and 11 per cent for cv. Avalon and 6 and 14 per cent for cv. Mercia.

Predicted increases in maximum temperature for the 2050HI scenario are between 2 and 4°C with the highest value in August (figure 3, electronic supplementary material). The probability P^{T27}_{ant+10} that maximum temperature exceeds 27°C around flowering should be significantly affected by such a large increase in the temperature mean. However, because wheat development is driven by the thermal time, in a warmer climate

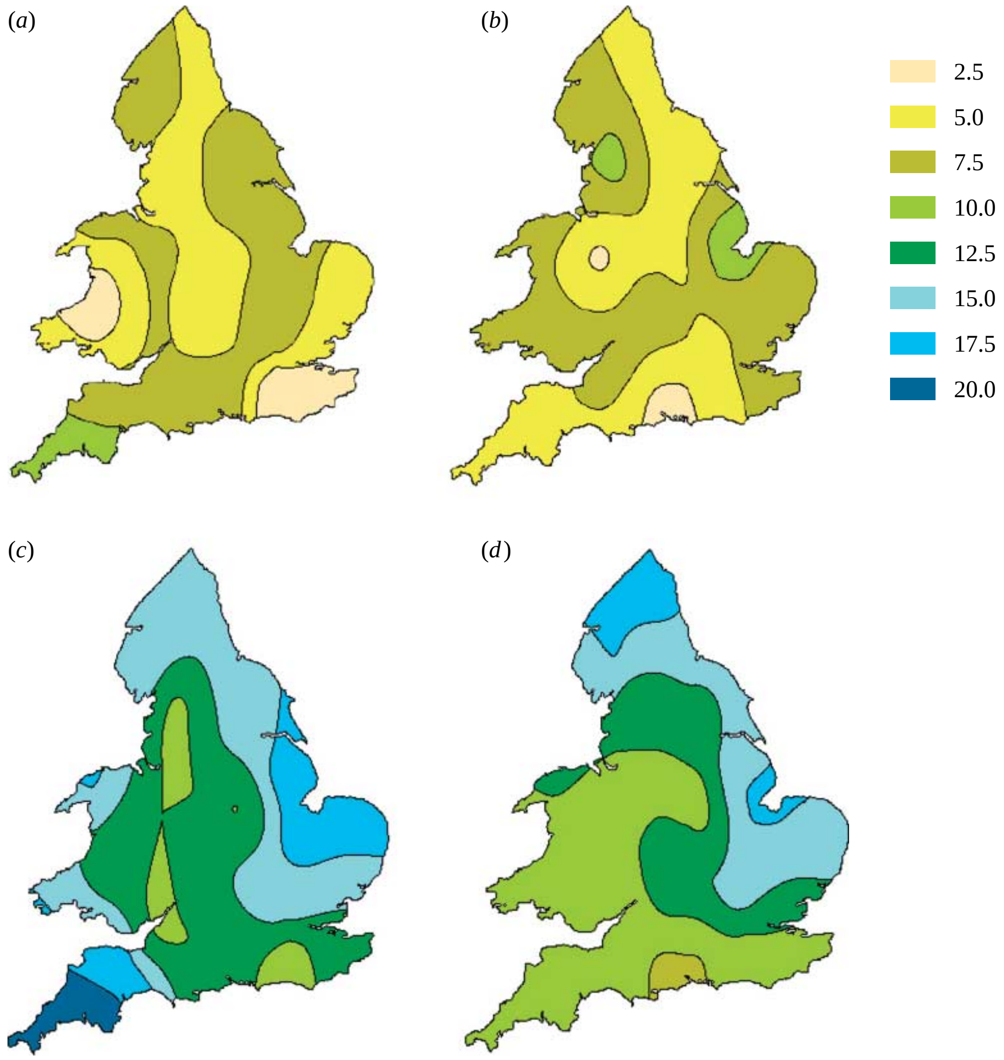

Figure 1. Relative changes in yield (%) for (*a*,*c*) cv. Avalon and (*b*,*d*) cv. Mercia for the (*a*,*b*) 2020HI and (*c*,*d*) 2050HI climate scenarios compared with the baseline scenario.

flowering will occur earlier in the season when temperatures are cooler due to the seasonal temperature cycle. Table 1 shows the average day (day of the year) of flowering and average maximum temperature $\bar{T}_{\max}$ for this day for cv. Avalon and Mercia for the baseline, 2020HI and 2050HI scenarios. The increase in $\bar{T}_{\max}$ at flowering was only 0.35 for cv. Avalon and 1.06°C for cv. Mercia for the 2050HI scenario, because the wheat flowered almost two weeks earlier. The probability $P^{\mathrm{T27}}_{\mathrm{ant}+10}$ for cv. Avalon changed very little in magnitude and spatial pattern for both the 2020HI and 2050HI scenarios compared with the baseline scenario (figure 2). For late-flowering cv. Mercia, changes in the probability $P^{\mathrm{T27}}_{\mathrm{ant}+10}$ were substantial. For the baseline scenario, $P^{\mathrm{T27}}_{\mathrm{ant}+10}$ was less than 0.15 for the majority of England and Wales. For the 2050HI scenario, $P^{\mathrm{T27}}_{\mathrm{ant}+10}$ was greater than 0.25 for more than half of England and Wales and exceeded 0.35 for the southeast of England.

To characterize the impact of water stress on wheat, we calculated the 95 percentile of the DSI distribution, Q^{95}_{DSI}, for cv. Avalon and cv. Mercia based on simulations for 150 years of daily weather for the baseline, 2020HI and 2050HI climate scenarios (figure 3). For the baseline scenario, the spatial patterns for Q^{95}_{DSI} are similar for both cultivars; Q^{95}_{DSI} is substantially higher for the eastern part of the region than for the western part with the value of 0.3 for cv. Avalon and the value of 0.4 for cv. Mercia. For late-flowering cv. Mercia, Q^{95}_{DSI} is generally predicted to be higher than that for cv. Avalon by 0.1, with the exception of the west of England and Wales where losses due to water stress are expected to be very low ($Q^{95}_{\mathrm{DSI}} < 0.05$). For the future scenarios, despite the fact

Table 1. The average date of flowering and maturity and the average maximum temperature $\bar{T}_{\max}$ at flowering calculated for cv. Avalon and cv. Mercia and for the baseline, 2020HI and 2050HI climate scenarios at Rothamsted.

cultivar	baseline	2020HI	2050HI
Avalon			
flowering	9 Jun	4 Jun	24 May
maturity	8 Aug	1 Aug	18 July
$\bar{T}_{\max}$ at flowering, °C	18.50	18.56	18.85
Mercia			
flowering	19 Jun	15 Jun	5 Jun
maturity	23 Aug	16 Aug	2 Aug
$\bar{T}_{\max}$ at flowering, °C	19.36	19.87	20.42

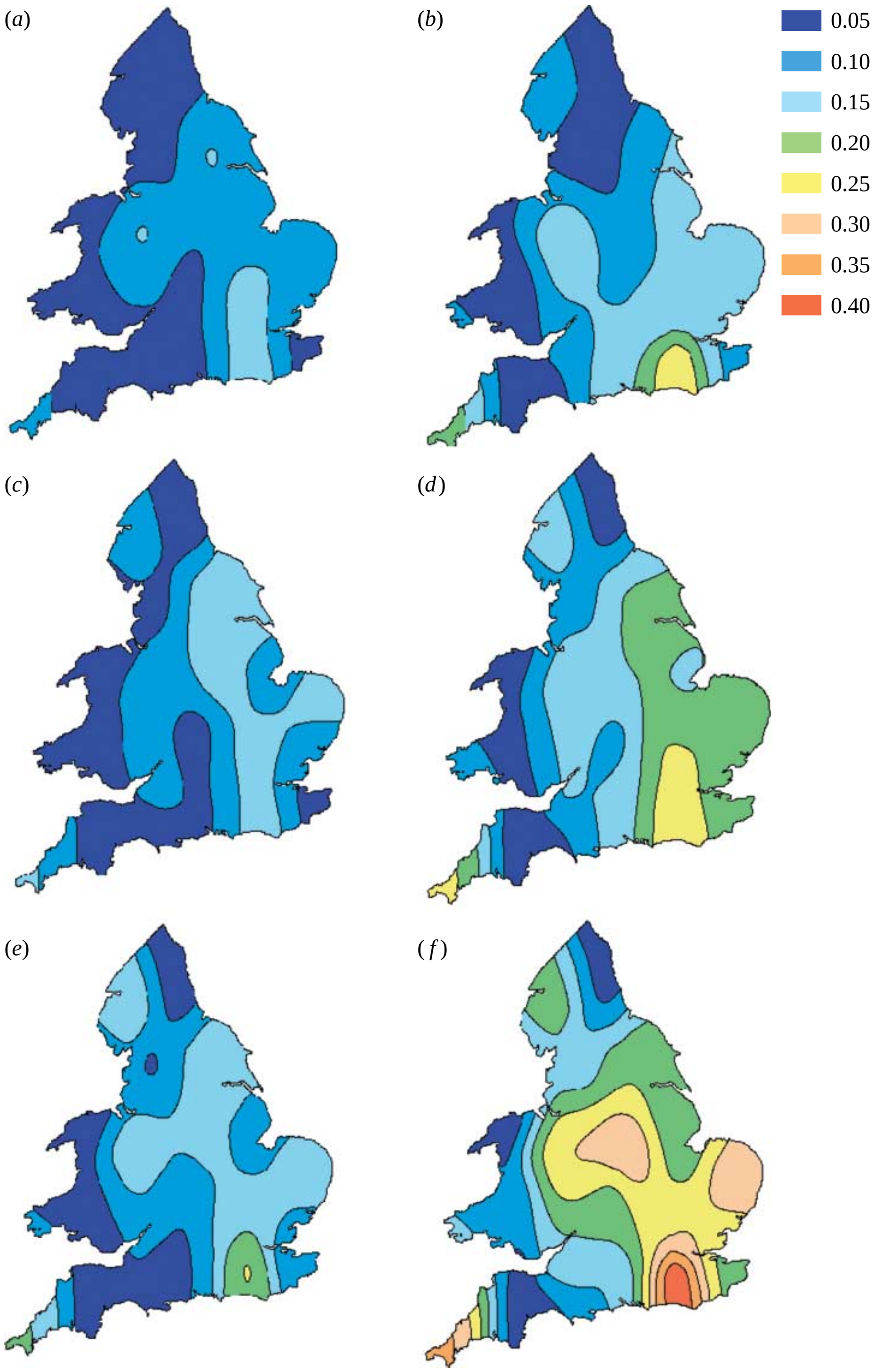

Figure 2. The probability of maximum temperature exceeds 27°C around flowering for (*a*,*c*,*e*) cv. Avalon and (*b*,*d*,*f*) cv. Mercia for the (*a*,*b*) baseline, (*c*,*d*) 2020HI and (*e*,*f*) 2050HI climate scenarios.

that monthly precipitation would be lower for all months from May to October, Q_{DSI}^{95} is predicted to decrease by approximately 0.05 for 2020HI and by 0.1 for 2050HI for the east of England. There are two factors contributing to a decrease in Q_{DSI}^{95}. The first factor is related to wheat phenology: in a warmer climate, wheat will mature earlier. Both cultivars are predicted to mature almost three weeks earlier for the 2050HI scenario compared with the baseline scenario (table 1). Because soil water deficit increases towards the end of crop growth, a crop can avoid the most severe drought stress. The second factor is related to changes in the precipitation pattern. Although summer is predicted to be drier for the UKCIP02 projections, winter is predicted to be wetter (figure 3, electronic supplementary material). Additional precipitation during winter and early spring would be stored in the soil (the exact amount of stored water will depend on soil AWC; figure 1 of the electronic supplementary material) and made available to the crop during late spring and early summer.

These results demonstrate that the impacts of changing climate on wheat can be counter-intuitive and that the severity of the impact depends strongly on cultivar characteristics and the spatial and temporal

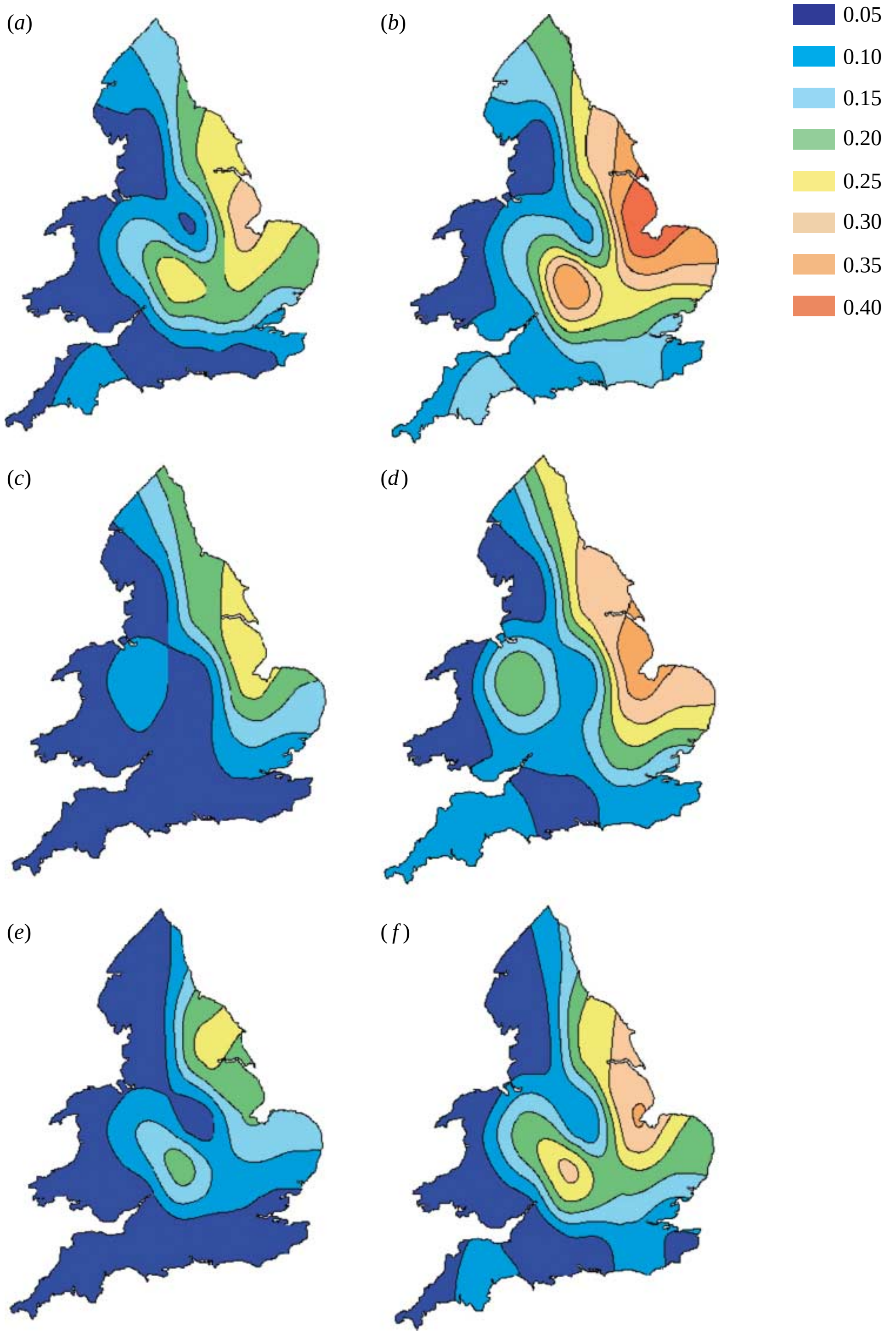

Figure 3. Ninety-five percentile for the DSI for (*a*,*c*,*e*) cv. Avalon and (*b*,*d*,*f*) cv. Mercia for the (*a*,*b*) baseline, (*c*,*d*) 2020HI and (*e*,*f*) 2050HI climate scenarios.

patterns of climate changes. Drought is the most significant environmental stress in agriculture worldwide, and improving yield in water-limited environments is a major goal of plant breeding (Cattivelli *et al.* 2008). Some researchers suggest that the impact of drought will increase with climate change (Witcombe *et al.* 2008), emphasizing the importance of breeding for drought-tolerant crops. Our results demonstrate that the impact of drought stress on two existing wheat cultivars in the UK is predicted to decrease with climate change. Drier and warmer summers, which are expected in the UK, do not necessarily mean additional yield losses due to water stress. Analysis showed that a more serious problem associated with global warming might be an increase in the frequency of heat stress around flowering, which represents a greater risk for sustainable wheat production (Barnabas *et al.* 2008). For late-flowering cv. Mercia, the probability of heat stress around flowering, $P^{\mathrm{T27}}_{\mathrm{ant+10}}$, may increase almost twofold for most of England.

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