https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions

Resilience of UK crop yields to changing climate extremes

Louise J. Slater[1*], Chris Huntingford[2], Richard F. Pywell[2], John W. Redhead[2], Elizabeth J. Kendon[3,4]

[1]School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK
[2]UK Centre for Ecology and Hydrology, Wallingford, Oxon, OX10 8BB, UK
[3]Met Office, FitzRoy Road, Exeter, Devon, EX1 3PB, UK
[4]Bristol University, Faculty of Science, BS8 1UH, UK

**Correspondence to*: Louise J. Slater (louise.slater@ouce.ox.ac.uk)

Abstract. Recent extreme weather events have had severe impacts on UK crop yields, and so there is concern that a greater frequency of extremes could affect crop production in a changing climate. Here we investigate potential future impacts of climate projections on wheat, the most widely grown cereal crop globally, in a temperate country with currently favourable wheat-growing conditions. Past and projected climate conditions are considered for key wheat growth stages (Foundation, Construction and Production). Historically, following the plateau of UK wheat yields since the 1990s, we find there has been a recent significant increase in wheat yield volatility, which is partially explained by seasonal metrics of temperature and precipitation, including mean, extremes, and intra-seasonal variability. Strong associations between climate and yield anomalies occur during years with cumulative climate impacts across growth stages, when climate extremes 'escape' the ability of farmers to adapt through agronomic means. We then analyse the latest 2.2km UK Climate Projections for the UK's three main wheat-growing regions. Climate projections indicate that on average across the three regions, the Foundation growth stage (broadly 1st October to 9th April) is likely to become warmer and wetter, while the Construction (10th April to 10th June) and Production (11th June to 26th July) stages are likely to become warmer and slightly drier. An analogue approach, comparing historical climate conditions with future climate projections, reveals a mixed picture of future climate conditions for UK crop yields. Projected warmer winter night temperatures are likely to prove beneficial in the Foundation stage, but concurrent increases in heavy rain may be detrimental. Similarly, warmer and drier mean conditions may enhance yields during the Production stage, but increases in high temperatures and heat variability may increase plant stress, while decreases in rainfall may also threaten adequate water supply. Since future climatic conditions are likely to move outside the historically observed range, there may be challenges for agriculture to adapt management practices to realise any potential benefits.

1 Introduction

Globally, wheat is the most widely grown cereal crop by area, with more than 214 million hectares harvested and an annual production of about 730 million tonnes (FAO, 2018). In the UK, wheat is the most prevalent arable crop, with an annual planting of approximately 1.7 million hectares (ha) (DEFRA, 2018a). The UK climate has historically been well suited to growing wheat (Reynolds, 2010), with yields of approximately 8 t ha^{-1} (**Figure 1a-b**) compared to a global average of 3.5 t ha^{-}

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

[1] (FAO, 2018). However, recent climate extremes such as the UK hot summer of 2018 and wet autumn of 2019 had substantial negative impacts on farm businesses, with significant reductions in crop yields. This climate-mediated reduction of yields is supported by evidence from the UK government (DEFRA, 2018b, 2019), the farming industry (ADHB, 2020) and real-time precision yield monitoring (Hunt et al., 2019).

Observed, direct impacts of climate change on crop yields are emerging globally (Brisson et al., 2010; Grassini et al., 2013; Hochman et al., 2017). Combined with the nutrition demands of a rapidly growing global population, there is an urgent requirement to estimate these effects on future crop yields. Breeding and evaluating new wheat varieties tolerant of hotter, drier summers may take decades (Zheng et al., 2012), and it is unclear whether advances in agronomy are occurring fast enough to mitigate the impacts of any accelerating frequency of extreme climatic events (Chen, D. et al., 2021). Changing climatic conditions may also affect yields indirectly by constraining the ability of farmers to undertake key management actions of tillage, sowing and harvest, or by causing damage to natural capital, such as soil erosion. These new constraints on yields may overtake any gains from physiological and phenological advances obtained through plant breeding.

In order to assess this risk to future food production, there is a critical need to understand how climate extremes are likely to evolve during the seasonal growth phases that are most relevant to the farming industry. Observational evidence has revealed changes in the intensity, frequency, duration, and extent of weather extremes, such as heavy rainfall events and hot days, across certain regions and continents (Rahmstorf and Coumou, 2011; Slater et al., 2021). Most climate research has described weather extremes by using seasonal or annual metrics rather than focussing on the specific periods most relevant to crop growth (Frich et al., 2002; Zhang et al., 2011), although some have related weather indices to potential crop variability or projected damage (Harkness et al., 2020; Iizumi and Ramankutty, 2016; Rosenzweig et al., 2001; Trnka et al., 2014). Of the total annual crop losses in world agriculture, many are due to direct weather and climatic effects such as drought, flash floods, heavy rainfall in otherwise dry periods, frost, hail, and storms (Ray et al., 2019; Sultan et al., 2019). High temperatures and heat stress lead to stomatal closure and therefore reduced photosynthesis due to restricted CO_2 diffusion (Chaves et al., 2003), offsetting potential yield gains that might otherwise occur with greater fertilization in a CO_2-enriched environment. In some regions of the mid and high latitudes, water excess may prove more detrimental to wheat yields than drought (Zampieri et al., 2017). Overall, there is thus a need to investigate historical data to elucidate the linkage between extreme temperature and rainfall over the agricultural phases of relevance to crop growth. Climate models may then be employed to explore how such linkages might evolve as atmospheric greenhouse gas concentrations rise.

This work thus investigates: (1) whether statistically significant associations exist between observed temperature/precipitation metrics and historical wheat yields during the three crop growth stages, in the three main wheat-growing regions of the UK; and (2) the extent to which projections of future temperature and precipitation extremes under a high-emissions scenario may impact future crop yields. To assess future changes in precipitation and temperature extremes, we employ state-of-the-art UK Climate Projections Local (UKCP 2.2km) convection-permitting simulations, which constitute a step-change in resolving

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

small-scale processes in the atmosphere. These climate projections are considered the most reliable simulations presently available in terms of their ability to project future changes in meteorological extremes over the UK.

2 Methods

2.1 Wheat yield data

Geographically, we focus on the three main wheat-growing regions outlined using the EU "NUTS" classification (European Commission, 2010). These three regions are (i) North Eastern Scotland, Eastern Scotland, and the North East English region (SNE); (ii) East Midlands, Yorkshire and the Humber regions (EMYH); and (iii) South East and Eastern region (SEE) (**Figure 1c-d**). These three regions account for over 80% of total UK wheat production by tonnage (DEFRA, 2015) and correspond with the yield reporting boundaries of available data. The regional wheat yield data were obtained from the UK Department for Environment, Food and Rural Affairs (Defra) (DEFRA, 2015). The data are drawn from the England Cereals and Oilseeds Production Survey and Scotland Cereal Production and Disposal Survey, part of an annual survey of the UK agricultural industry. For full details of the survey methodology, see (DEFRA, 2018b). The data were summarised by Defra to average yield at the national (1885-2020) and regional (1990-2020) levels, resulting in 136 and 31 years of data, respectively.

The dates for the Foundation, Construction, and Production growth stages are taken from benchmarks in the UK's 'Wheat growth guide', in **Table 1** (AHDB, 2018). Absolute anomalies of wheat yields were computed by fitting a locally-weighted scatterplot smoothing curve (LOESS) to obtain the running mean (red lines shown in **Figure 1a-b**), and subtracting this running mean from each annual value (resulting anomalies shown in **Figure 1c**).

2.2 Historical precipitation and temperature reference data

As historical climate data we employ the HadUK gridded 5km observational data from the National Climate Information Centre (NCIC) (Hollis et al., 2019). Provisional HadUK data were employed for the year 2020, produced as per previous years (Hollis et al., 2019); provisional data may have very small differences at regional scales compared with the final published dataset, available later in the year. Observed precipitation and temperature data were checked for completeness: any incomplete crop growth stages (i.e. a Foundation phase with less than 187 days; a Construction phase with less than 60 days, or a Production phase with less than 46 days) were removed, to ensure consistency and comparability across years.

To investigate the association with crop yields, we computed climate metrics within each geographical region and wheat growth stage (**Table 2**), using region-averaged values of temperature (°C) and precipitation (mm). For temperature, we assessed the maximum, mean, and minimum of the region-averaged maximum daily temperature (*max_maxT*, *mean_maxT*, *min_maxT*), of the mean daily temperature (*max_meanT*, *mean_meanT*, *min_meanT*), and of the minimum daily temperature (*max_minT*, *mean_minT*, *min_minT*). For example, *max_maxT* indicates the day with the hottest (maximum hourly) temperature, and *max_minT* indicates the day with the warmest night-time (minimum hourly) temperature, during a given

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics Discussions

growth stage. We also assess metrics representing the daily variability of temperature (*var_dailyT*) and its seasonal variability (*var_maxT*, *var_meanT*, *var_minT*). For instance, *var_maxT* indicates the difference between the highest/lowest daily values of maximum hourly temperature in a season.

For precipitation, we computed metrics representing the total region-averaged daily precipitation within a growth stage (*total_P*) and its quantiles (*max_dailyP* or *mean_dailyP*), where *max_dailyP* is the maximum total daily precipitation within a growth stage. We also considered the variability of daily precipitation across a growth stage (*varP_Q0.95-Q0.05*); the number of heavy rainfall days where precipitation exceeds 10mm (*days_P>10mm*); and the number of dry days where precipitation is less than 0.01mm (*days_P<0.01mm*) (**Table 2**).

2.3 UKCP Local (2.2km) projections

The UKCP Local (2.2km) simulations are notable for their ability to represent convective precipitation events (see (Kendon et al., 2019, 2020) for details), thus providing credible projections of future changes in short-duration precipitation extremes, and in particular for summer months. The UKCP Local simulations were initially released in September 2019 (Kendon et al., 2019) but were then updated in July 2021 after correction of an error in the representation of graupel (soft ice pellets) (Kendon et al., 2021). Here we use the new updated Local 2.2km projections. The local 2.2km model (HadREM3-RA11M) spans the UK and is nested within the 12km regional model (HadREM3-GA705), which is in turn driven by the 60km global model (HadGEM3-GC3.05) (Andrews et al., 2019; Williams et al., 2018). The 2.2km-projections are available for three 20-year periods of 1981-2000, 2021-2040 and 2061-2080. Known atmospheric GHG concentrations are prescribed as forcings to the historical period. For the second and third periods, the projections employed follow the RCP8.5 scenario, which assumes substantial on-going human burning of fossil fuels. The 2.2km projections consist of an ensemble of 12 members (**Table 3**), each of which can be considered as a plausible realisation of the climate. The local members are driven by different members of the global coupled model ensemble, and corresponding regional model ensemble, created by perturbing uncertain parameters in the model physics. Thus, the range of the 2.2km projections provides an estimate of the uncertainty in future changes due to natural variability and uncertainty in the physics of the driving global climate model. We computed regionally-averaged UKCP temperature and precipitation projections for each of the three regions shown in **Figure 1d**, and for each of the crop growth stages indicated in **Table 1**.

2.4 Bias correction

UKCP Local simulations of area-averaged precipitation and temperature were bias-corrected against the 5km area-averaged observed daily HadUK data (Hollis et al., 2019) for each geographical region, using the entire the historical period of Dec 1980 to Nov 2000 (**Table 3**). The bias correction scaling factors were identified and applied with the "hyfo" (Xu, 2020) package in the software R. The UKCP data have 30 days in each month, therefore, to perform the bias correction we added calendar days for each of the three 20-year periods (e.g. from 1980-12-01 to 2000-11-30 with only 30 days in each month) and

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics Discussions

merged the historical period with observed data, removing any non-matched days (e.g. dropping the 31st of the month from the observed data, or dropping February 29th-30th from the projections). This produced two overlapping time series of equal length over the period of Dec 1980 to Nov 2000 to perform the bias correction. The bias correction factors are multiplicative for precipitation (one factor per ensemble, per region), and additive for temperature. We make the assumption these present-day biases are likely to extend into the future periods, a key caveat of any bias correction method. The bias correction factors are relatively small, which suggests the simulations are well-aligned with the historical observations: x0.89 on average for precipitation for the three regions (individual factors for each member and region are shown in **Table 3**); −0.04°C for minimum daily temperature, +0.54°C for mean daily temperature, and +1.14°C for maximum daily temperature. We apply the bias corrections to the two future UKCP periods (Dec 2020 to Nov 2040 and Dec 2060 to Nov 2080, recalling these are for the RCP8.5 scenario). The bias correction performs well at the annual scale (**Figure 2**) but may differ across specific growth stages and regions (e.g. in the Foundation phase, median precipitation is slightly overestimated in EMYH and SEE regions) (**Figure 3**). Bias-corrected projections inevitably contain some uncertainty, and should be considered as providing general directions of change. 1989-1960+1

3 Results and Discussion

3.1 Historical increases in wheat yields and interannual yield volatility

Since the late 1800s, and especially since the 1950s, there has been exceptional growth in UK wheat yields due to rapid advances in crop breeding, increasing farm mechanisation and the availability of agrochemical inputs, such as fertilisers (**Figure 1a**). Sustained increases throughout the 1980s-90s reflect the development of farming technologies, varieties, improved nutrient use efficiency and effective pesticides and growth regulators. Available time series of crop yields are much shorter when disaggregated to the regional level (**Figure 1b**) than at the national level (**Figure 1a**). Of particular note, though, is that the EMYH and SNE regions exhibit a levelling of wheat yields since 1990, mirroring the national trend, while the southernmost region, SEE, has seen some continued increases (**Figure 1b**).

In addition to increases in mean yields, the national yield time series exhibits a visible increase in the variance of yields in the last few decades (**Figure 1c**). This increase in volatility is not solely driven by increases in the mean of the time series. A comparison of the variance of crop yields between the periods 1885-1989 (105 years) and 1990-2020 (31 years) using both Levene's test ($p=0.022$) and the non-parametric Fligner-Killeen's test ($p=0.093$) indicates that there is a significant difference in the variance. The results are even more significant when comparing periods of similar length, 1960-1989 and 1990-2020 (30-31 years) for both Levene ($p=0.002$) and Fligner-Killeen ($p=0.003$), or focussing on the last two decades, 1970-1999 and 2000-2020 (30-21 years); $p<0.001$ for both tests. A question of notable interest, therefore, is understanding why the growth in yields has been levelling off (Knight et al., 2012) while the variance has significantly increased, and whether it is associated with more frequent or intense weather extremes.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics Discussions

3.2 Association between climate extremes and wheat yields in each crop growth stage

We assess the association between seasonal climate and crop yields by using precipitation and temperature during the three crop growth stages. In **Figures 4-5**, we employ *total_P*, *max_minT*, and *max_maxT* in each growth stage, as these are some of the most relevant metrics in the historical data (**Table 2**). It is indisputable that some of the worst UK wheat yields in recent decades have occurred during years with anomalously high or low seasonal rainfall (**Figure 4**; 1976, 2001, 2007, 2012, 2020). Further, prolonged heat is also an important indicator of crop heat stress (Arnell and Freeman, 2021); figures produced using *max_maxT* give very similar patterns to *max_meanT* (not shown).

From a crop physiology perspective, in the Foundation phase (October to early April; **Table 1**), prolonged waterlogging of the soil may suppress wheat yields by restricting root development and plant growth (AHDB, 2018). Some reduced yields have occurred in years with anomalously wet Foundation stages (e.g. years 2001, 2020; **Figure 4a**). In particular, in the Foundation stage, we find a significant negative association between crop yields and the number of heavy rainfall days in the EMYH region (**Table 2**, *days_P>10mm*). In the winter of 2000/01, for instance, wet autumn and winter conditions resulted in delayed sowing and poor seedbed conditions. Additionally, colder-than-usual conditions in the Foundation stage (e.g. year 2013, not shown) may delay or prevent crop tillering. Frost can damage early drilled and fast-growing varieties, while frost heave can kill seedlings. As confirmation, during the Foundation phase, we find significant positive associations between yield and *max_minT* at the national scale and in the EMYH region, and with *min_meanT* and *min_minT* in the SEE region (**Table 2**). The positive associations indicate that warming temperatures may benefit UK wheat yields in a warming climate.

While crops are growing rapidly during the Construction phase (April to early June), both late frosts and dry weather can reduce crop growth (**Table 1**). For this period in each year, we find no significant associations between climate characteristics and crop yields (**Table 2**). Both low yields (e.g. years 1976, 2001, 2020; **Figure 4b**) and some high yields (1962, 1984) have occurred during drier-than-average Construction phases. Overall, wheat yields seem to be more sensitive to climate conditions during the Foundation or Production phases.

The clearest association between climate extremes and crop yields seems to be in the Production phase, which is the time from post-flowering to harvest (summer: June and July). It is during this phase that yields may be susceptible to both drought and water logging (**Table 1**). We find a consistently negative association between heavy rainfall (both *total_P* and *days_P>10mm*) and crop yield in all three regions. For *total_P* the association is significant in EMYH and at the national scale, and for *days_P>10mm* in EMYH (**Table 2**). The association between low wheat yields and high summer rainfall is apparent in specific years such as 2007 and 2012 (top left of **Figure 4c** and **Figure 5c**). For example, year 2012 witnessed exceptionally poor yields due to high spring and summer rain, a high incidence of fungal disease (e.g. *Septoria tritici*) (DEFRA, 2012) and low sunlight during the grain-filling period (i.e. the first part of the production period, when the grain is swelling and requires sunlight for photosynthesis). In contrast, good yield years are associated with warm summer temperatures, and moderate to low rainfall (e.g. years 2015, 2019; **Figure 4c, Figure c**). This can be seen in the positive associations between wheat yields

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

and *max_maxT* or *max_meanT,* which are significant both nationally and in EMYH (**Table 2**). During the Production phase, meteorological drought conditions may also have negative impacts. Hot, dry weather shortens the growth period, resulting in early canopy senescence and reduced grain weight (**Table 1**). Indeed, some of the UK's poorest crop yields occurred during warm, dry summers (e.g. years 1976, 2013, 2018; **Figures 4c-5c**). The benchmark grain-filling period is 45 days from flowering until maximum dry weight in late July, but it can be as short as 28 days during severe droughts (AHDB, 2018).

3.3 Explaining the association between crop yields and climate extremes: cumulative impacts across growth stages

It can be challenging to systematically identify the weather conditions to which wheat yields are most vulnerable within individual growth phases. The often relatively weak association between climate anomalies and wheat yields at the level of individual stages (**Table 2**) can be explained partly by the combined resilience of the wheat plant (i.e. physiological reproductive mechanisms) and the husbandry skills of farmers and agronomists in mitigating these impacts by adjusting to climatic extremes. Farmers can dampen the effects of climatic variation through crop management, such as changing the timing or amount of inputs of nutrients, pesticides and growth regulators (Knight et al., 2012). The relatively input-intensive nature of UK wheat production (Hillocks, 2012; Wesseler et al., 2015) may, under contemporary climate conditions, be sufficient to mask crop responses to interannual climatic variation (Gagic et al., 2017). Growing a diversity of crop types has equally been effective in managing the risks posed to food production by extreme weather in temperate regions. Wheat cultivars are bred with a measure of resistance to certain climatic variables, so a farmer can select a cultivar appropriate to local climatic conditions (Kahiluoto et al., 2019). Low correlations between climate and yield anomalies over seasonal wheat growth stages may also reflect compensatory effects between growing phases. For instance, a less than ideal Foundation phase might be offset by a favourable Production phase or *vice versa*.

Conversely, we find that cumulative detrimental impacts of climate across stages (e.g. accumulated rainfall and subsequent waterlogging) may be one of the most damaging factors affecting overall annual crop yields. In other words, the flexibility and techniques farmers have at their disposal to adapt to climate variability are bounded. For instance, low yields in year 2018 were due to very dry conditions in the Foundation stage, followed by very hot and dry conditions in the Construction and Production stage (DEFRA, 2018a). In contrast, very low yields in years 2001 and 2007 were caused by a combination of high rainfall in the Foundation and Production stages (**Figure 4**). The exceptionally wet winter of 2019 (affecting the 2020 harvest in **Figure 4**) also imposed severe constraints on farming operations and resulted in a reduction in the areas of autumn-sown crops. These examples illustrate why a full understanding of projected changes to temperature and precipitation across wheat growth stages is required.

To assess the additive effects of climate across growth stages, we develop a simple climate scoring system, accounting for both positive and negative climate impacts on wheat yield across a year. Such an approach allows the relevant climate index to vary for each individual phase. For instance, it may be heavy precipitation events during the Foundation phase, followed by meteorological drought and hot temperature events during the Production phase, that combine to give low yields. Using **Table**

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics Discussions

2, we select just two metrics per phase to test the approach, avoiding correlated metrics. For the Foundation (*max_minT*) and Production (*max_maxT*) phases, we assign a negative (positive) score of −1 (+1) when the *max_minT*/*max_maxT* drops below the 20th percentile (exceeds the 80th percentile) of the historical observations. For both phases, we assign a negative (positive) score of −1(+1) when *total_P* exceeds the 80th percentile (drops below the 20th percentile) of the historical observations. Alternative metrics could also be selected, such as *var_dailyT or var_maxT* in the Production phase, or *days_P>10mm* in either phase (but these are likely to show similar relationships). The Construction phase is ignored as it shows no consistent associations with wheat yields. We find a significant positive association between the combined climate score and wheat yields for EMYH, SEE, and the national scale (**Figure 6**), but not SNE (p=0.12), where the association is weaker. Even stronger associations are found when using the 10th and 90th percentiles as thresholds (not shown), although there is still scatter, as might be expected. Strong associations between climate and yield anomalies thus seem to occur during years with cumulative climate impacts across phases, when climate extremes 'escape' the ability of farmers to adapt through agronomic means.

3.4 Annual projections of future crop-growing conditions

For the future period, to estimate changing meteorological conditions due to climate change, we employ simulations associated with the RCP8.5 scenario for atmospheric greenhouse gas concentrations. While the likelihood of such high on-going emissions is considered low (Chen, D. et al., 2021), RCP8.5 is still a plausible scenario and commonly used to facilitate detection of climate signals in future projections above natural variations in the climate. The UKCP18 HadGEM3 climate model simulations (in which the UKCP Local simulations are nested) were only performed for the RCP8.5 pathway.

At the annual scale, projections of future maximum hourly temperature are available for the periods 2021-2040 and 2061-2080 from the UKCP Local simulations. The interquartile range of projected temperature for 2021-2040 lies well above the median of historical extremes (**Figure 2a-c**). Future high-temperature conditions generally fall beyond the bounds of annual variability experienced in the contemporary period for all three wheat-growing regions (**Figure 2c**). As expected, changes are largest for the later modelled period 2061-2080, corresponding to higher atmospheric greenhouse gas concentrations. This exceedance of historical thresholds by temperature projections is true for all 12 UKCP Local ensemble members, independent of uncertainty in changes in the large-scale conditions sampled by perturbing parameters in the Hadley Centre global climate model. However, it is important to note that the 12 climate model members (**Table 3**) do not sample the full range of uncertainty, evident in differences between all available global climate models (Kendon et al., 2021). In particular, UKCP simulations tend to sample greater future warming and drying in summer compared to the full CMIP5 ensemble.

For total annual precipitation (**Figure 2d**), the projections do not indicate a very obvious increase or decrease in any of the three regions relative to the historical period, although SNE may seem very slightly wetter, and SEE very slightly drier on average (comparing medians) in the later period (2061-2080). This lack of trend in yearly data may be explained by the opposing changes in the different seasons: in general the winter season is projected to become wetter and the summer drier (Kendon et al., 2021). Importantly, there are also changes in the underlying intensity and frequency of precipitation (e.g.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

significant increases in *days_P>10mm* in the Foundation phase, **Figure 7**), which are not evident from simply looking at trends in annual mean precipitation.

3.5 Seasonal projections of future crop-growing conditions

When considering UKCP Local projections by wheat growth stages (instead of at the annual scale), clearer patterns become apparent (**Figure 3**). For the Foundation phase (October to early April), all regions can expect to see progressively warmer, wetter conditions in the coming decades according to the UKCP simulations. Significant projected increases in *max_minT*, *max_maxT*, and *total_P* are evident in all three regions during the Foundation phase (**Figure 7**). Such conditions might not necessarily adversely affect wheat production (**Figure 4**), and are likely to be beneficial in decreasing the risk of frost damage (**Table 2**). When considering *max_minT* and *total_P*, the projections indicate that there is a good chance of seeing more winters similar to the one preceding year 2015, where Foundation conditions were warm and not too wet, resulting in high crop yields (**Figure 4a**); however, the projected increases in total and heavy rain (*total_P* and *days_P>10mm*; **Figure 7**) may equally prove problematic. In very wet years, the UK may also experience winters more like those of 2001 and 2020, which led to low yields across the UK (**Figure 4a**), especially in EMYH/SEE (**Figure 5a**).

In the Construction phase (mid-April to mid-June), the projections indicate significant decreases in *total_P* in EMYH and SEE, but not SNE (**Figure 7**). There are no evident changes in heavy rain (*days_P>10mm*; **Figure 7**), and we find considerable overlap with both good and poor yields in the historical data (**Figure 4b**). These findings suggest that the Construction phase may not necessarily be the most at-risk in terms of the impacts of changing UK climate to crop yields.

In the Production phase (mid-June to end of July), UKCP simulations project both much warmer and somewhat drier conditions in all three regions (**Figure 3**). The drying signal is relatively similar across the three regions and becomes more apparent in the later simulations towards the end of the century. Projected trends indicate significant, strong increases in *max_minT*, *max_maxT*, and equally in temperature variability (*var_dailyT* and *var_maxT*; **Figure 7**). A simple analogue approach suggests we may see more Production phases similar to years 2006, 2015 and 2019 in the EMYH/SEE regions, conducive to high yields (**Figure c**). Both the national and the regional data suggest all regions may benefit from a warmer and drier Production phase (**Figure 4c-5c**). The projected trends reveal significant decreases in *total_P* but no apparent decreases in heavy rain (**Figure 7**). However, individual anomalous years with poor yields and warm dry conditions remain plausible, such as year 1976 at the national scale (**Figure 4c**), and 2013 in the SNE and SEE areas (**Figure 5c**). Because the projected high-temperature conditions are outside those experienced in the historic period, there is also a risk that the positive association between hotter, drier Production phases and enhanced yield will no longer hold. Droughts and heatwaves severe enough to have a substantial impact on yield are rare in the historic data (Knight et al 2012), and so we have little data by which to determine at what thresholds temperature and dryness cease to be beneficial for wheat and begin to have negative impacts. However, the anomalous years (e.g. 1976 and 2013) suggest that this can occur, and recent research indicates that days exceeding heat stress temperatures for wheat are likely to increase under climate change (Arnell et al., 2021). The increase in high temperatures and their variability is evident in the Production phase across the three regions (*max_maxT* and *var_maxT*, **Figure 7**).

Overall, projections of future temperature and precipitation conditions do not significantly aggravate our simple combined climate score, when relying on *max_minT, max_maxtT* and *total_P* (**Figure 6**). Some highly positive climate scores, suggesting higher yields, are found in the far-future period (2061-2080), likely due to the effect of warming conditions and thus reduced frost risk in the Foundation phase. These beneficial impacts may however be offset by significant increases in heavy rainfall projected in the Foundation phase and enhanced drought conditions in the Production phase (**Figure 7**).

4 Conclusions

Mean UK crop yields saw a rapid growth in the 1950s followed by a plateau in the 1990s, then substantial increases in the inter-annual variability of yields. This acceleration has been challenging for UK wheat farmers, since inter-annual crop yields over the past two decades (2000-2020) have been significantly more volatile than over the previous century (**Figure 1**). A key question is thus our ability to explain such changes. While the plateau in yields can be explained by a variety of technological and agronomic factors, the recent raised volatility of yields is partially explained by one-to-one correlations with temperature or precipitation extremes during the individual growth stages (**Table 2**), and more fully explained when considering a combined climate score (**Figure 6**), characterising additive impacts of climate across growth phases (e.g. detrimental impact of very cold temperatures in Foundation phase followed by very high precipitation in the Production phase). Such a scoring approach could be refined further (e.g. beneficial impacts of a warm and dry Production phase, but only up to certain thresholds relevant to plant stress). We find the association between historical climate and crop yields is most evident in years which saw climate anomalies across multiple growth stages (e.g. 2007, 2012, 2020, **Figures 4-5**), 'escaping' the ability of farmers to adapt through agronomic means. Outside these combined extremes, the data indicate a strong inter-annual resilience of wheat production, implying that at present farmers can, and do, successfully utilise crop husbandry to maintain yield levels.

Overall, the comparison between climate and crop yields provides mixed evidence of both favourable and detrimental future climate conditions. High seasonal values of minimum temperatures (*max_minT*) during the Foundation phase are correlated positively and significantly with crop yields (**Table 2**), suggesting that the future increases in temperature projected by the UKCP Local simulations (**Figure 3a**) are likely to provide more beneficial growing conditions during the winter. Later in the year during the Production phase, where high rainfall totals adversely affect growing and production conditions (**Table 2**), the UKCP local simulations project significantly warmer and drier mean conditions (**Figure 7**), which may be conducive to positive yields, similar to the years 2015 and 2019 (**Figure 4**). However, significant increases in heavy rainfall (*days_P>10mm*) in the Foundation phase and enhanced likelihood of drought, with increasingly variable maximum temperatures (*var_maxT*) and decreased rainfall (*total_P*) in the Production phase could equally be detrimental to wheat yields (**Figure 7**). Future anomalous years similar to 2020, with a wet crop Foundation phase and a much drier Construction phase that significantly suppressed yields (**Figure 4**), are a real possibility. It seems plausible that the farming community may also face increased inter-annual variability in the future, e.g. a sequence of dry years (similar to 2019) followed by very wet years (2001, 2012) against a backdrop of warmer and wetter/drier conditions. Further analyses could equally assess whether the optimal time and place to grow wheat is changing, as more data becomes available over time.

In summary, this work provides some evidence that the recent increase in yield volatility is associated with combined climate metrics, especially across the crop Foundation and Production phases. However, the relationships between past wheat yields and historic climatic conditions may not be adequate guides to the risks associated with projected future conditions, as future temperature extremes and rainfall lie outside the range of conditions that UK agriculture has so far experienced. Out of caution, therefore, a priority is to continue developing resilient agricultural systems to emerging climate patterns, as the global demand for wheat and other crops has been projected to double from 2005 to 2050 (Tilman et al., 2011). Further research into robust process-based or AI-informed crop models, alongside improved collaboration across spatial, governance and supply-chain scales (Holman et al., 2021), will be required to help farmers adapt to evolving climate conditions and maintain the security of wheat production.

References

ADHB: AHDB Harvest Report. Report 6-Week 13. Week ending 6th October. [online] Available from: https://ahdb.org.uk/cereals-oilseeds/gb-harvest-progress, 2020.

AHDB: Wheat growth guide, Kenilworth, Warwickshire. [online] Available from: https://cereals.ahdb.org.uk/media/185687/g66-wheat-growth-guide.pdf, 2018.

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., Menary, M. B., Ridley, J., Ringer, M. A., Sellar, A. A., Senior, C. A. and Tang, Y.: Forcings, Feedbacks, and Climate Sensitivity in HadGEM3-GC3.1 and UKESM1, J. Adv. Model. Earth Syst., 11(12), 4377–4394, doi:10.1029/2019MS001866, 2019.

Arnell, N. W. and Freeman, A.: The effect of climate change on agro-climatic indicators in the UK, Clim. Change, 165(1–2), 40, doi:10.1007/s10584-021-03054-8, 2021.

Arnell, N. W., Freeman, A., Kay, A. L., Rudd, A. C. and Lowe, J. A.: Indicators of climate risk in the UK at different levels of warming, Environ. Res. Commun., 3(9), 095005, doi:10.1088/2515-7620/ac24c0, 2021.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F. X. and Huard, F.: Why are wheat yields stagnating in Europe? A comprehensive data analysis for France, F. Crop. Res., 119(1), 201–212, doi:10.1016/j.fcr.2010.07.012, 2010.

Chaves, M. M., Maroco, J. P. and Pereira, J. S.: Understanding plant responses to drought - From genes to the whole plant, Funct. Plant Biol., 30(3), 239–264, doi:10.1071/FP02076, 2003.

Chen, D., Rojas, M., Samset, B. H., Cobb, K., Diongue Niang, A., Edwards, P., Emori, S., Faria, S. H., Hawkins, E., Hope, P., Huybrechts, P., Meinshausen, M., Mustafa, S. K., Plattner, G. K. and Tréguier, A. M.: Framing, Context, and Methods. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change., 2021.

DEFRA: Farming Statistics: Final Crop Areas, Yields, Livestock Populations and Agricultural Workforce at 1 June 2012, United Kingdom. [online] Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/183200/defra-stats-foodfarm-landuselivestock-farmingstats-june-statsrelease-june12finaluk-121220.pdf, 2012.

DEFRA: UK Production by Region, 2015.

DEFRA: Agriculture in the United Kingdom 2018, Dep. Environ. Food Rural Aff. London, UK, 1–111 [online] Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/741062/AUK-2017-18sep18.pdf, 2018a.

DEFRA: June survey of agriculture and horticulture in England. Final crop areas, yields, livestock populations and agricultural workforce., (June), 1–22 [online] Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/267619/structure-jun2013final-UK-19dec13.pdf, 2018b.

DEFRA: June survey of agriculture and horticulture in England. Final crop areas, yields, livestock populations and agricultural workforce., Natl. Stat., (June), 1–22 [online] Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/865769/structure-jun2019final-uk-22jan20-rev_v2.pdf, 2019.

European Commission: Eurostat NUTS Administrative statistical units., [online] Available from: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts, 2010.

FAO: FAOSTAT crops [web database]., [online] Available from: http://www.fao.org/faostat/en/#data/QC, 2018.

Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Tank Klein, A. M. G. and Peterson, T.: Observed coherent changes in climatic extremes during the second half of the twentieth century, Clim. Res., 19(3), 193–212, doi:10.3354/cr019193, 2002.

Gagic, V., Kleijn, D., Báldi, A., Boros, G., Jørgensen, H. B., Elek, Z., Garratt, M. P. D., de Groot, G. A., Hedlund, K., Kovács-Hostyánszki, A., Marini, L., Martin, E., Pevere, I., Potts, S. G., Redlich, S., Senapathi, D., Steffan-Dewenter, I., Świtek, S., Smith, H. G., Takács, V., Tryjanowski, P., van der Putten, W. H., van Gils, S. and Bommarco, R.: Combined effects of agrochemicals and ecosystem services on crop yield across Europe, Ecol. Lett., 20(11), 1427–1436, doi:10.1111/ele.12850, 2017.

Grassini, P., Eskridge, K. M. and Cassman, K. G.: Distinguishing between yield advances and yield plateaus in historical crop production trends, Nat. Commun., 4, doi:10.1038/ncomms3918, 2013.

Harkness, C., Semenov, M. A., Areal, F., Senapati, N., Trnka, M., Balek, J. and Bishop, J.: Adverse weather conditions for UK wheat production under climate change, Agric. For. Meteorol., 282–283(December 2019), 107862, doi:10.1016/j.agrformet.2019.107862, 2020.

Hillocks, R. J.: Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture, Crop Prot., 31(1), 85–93, doi:10.1016/j.cropro.2011.08.008, 2012.

Hochman, Z., Gobbett, D. L. and Horan, H.: Climate trends account for stalled wheat yields in Australia since 1990, Glob. Chang. Biol., 23(5), 2071–2081, doi:10.1111/gcb.13604, 2017.

Hollis, D., McCarthy, M., Kendon, M., Legg, T. and Simpson, I.: HadUK-Grid—A new UK dataset of gridded climate observations, Geosci. Data J., 6(2), 151–159, doi:10.1002/gdj3.78, 2019.

Holman, I. P., Hess, T. M., Rey, D. and Knox, J. W.: A Multi-Level Framework for Adaptation to Drought Within Temperate Agriculture, Front. Environ. Sci., 8(January), 1–14, doi:10.3389/fenvs.2020.589871, 2021.

Hunt, M. L., Blackburn, G. A., Carrasco, L., Redhead, J. W. and Rowland, C. S.: High resolution wheat yield mapping using Sentinel-2, Remote Sens. Environ., 233(December 2018), 111410, doi:10.1016/j.rse.2019.111410, 2019.

Iizumi, T. and Ramankutty, N.: Changes in yield variability of major crops for 1981-2010 explained by climate change, Environ. Res. Lett., 11(3), doi:10.1088/1748-9326/11/3/034003, 2016.

Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J. E., Ruiz-Ramos, M., Gobin, A., Kersebaum, K. C., Takáč, J., Ruget, F., Ferrise, R., Bezak, P., Capellades, G., Dibari, C., Mäkinen, H., Nendel, C., Ventrella, D., Rodríguez, A., Bindi, M. and Trnka, M.: Decline in climate resilience of European wheat, Proc. Natl. Acad. Sci. U. S. A., 116(1), 123–128, doi:10.1073/pnas.1804387115, 2019.

Kendon, E., Short, C., Pope, J., Chan, S., Wilkinson, J., Tucker, S., Bett, P. and Harris, G.: Update to UKCP Local (2.2km) projections, Science Report, Met Office Hadley Centre, Exeter, UK. [online] Available from: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp18_local_update_report_2021.pdf, 2021.

Kendon, E. J., Fosser, G., Murphy, J., Chan, S., Clark, R., Harris, G., Lock, A., Lowe, J., Martin, G., Pirret, J. and others: UKCP Convection-permitting model projections, Science report, Met Office Hadley Centre. [online] Available from: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP-Convection-permitting-model-projections-report.pdf, 2019.

Kendon, E. J., Roberts, N. M., Fosser, G., Martin, G. M., Lock, A. P., Murphy, J. M., Senior, C. A. and Tucker, S. O.: Greater future U.K. winter precipitation increase in new convection-permitting scenarios, J. Clim., 33(17), 7303–7318, doi:10.1175/JCLI-D-20-0089.1, 2020.

Knight, S., Kightley, S., Bingham, I., Hoad, S., Lang, B., Philpott, H., Stobart, R., Thomas, J., Barnes, A. and Ball, B.: Desk study to evaluate contributory causes of the current 'yield plateau' in wheat and oilseed rape. AHDB Project Report No. 502. [online] Available from: https://cereals.ahdb.org.uk/media/198673/pr502.pdf, 2012.

Rahmstorf, S. and Coumou, D.: Increase of extreme events in a warming world, Proc. Natl. Acad. Sci., 108(44), 17905–17909, doi:10.1073/pnas.1101766108, 2011.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V. and Chatterjee, S.: Climate change has likely already affected global food production, PLoS One, 14(5), 1–18, doi:10.1371/journal.pone.0217148, 2019.

Reynolds, M. P.: Climate change and crop production, Cabi., 2010.

Rosenzweig, C., Iglesias, A., Yang, X. B., Epstein, P. R. and Chivian, E.: Implications for food production, plant diseases, and pests, Glob. Chang. Hum. Heal., 2(2), 90–104 [online] Available from: http://link.springer.com/10.1023/A:1015086831467, 2001.

Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal, K., Lees, T., Matthews, T., Murphy, C. and Wilby, R. L.: Nonstationary weather and water extremes: A review of methods for their detection, attribution, and management, Hydrol. Earth Syst. Sci., 25(7), 3897–3935, doi:10.5194/hess-25-3897-2021, 2021.

Sultan, B., Defrance, D. and Iizumi, T.: Evidence of crop production losses in West Africa due to historical global warming in two crop models, Sci. Rep., 9(1), 1–15, doi:10.1038/s41598-019-49167-0, 2019.

Tilman, D., Balzer, C., Hill, J. and Befort, B. L.: Global food demand and the sustainable intensification of agriculture, Proc. Natl. Acad. Sci. U. S. A., 108(50), 20260–20264, doi:10.1073/pnas.1116437108, 2011.

Trnka, M., Rötter, R. P., Ruiz-Ramos, M., Kersebaum, K. C., Olesen, J. E., Žalud, Z. and Semenov, M. A.: Adverse weather conditions for European wheat production will become more frequent with climate change, Nat. Clim. Chang., 4(7), 637–643, doi:10.1038/nclimate2242, 2014.

Wesseler, J., Bonanno, A., Drabik, D., Materia, V. C., Malaguti, L., Meijer, M. and Venus, T. J.: Overview of the agricultural inputs sector in the EU, European Parliament, Policy Department B: Structural and Cohesion Policies European, Brussels., 2015.

Williams, K. D., Copsey, D., Blockley, E. W., Bodas-Salcedo, A., Calvert, D., Comer, R., Davis, P., Graham, T., Hewitt, H. T., Hill, R., Hyder, P., Ineson, S., Johns, T. C., Keen, A. B., Lee, R. W., Megann, A., Milton, S. F., Rae, J. G. L., Roberts, M. J., Scaife, A. A., Schiemann, R., Storkey, D., Thorpe, L., Watterson, I. G., Walters, D. N., West, A., Wood, R. A., Woollings, T. and Xavier, P. K.: The Met Office Global Coupled Model 3.0 and 3.1 (GC3.0 and GC3.1) Configurations, J. Adv. Model. Earth Syst., 10(2), 357–380, doi:10.1002/2017MS001115, 2018.

Xu, Y.: hyfo: Hydrology and Climate Forecasting. R package version 1.4.2, [online] Available from: https://cran.r-project.org/package=hyfo, 2020.

Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A.: Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales, Environ. Res. Lett., 12(6), doi:10.1088/1748-9326/aa723b, 2017.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B. and Zwiers, F. W.: Indices for monitoring changes in extremes based on daily temperature and precipitation data, Wiley Interdiscip. Rev. Clim. Chang., 2(6), 851–870, doi:10.1002/wcc.147, 2011.

Zheng, B., Chenu, K., Fernanda Dreccer, M. and Chapman, S. C.: Breeding for the future: What are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (Triticum aestivium) varieties?, Glob. Chang. Biol., 18(9), 2899–2914, doi:10.1111/j.1365-2486.2012.02724.x, 2012.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions

Acknowledgements

L.J.S gratefully acknowledges the UK Research and Innovation FLF scheme (MR/V022008/1). C.H., R.F.P. and J.R. gratefully acknowledge the Agland project. C.H. also acknowledges the NERC CEH National Capability Fund. R.F.P., C.H. and J.R. were supported by research programme NE/N018125/1 LTS-M ASSIST - Achieving Sustainable Agricultural Systems, funded by NERC and BBSRC. E.J.K. gratefully acknowledges funding from the Joint UK BEIS/Defra Met Office Hadley Centre Climate Programme grant no. GA01101.

Code/Data Availability

All data employed in the manuscript are publicly available as described in the Methods. (1) HadUK gridded 5km observational temperature and precipitation data were obtained from the National Climate Information Centre. (2) UKCP 2.2km Local temperature and precipitation projections were obtained from the UK Met Office. (3) UK wheat yields were obtained from the UK Department for Environment, Food and Rural Affairs (DEFRA). The code to produce the analyses can be obtained from the corresponding author upon reasonable request.

Author contributions

All authors contributed to designing the experiments and L.J.S. carried them out. L.J.S. led the coding, visualization and analysis. C.H. extracted the regional UKCP Local projections. All authors contributed to writing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions
Open Access

Table 1: Three standardised wheat growth stages, modified by one day to avoid overlap across stages (AHDB, 2018).

Growth Stage	Benchmark start date	Benchmark end date	Potential climate impacts on the crop
Foundation phase	1st October	9th April	Crop is germinating and growing slowly. Susceptible to waterlogging and frost damage
Construction phase	10th April	10th June	Crop is green and growing rapidly. Needs adequate light, can be affected by late frosts
Production phase	11th June	26th July	Period of post-flowering to harvest, grains fill and ripen. Susceptible to drought and waterlogging

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions
Open Access

Table 2: Association between observed climate metrics and wheat yields in each crop growth stage and region. Table indicates Pearson's correlation coefficients and their p-values (* indicates p<0.01, ** p<0.05, * p<0.10). National data is tailored to the same time period as regional data here (31 years between 1990-2020) for comparability. Note: *total_P* and *mean_dailyP* are equivalent. Some of the most relevant metrics with relatively consistent sign are indicated in bold font (see Figure 7 for trends in these metrics).**

			Foundation				Construction				Production			
			SEE	EMYH	SNE	National	SEE	EMYH	SNE	National	SEE	EMYH	SNE	National
Maximum daily temperatures	Quantiles of the region-averaged maximum daily temperature across the phase/year (e.g. *max_maxT* is the highest daily maximum temperature)	***max_maxT***	0.01	0.01	0.10	0.03	0.11	-0.27	-0.11	-0.19	**0.26**	**0.42****	**0.22**	**0.42****
		mean_maxT	0.08	0.05	0.16	0.08	-0.06	-0.09	0.09	-0.10	0.14	0.22	0.24	0.20
		min_maxT	0.17	0.01	0.01	0.04	0.05	0.09	0.14	0.00	0.06	-0.06	0.09	-0.01
Mean daily temperatures	Quantiles of the region-averaged mean daily temperature across the phase/year (e.g. *max_meanT* is the highest daily mean temperature)	*max_meanT*	0.24	0.21	0.12	0.24	0.23	-0.16	-0.26	-0.11	0.23	0.41**	0.14	0.46***
		mean_meanT	0.06	0.05	0.16	0.09	-0.03	-0.07	0.07	-0.07	0.07	0.11	0.16	0.11
		min_meanT.	0.30*	0.02	-0.03	0.09	-0.08	-0.21	0.07	-0.23	0.17	-0.03	0.07	-0.01
Minimum daily temperatures	Quantiles of the region-averaged minimum daily temperature across the phase/year (e.g. *max_minT* is the highest minimum temperature)	***max_minT***	**0.29**	**0.30***	**0.15**	**0.35***	-0.06	-0.19	-0.16	-0.14	0.18	0.28	0.05	0.27
		mean_minT	0.03	0.05	0.16	0.09	0.02	-0.03	0.05	-0.03	-0.07	-0.11	-0.01	-0.08
		min_minT	0.31*	0.11	-0.01	0.07	0.00	-0.26	-0.02	-0.24	0.18	0.00	0.02	0.12
Daily temperature variability	Mean daily temperature variability (daily maximum - minimum) over the phase/year	***var_dailyT***	0.13	0.03	0.06	0.02	-0.10	-0.11	0.07	-0.11	**0.22**	**0.36****	**0.34***	**0.32***
Seasonal temperature variability	Intra-phase/annual variability (max-min) of the max, mean or minimum daily temperatures (e.g. difference between the highest/lowest maximum daily temperature)	***var_maxT***	-0.10	0.00	0.07	0.00	0.05	-0.29	-0.20	-0.14	**0.21**	**0.42****	**0.16**	**0.41****
		var_meanT	-0.06	0.13	0.09	0.09	0.22	0.06	-0.25	0.11	0.09	0.36**	0.08	0.41**
		var_minT	-0.05	0.09	0.09	0.17	-0.04	0.06	-0.10	0.08	-0.05	0.25	0.02	0.10
Precipitation magnitude	Total region-averaged precipitation (P) over the phase/year	***total_P***	**-0.20**	**-0.28**	**0.12**	**-0.14**	0.06	0.08	0.03	0.08	**-0.27**	**-0.45****	**-0.27**	**-0.39****
	Quantiles of daily precipitation computed across the phase/year (e.g. *max_dailyP* is the highest daily precipitation)	*max_dailyP.*	0.08	-0.44**	0.17	-0.18	0.07	0.07	0.07	0.16	0.02	-0.34*	-0.19	-0.16
		mean_dailyP.	-0.20	-0.28	0.12	-0.14	0.06	0.08	0.03	0.08	-0.27	-0.45**	-0.27	-0.39**
Seasonal precipitation variability	Intra-phase/annual variability of daily precipitation	*varP_ Q0.95-Q0.05*	-0.15	-0.32*	0.04	-0.17	0.11	0.12	0.02	0.19	-0.19	-0.36**	-0.2	-0.15
Precipitation frequency	Number of days in the phase/year where P exceeds 10 mm (less than 0.01 mm)	***days_P >10 mm***	**-0.23**	**-0.41****	**0.13**	**-0.18**	0.00	0.05	-0.01	-0.02	**-0.30**	**-0.31***	**-0.25**	**-0.16**
		days_P <0.01 mm	-0.01	-0.10	-0.07	-0.27	-0.27	-0.20	-0.06	-0.27	0.14	0.23	0.19	0.13

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

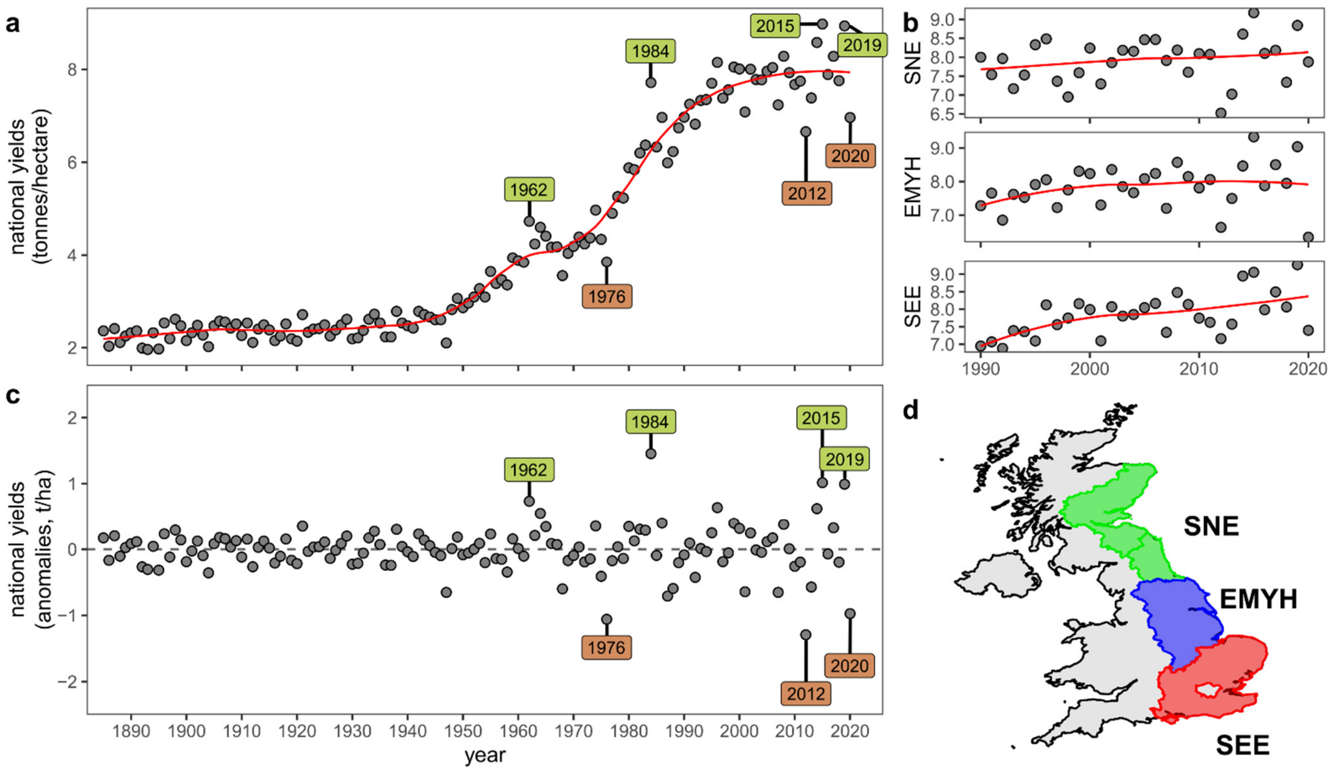
Earth System Dynamics
Discussions
Open Access

Table 3: Bias correction factors for region-averaged total daily precipitation and minimum/mean/maximum daily temperature for each of the three regions (columns) and each of the 12 UKCP ensemble members (rows) relative to HadUK observed data. These are the complete data (ensembles 02, 03, and 14 do not exist in the UKCP Local dataset). Bias correction is performed using daily data over the common historical period 1980-01-12 to 2000-30-11. The bias correction factors are multiplicative for precipitation and additive for temperature.

	Precipitation			Minimum temperature			Mean temperature			Maximum temperature		
ensemble	**EMYH**	**SEE**	**SNE**	**EMYH**	**SEE**	**SNE**	**EMYH**	**SEE**	**SNE**	**EMYH**	**SEE**	**SNE**
01	0.82	0.88	0.88	-0.30	-0.54	0.17	0.35	0.18	0.73	0.97	0.89	1.38
04	0.79	0.80	0.91	0.12	-0.12	0.54	0.82	0.69	1.11	1.47	1.47	1.75
05	0.84	0.91	0.9	-0.14	-0.28	0.17	0.57	0.51	0.76	1.24	1.27	1.43
06	0.87	0.96	0.92	-0.03	-0.22	0.35	0.57	0.42	0.88	1.18	1.06	1.53
07	0.88	0.95	0.94	0.13	-0.10	0.62	0.69	0.51	1.08	1.25	1.14	1.65
08	0.81	0.85	0.86	-0.51	-0.70	-0.17	0.08	-0.05	0.37	0.64	0.59	0.97
09	0.97	1.06	0.97	0.26	0.10	0.68	0.69	0.55	1.05	1.13	1.02	1.55
10	0.87	0.95	0.92	0.03	-0.18	0.39	0.47	0.29	0.78	0.91	0.75	1.28
11	0.80	0.84	0.89	-0.13	-0.36	0.26	0.58	0.42	0.86	1.22	1.15	1.52
12	0.89	1.00	0.93	1.08	0.75	1.73	1.66	1.42	2.21	2.27	2.10	2.84
13	0.85	0.94	0.87	-0.67	-0.87	-0.27	-0.13	-0.31	0.24	0.39	0.26	0.82
15	0.82	0.89	0.85	-1.14	-1.36	-0.7	-0.6	-0.79	-0.16	-0.13	-0.27	0.39
mean	0.85	0.92	0.90	-0.11	-0.32	0.31	0.48	0.32	0.83	1.05	0.95	1.43

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

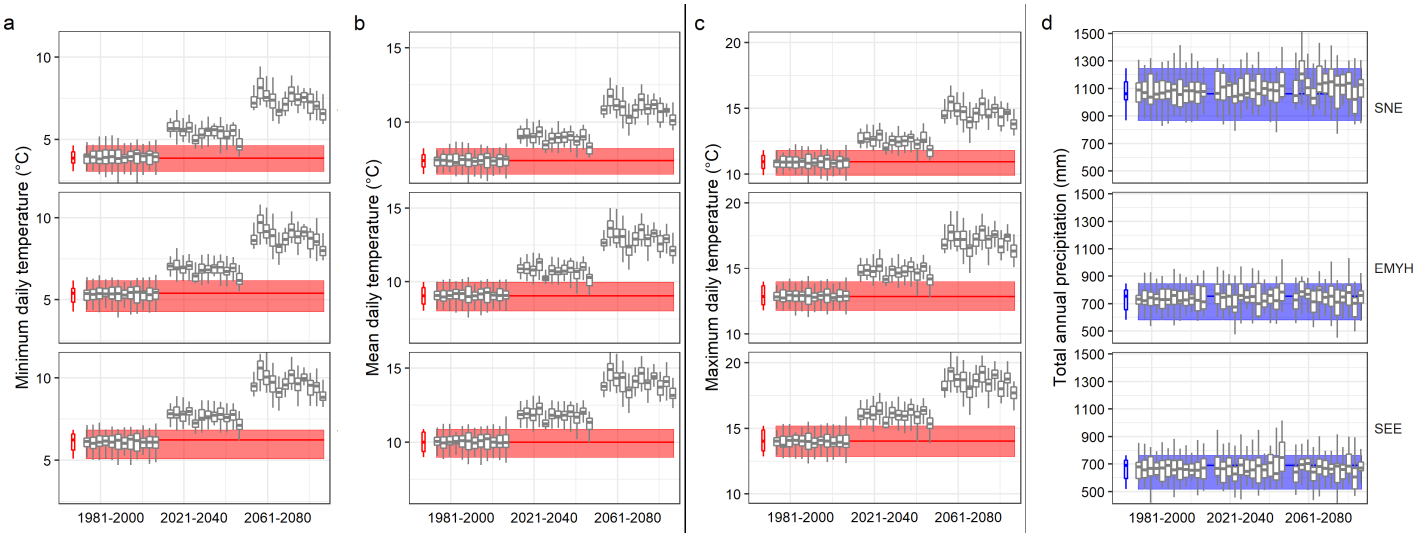
Earth System Dynamics
Discussions



485 **Figure 1: UK national and regional wheat yields. (a) National wheat yield (grey circles) and locally weighted scatterplot smoothing (loess) curve (red line). Green (brown) labels indicate examples of years with anomalously high (low) yields. (b) Same as (a) for three main wheat-growing regions (data only available for 1990-2020 at regional scale). (c) Anomalies of wheat yields computed by subtracting the Loess moving mean from the annual values. (d) Map of the three wheat-growing regions. Green indicates North Eastern Scotland, Eastern Scotland, and the North East English region (SNE); blue indicates East Midlands, Yorkshire and the Humber regions (EMYH); red indicates the South East and Eastern regions (SEE).**

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions



495 **Figure 2: Bias-correction of each UKCP 2.2km ensemble member, for (a-c) the minimum, mean and maximum daily temperature (*mean_minT*, *mean_meanT* and *mean_maxT*), respectively; and (d) total precipitation (*total_P*), in each year, for each of the three regions (SNE, EMYH, SEE). Red (blue) boxplots and rectangles indicate the range of observed temperature (precipitation) over the first period (1981-2000), based on the HadUK dataset. Grey boxplots indicate projections (one for each of the 12 UKCP Local ensembles) for three periods (historical – 1981-2000; future – 2021-2040; 2061-2080) using RCP8.5. Boxplot hinges represent 25th and 75th percentiles, and horizontal bar indicates the median. Whiskers extend to the largest value no further than 1.5 times the interquartile range (distance between 25th-75th percentiles) from the hinge.**

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions
Open Access
EGU

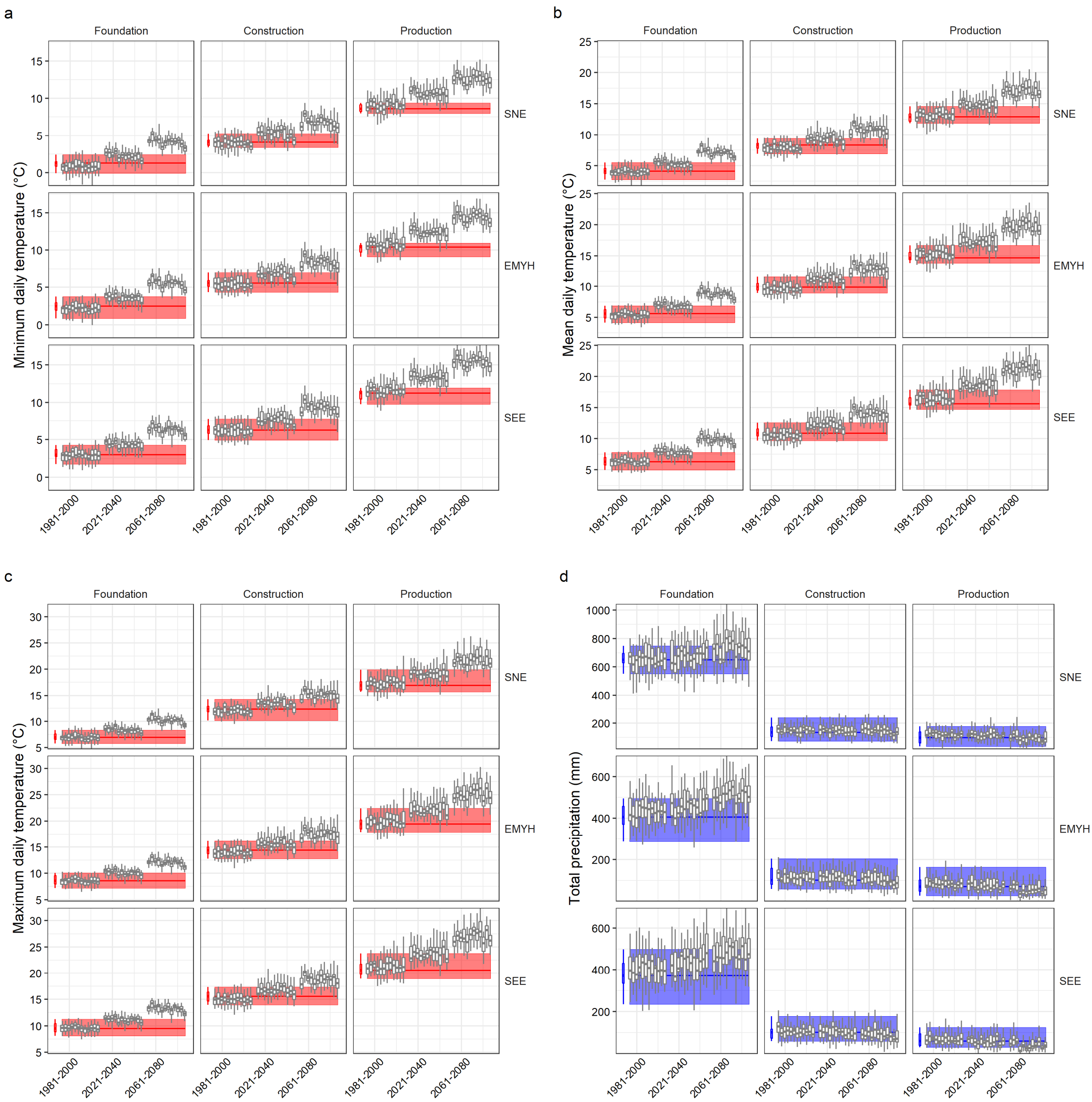


Figure 3: Bias-correction of each UKCP 2.2km ensemble member, for (a-c) the minimum, mean and maximum daily temperature (*mean_minT*, *mean_meanT* and *mean_maxT*), respectively; and (d) total precipitation (*total_P*), within each phase, for each of the three regions (SNE, EMYH, SEE). Red (blue) boxplots and rectangles indicate the range of observed temperature (precipitation) over the first period (1981-2000), based on the HadUK dataset. Grey boxplots indicate projections (one for each of 12 UKCP Local ensembles) for three periods (historical – 1981-2000; future – 2021-2040; 2061-2080) using RCP8.5. Boxplot hinges represent 25th and 75th percentiles, and horizontal bar indicates the median. Whiskers extend to the largest value no further than 1.5 times the interquartile range (distance between 25th-75th percentiles) from the hinge.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions

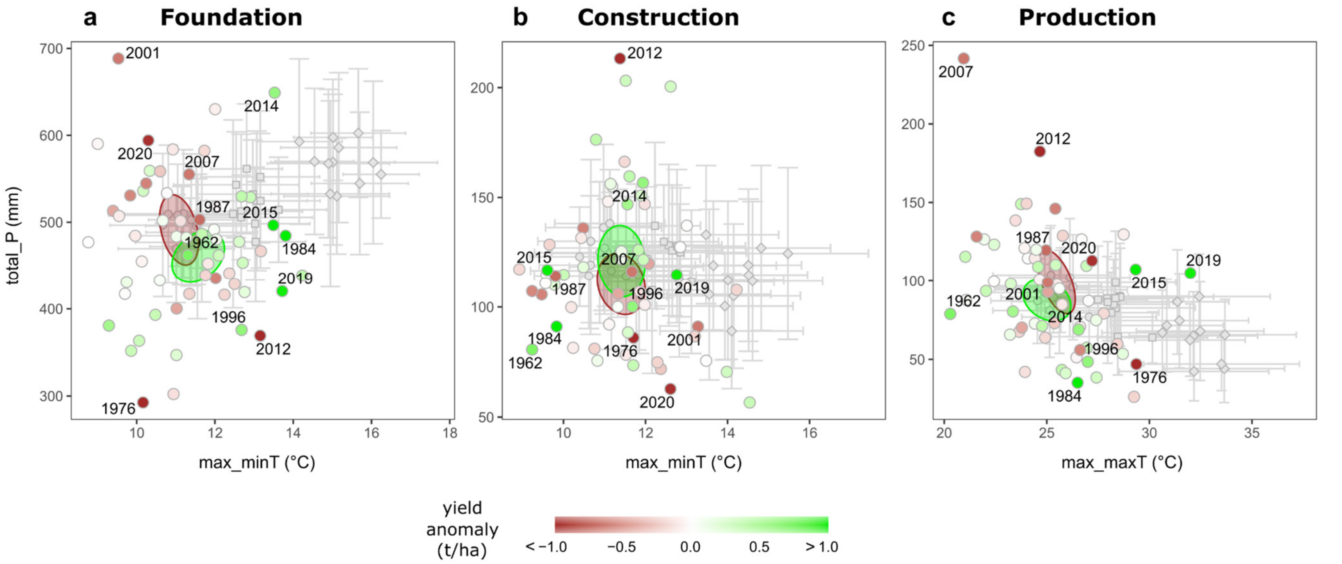


Figure 4: Association between wheat yields and climate during the three wheat-growing phases. Anomalies of observed UK wheat yields are shown for total area-averaged precipitation (*total_P*) and the maximum of area-averaged minimum/maximum daily temperature within each phase (i.e. the metrics *total_P*, *max_minT*, and *max_maxT*, chosen for their associations with crop yields; Table 2), alongside UKCP projections. Columns: Foundation phase (01st October to 09th April); Construction phase (10th April to 10th June); Production phase (11th June to 26th July). Yield time series are shown for the national scale here (longer than regional time series, see Figure 1a vs 1b) and are the same in the three panels. Small green (brown) circles indicate positive (negative) yield anomalies for individual years. Large green (brown) ellipses are 95% confidence ellipses for all the years with positive (negative) wheat yield anomalies, respectively. Grey diamonds and error bars indicate UKCP Local projections of temperature and precipitation for the historical (circle: 1981-2000) and future (square: 2021-2040; diamond: 2061-2080) periods, where each cross indicates one of the 12 ensemble members and the bars extend +/-1 standard deviation. Specific years mentioned in the main text are labelled.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions

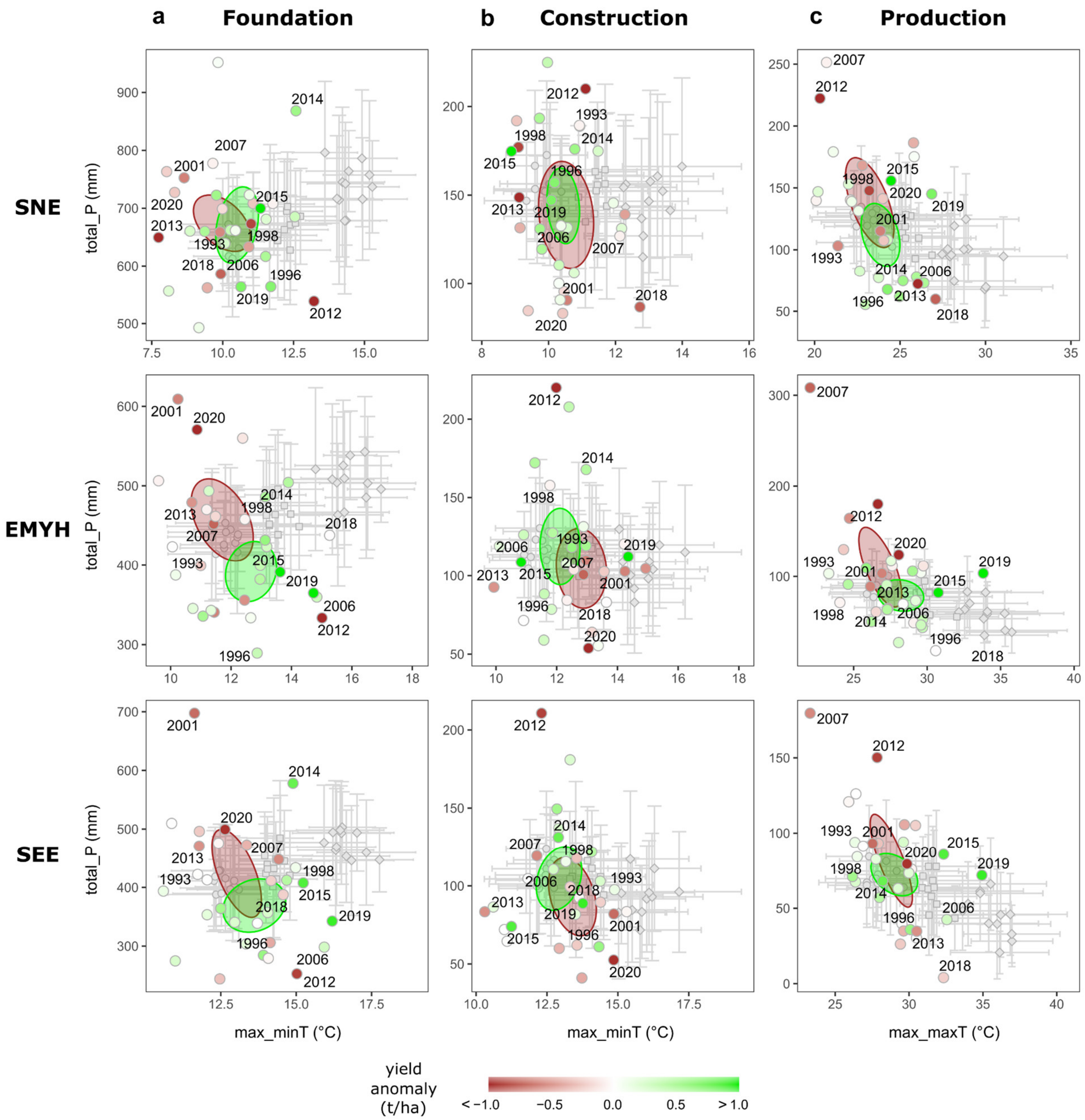
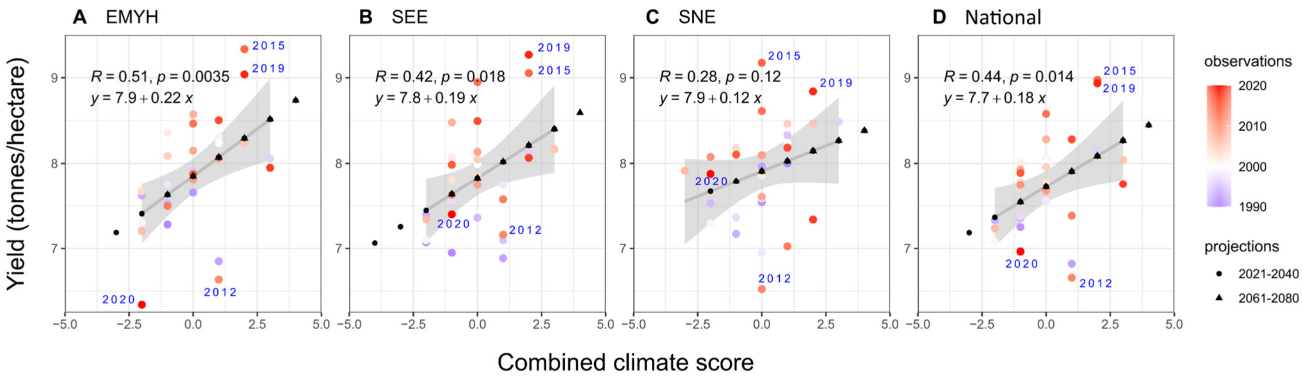


Figure 5: Association between wheat yields and climate during the three wheat-growing phases and in each of the three UK wheat-growing regions. Anomalies of observed UK wheat yields are shown for total area-averaged precipitation (*total_P*) and the area-averaged minimum/maximum daily temperature within each phase (i.e. the metrics *total_P*, *max_minT*, and *max_maxT*, chosen for their associations with crop yields; Table 2), alongside UKCP projections. Columns: same as Figure 4. Rows: SNE, EMYH, SEE. Yield time series are shorter at regional scale than national (see Figure 1b). Small green (brown) circles indicate positive (negative) yield anomalies for individual years. Symbology is the same as Figure 4.

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

Earth System Dynamics
Discussions



540 **Figure 6: Association between regional/national wheat yields and a simple combined annual climate score, shown for both the historical period (observations: colour circles) and UKCP projections (black circles for 2021-2040 and black triangles for 2061-2080). The combined score in a given year is computed using just two of the metrics that display relatively consistent associations with yields in the Foundation and Production phases (Table 2; Fig 4-5): *max_minT* in the Foundation phase and *max_maxT* in the Production phase (positive association); *total_P* in the Foundation and Production phases (negative association).**

https://doi.org/10.5194/esd-2021-92
Preprint. Discussion started: 20 December 2021

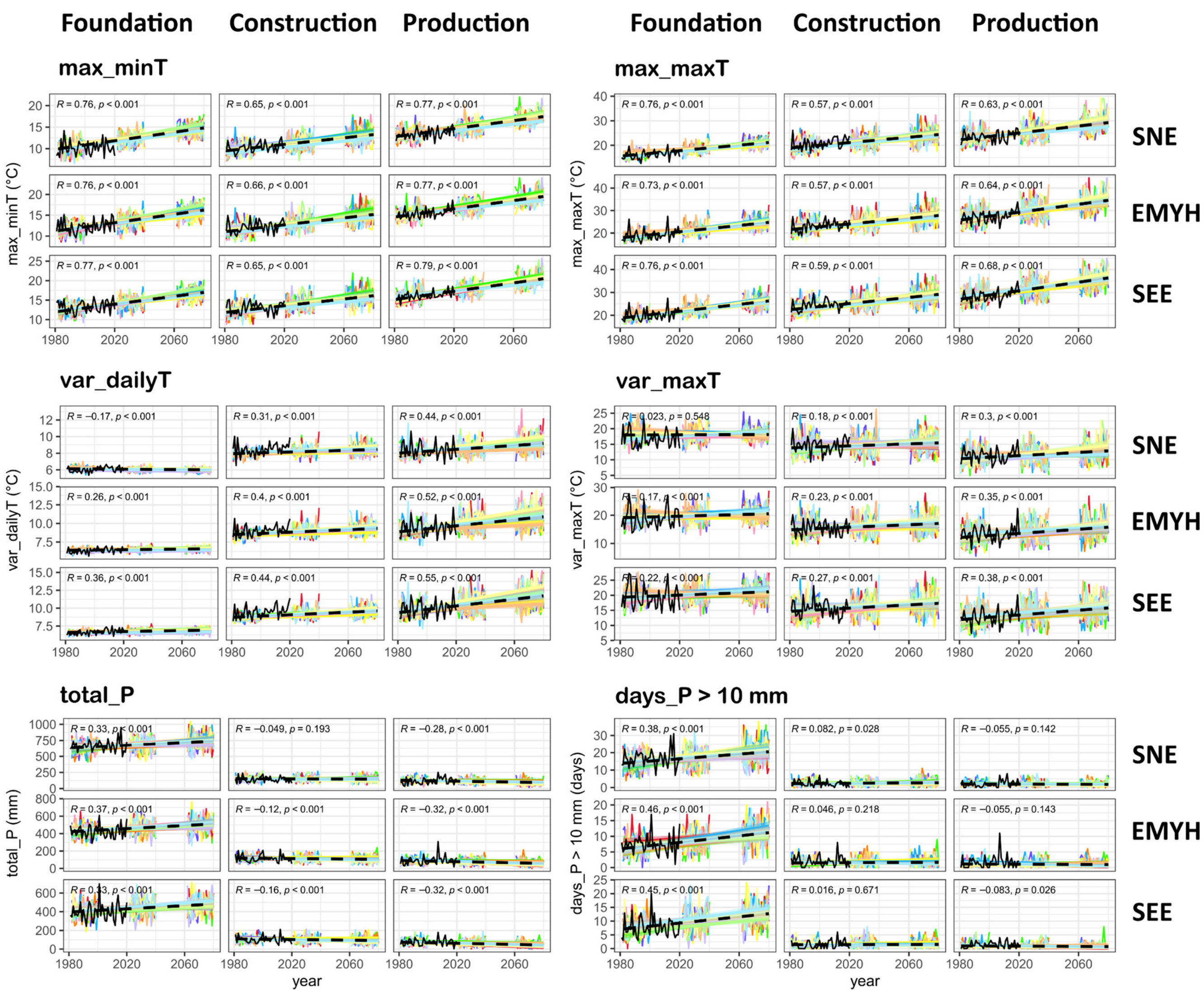


Figure 7: Trends in key climate metrics for the three growth stages (columns) and three regions (rows). Metrics are selected from (and defined in) Table 2: *max_minT*, *max_maxT*, *var_dailyT*, *var_maxT*, *total_P* and *days_P>10mm*. Black lines indicate observations; color lines indicate each of the 12 UKCP Local members. Linear trend lines are shown for each member (colour) and for all members (black dashed lines).