Resilience of UK crop yields to changing climate extremes

Response to Reviewer Comment 1 (RC1):
'Comment on esd-2021-92', Anonymous Referee #1, 05 Jan 2022

Summary

The submitted manuscript describes a study of the historic link between extreme weather conditions and wheat yields in the United Kingdom (UK), extended with an analysis of relevant future weather changes. It is shown that mean yields have systematically increased over time, which can be explained by technological advances, but interestingly year-to-year variability of yield has also increased in recent decades (Fig 1c). The authors then set out an analysis in which correlations between various (extreme) weather indices for temperature and precipitation, across three important wheat growing stages, and end-of-season yield are investigated. They develop a simple scoring metric that describes some of the cumulative effect of weather conditions on yield. This analysis is extended by very high resolution climate model-based projections of future temperature and precipitation conditions under a high-emission scenario, and describes future weather conditions for wheat growing.

We thank the reviewer for their thoughtful comments on our manuscript, which will help us strengthen the research. We are glad the reviewer finds the increase in yield variability interesting and agrees that the use of wheat growing stages is important. We address each of their comments and suggestions point-by-point in blue italic font below.

General remarks

RC1.1 Whilst I appreciate that the topic is of large societal relevance, I struggle to see where the manuscript answers its research questions or if promises delivered. The link between weather and agricultural impacts is highly complex and non-linear. The authors acknowledge this in their introduction, and set out on logical path of addressing the topic and ultimately provide specific wheat sector-relevant climate projections. I fear however that the relationships are of such highly complex nature, that the present analysis does not provide satisfactory answers to the questions posed.

We apologise if the reviewer feels our main findings were not sufficiently well highlighted. We think the issue is largely presentational. Our manuscript's key questions and conclusions are as follows:

Q1. Do 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?

- *In the Foundation stage, when the crop is germinating and growing slowly, there is a significant negative association between crop yields and the number of heavy rainfall days in the EMYH region (days_P>10mm). We also 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, suggesting that yields benefit from warming temperatures (less frost).*
- *In the Construction phase, when the crop is green and growing rapidly, we find no significant associations between climate characteristics and crop yields.*
- *In the Production phase, from post-flowering to harvest, 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. In contrast, good wheat yields are associated with warm summer temperatures, which can be seen in the positive associations with max_maxT or max_meanT, which are significant both nationally and in EMYH.

- *We find cumulative climate impacts across individual growth stages, with a significant positive association between the combined climate score and wheat yields for EMYH, SEE, and the national scale, but not SNE, where the association is weaker.*

Q2. To what extent might projections of future temperature and precipitation extremes under a high-emissions scenario impact future crop yields?

- *Future high-temperature conditions generally fall beyond the bounds of annual variability experienced in the contemporary period for all three wheat-growing regions.*
- *For total annual precipitation, the projections do not indicate a visible increase or decrease in any of the three regions relative to the historical period; however, changes are significant when considering precipitation projections by wheat growth stages.*
- *In the Foundation phase, all regions can expect to see progressively warmer, wetter conditions in the coming decades, with significant increases in max_minT, max_maxT, total_P, and days_P>10mm. Warmer winter night temperatures are likely to prove beneficial in decreasing the risk of frost damage, but concurrent increases in heavy rain may be detrimental to wheat yields.*
- *In the Construction phase, the projections indicate significant decreases in total_P in EMYH and SEE, but not SNE. There are no evident changes in heavy rain (days_P>10mm).*
- *In the Production phase, we find much warmer and somewhat drier conditions in all three regions, with significant increases in max_minT, max_maxT, and equally in temperature variability (var_dailyT and var_maxT). Warmer and drier mean conditions may enhance wheat yields, but increases in high temperatures (outside the range experienced in the historic period) and heat variability may increase plant stress, while the significant decreases in rainfall (total_P) may threaten adequate water supply.*
- *Projections of future temperature and precipitation conditions do not significantly aggravate our simple combined climate score (relying on max_minT, max_maxT and total_P), suggesting the beneficial impacts of warming conditions (e.g. reduced frost risk) may be offset by significant increases in heavy rainfall in the Foundation phase and enhanced drought conditions in the Production phase.*

We purposely adopted a nuanced approach in answering these questions as we believe it is important to highlight that this is a complex topic (as the reviewer points out), without seeking to over-interpret the findings. We will revise the text to ensure that the findings are clearly laid out, emphasising where associations are significant (as above). We will also explain any assumptions and limitations, as discussed in our reply to RC1.10.

RC1.2 The first research aim (finding statistical associations) results in Table 2. Only one of three regions shows any stat.significant relations (at p=0.05 level) between the weather indices and yield. **RC1.3** The accompanying text leans very heavily on anecdotical evidence, which I fear may lean towards overinterpretation of single events. **RC1.4** To account for temporally compounding effects a simple scoring metric is developed (Fig 6), failing to take into account developments in agricultural science. Why haven't the authors followed their own advise (last sentence) and employed process-based crop models or AI methods to find robust relationships between weather and yield?

***A1.2** As the reviewer rightly points out, the strength of the associations between climate metrics and crop yields varies depending on the growth phase and region. For transparency, we show all the associations and their relative strength. We feel it is just as important to show* *where these associations are non-significant as where they are significant, based on the historical data.*

A1.3 *We believe that descriptions of some individual events are important: many of the answers to our questions are understood by farmers and are present in the grey literature, but not in the academic literature. Without discussion of important historical events, the manuscript would be very dry. However, we entirely agree with the reviewer that individual events should only be used to illustrate significant associations, and we will carefully edit the text to make sure this is the case (i.e., in cases where the associations are not significant, we will say so explicitly).*

A1.4 *To be effective, process-based crop or AI-driven models of actual crop yields require parameterisation and calibration with large volumes of data on local conditions and agricultural management. Obtaining these data over large spatial extents remains challenging. Our approach circumvents these issues by trying to develop a generalisable approach to understand if there are associations in the observational data. Our final sentence is thus an ambition for future research rather than an alternative method for our current analysis.*

RC1.5 Then, the future climate projections are based on a single climate model. Though high-resolution modelling without doubt adds value, a multi-model perspective is needed to provide 'reliable' projections. I advise the authors to add a comparison of projections in CMIP6 or CORDEX to UKCP, such that readers may get a feeling of where these projections lie within the larger model-related uncertainty.

Some information from CMIP models is included through the comparison with UKCP Probabilistic projections. UKCP Local projections are generally within the 5-95% probability levels of the UKCP Probabilistic projections, which include multi-model information from CMIP5 (see reply RC1.22 below for details). We are sorry this was not as clear as it could have been.

The future UKCP Local climate projections are based on an ensemble of 12 convection-permitting (2.2km grid spacing) simulations, which sample uncertainty in the physics of the driving model. In particular, uncertain parameters within the model physics are perturbed within acceptable bounds, allowing a first estimate of uncertainty in future changes. This uncertainty however is likely to be underestimated, since UKCP Local only downscales perturbed physics versions of the Hadley Centre Climate Model. This is being addressed in new simulations, which are underway as part of an update to UKCP18, downscaling selected CMIP5 models to 2.2km resolution over the UK. These new simulations will augment UKCP Local, sampling a wider range of uncertainties. Unfortunately these results are not available currently and so cannot be included in this paper, but will be exploited in future analysis. The current analysis presented in this paper nevertheless is a major step forward in using state-of-the-art high-resolution climate projections that provide reliable information on changes in local weather extremes. In the revised manuscript, we will provide a clear description of how the UKCP projections compare with the larger model-related uncertainty.

RC1.6 But more importantly, rather than analysing how crops respond to future weather conditions (which is what the title of this manuscript implies), changing weather conditions in three growing stages are discussed. Given the limited relationships between weather and yield that were found, does this really provide useful information for the UK agricultural sector?

The title was chosen to encompass changing weather conditions in both the past and future ("Resilience of UK crop yields to changing climate extremes"). We respectfully disagree with the reviewer here, as the manuscript provides clear conclusions, which have implications for the UK agricultural sector. We refer to the detailed summary of conclusions in response to RC1.1.

Major points

RC1.7 Section 2.4 - In table 3 I see you have bias-corrected each ensemble member separately. Though I haven't worked with perturbed physics large ensembles, the normal procedure for bias correcting would be to do a single bias correction for all ensemble members, as differences are due to internal variability not indicative of different mean climates. Are the imposed physics changes so large that this is different in this case?

If we were using an ensemble with the same physical structure then the reviewer is correct: we would apply a single bias correction. In the case of a perturbed physics ensemble, however, each ensemble member is typically regarded as a different model, and so one bias correction is applied for each ensemble member. Here, the physics of the driving model have been perturbed. Thus, differences between the UKCP Local ensemble members are due to differences in the physics of the governing forcing ESM (which justifies a separate bias correction for each ensemble member) as well as natural variability. We will clarify and explain this point within the revised manuscript.

RC1.8 Section 3.2 - The relationships noted in this section are very anecdotical. Table 2 provides the quantitative correlation coefficients, which are only in a few cases statistically significant. Please add more quantitative evidence of the suggested relations, or note in the text that despite anecdotical evidence there is no statistical link. I think it is easy to overfit/overanalyse seemingly simple relations (e.g. wet conditions lead to low yield), when in reality the interactions between plant and weather is very complex and highly non-linear.

We agree with the reviewer that interactions between plants and weather are generally complex and nonlinear. We will carefully revise the manuscript to make sure that it is clear which associations are not significant. We will also make sure that we are not over-extrapolating from individual events.

RC1.9 Line 295, line 318 - I hadn't noted evidence in the results section supporting the conclusion that increased inter annual yield variability is linked to "one-to-one correlations with temperature or precipitation extremes" or "the recent increase in yield volatility is associated with combined climate metrics". Please either emphasise this more in the results section, or remove from the conclusions.

We will revise the text and revisit our results to make sure this point is either better explained or removed from the conclusions.

RC1.10 I miss a discussion of the assumptions that went into this work, and how these assumptions might influence the results. One item would be the use of fixed-in-time growth stages, in reality these are weather dependent, and plant vulnerabilities to extreme temperatures or precipitation can thus be different from one July to another July (for example).

Thank you for pointing this out; we will add a discussion of assumptions including the use of fixed-in-time growth stages. In the manuscript, we did not use the detailed (99) physiological growth stages (AHDB 2022), but rather the high-level growth stages (which are defined over long time periods) to split the year into key stages of wheat growth, and to mitigate against weather dependencies. Other assumptions that are worth describing include the assumption that all wheat varieties behave similarly (both in the past and future). However, one of the advantages of our empirical data-driven approach is that there are fewer assumptions than in a process-based model approach.

AHDB 2022, The growth stages of cereals, Agriculture and Horticulture Development Board, Kenilworth, Warwickshire, https://ahdb.org.uk/knowledge-library/the-growth-stages-of-cereals

Minor points

RC1.11 Fig 1 caption - I very much dislike the bracket-way of scientific writing. There is no word limit in ESD, I strongly encourage the authors to rewrite their statement in two sentences. “Green (brown) labels indicate examples of years with anomalously high 485 (low) yields.”

We are happy to make the change.

RC1.12 Line 50 - Indeed there is a lot of climate research into weather extremes, but there is a vast quantity of climate impact research as well in how these will influence for example crops. A slight rearrangement of this sentence is asked for. And maybe a few more recent examples from the literature (e.g. Ben-Ari et al 2018).

We will rearrange the sentence and add further examples from climate impact research and the crop literature (including the recommended paper).

RC1.13 Line 85 - Please clarify “any incomplete crop growth stages”, does this relate to gaps in the PR/TAS data, or too fast progression through the stage? If the latter, would that not be caused by climate extremes?

This relates to gaps in the data (incomplete seasons were removed). We will clarify this point in the text.

RC1.14 Line 104 - A model realistically simulating present-day climate is a requisite for making a seemingly reliable projection, but it is not guaranteed of course. The response to GHG forcing can still be very wrong. And since only RCP8.5 is used as forcing, further doubt on the ‘credibility’ of the projections is added (see e.g. Hausfather and Peters et al 2020). This does not discredit your analysis, but does put some limitations on the ‘credibility of projections’ made. Please add a sentence noting these issues (single model, single GHG scenario), maybe use the first paragraph of section 3.4 and remove it there.

The reviewer raises an important point. Although we did already mention the use of a single model, single GHG scenario, we will discuss these aspects further within an explicit ‘assumptions and limitations’ section. We will also better explain the benefits of using a perturbed physics ensemble.

RC1.15 Fig 2 - I originally thought the panels a-c showed the UK as a whole, only noting later that maybe the small region labels on the right count for all panels. Maybe add these inside the plot, or explicitly state this in the caption.

Thank you. We will make the labels more visible on the plot, and better phrase the caption.

RC1.16 Line 154 - I don’t understand why you would think those are related, on the one hand growth due to technology and on the other hand increased variance? I’d say for the first you have a very good argument, and the second is an interesting question indeed, with the link to increasing weather extremes as a good hypothesis.

This is a misunderstanding; our aim was not to imply that growth and variance were related. We will ensure the text is rephrased for clarity.

RC1.17 Line 169, Fig 4/5 - These figures show a lot of data in a small panel. As you don’t discuss any correlation between PR and TAS, why would you show them in this way? Wouldn’t a ‘simple’ scatter plot between PR and yield better show this conclusion? Furthermore, yes-low yield years show an extreme PR in one of the seasons, but how many normal/high yield years do the same? E.g. from Table2 only EMYH in the production phase shows a statistically significant correlation between PR and yield. Then, what do the grey crosses add to the figure?

The plots are not intended to show correlations but instead to show the spread of individual years and their associated yields throughout the climatic 'space' generated by the interaction between PR and TAS. The projections (crosses) then allow the reader to see how future seasons may compare with present seasons in terms of warming/wetting.

RC1.18 Table 2 - the horizontal line separating TAS and PR measures is one row too low.

Thank you for pointing this out - we will make the change.

RC1.19 Line 205 - Add here that the growing phases in real plants are determined by their growth, rather than calendar days. So a phase can last longer, to have the desired number of growing degree days for example, delaying the crop, but resulting in the expected yield. The calendar-fixed phases are a simplification of this process.

This is a good point; we will edit the text accordingly, thank you.

RC1.20 Fig 6 - A few remarks: (i) Please separate the projections from the observed data, maybe in a second row of figures below the first one. (ii) I don't understand where the future yield data are coming from? The relationship of black circles and triangles and grey shading is surprisingly (doubtfully?) linear, and fully captures the eye of the reader. The dots show very much variability, by eye alone I doubt one would have been able to draw the correct regression line through them. (iii) please add fitted regression lines using observed data (I assume the statistics plotted are those lines), and maybe for the national subplot also show data from before 1990.

(i-ii) The reviewer's comments are helpful and reveal that we should have better explained the figure. The black symbols are simply projections of the combined climate score, but do not estimate the future yield. We will clarify this in the caption and main text. By overlaying the observations and projections of the climate score, it is easier to compare them. (iii) We will make the regression lines more visible, and add the older data for the national subplot as suggested.

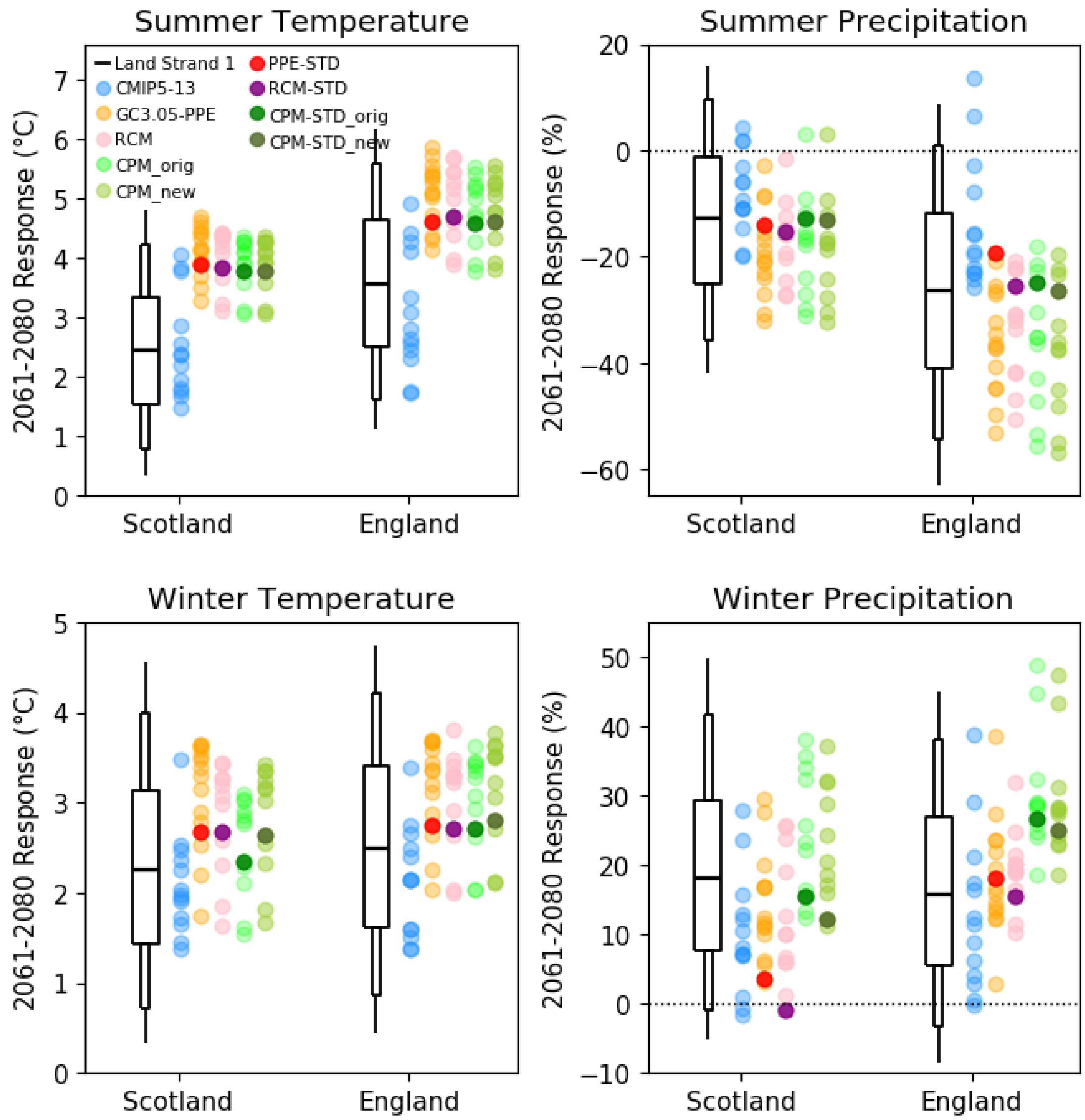
RC1.21 Section 3.4 - The section title is misleading, general forced climatic changes are discussed, not crop-specific climatic changes.

This is a good point; we will make the change, thank you.

RC1.22 Line 245 - I imagine the UKCP lie in the upper/lower-percentiles of the full CMIP5/6 ensemble, but not fully outside? "UKCP simulations tend to sample greater future warming and drying in summer compared to the full…"

This is a good question; we will add a more detailed discussion in the manuscript of how the UKCP compare to the CMIP ensemble. The figure below from Kendon et al. (2021) shows that UKCP Local projections (olive green dots) are generally within the 5-95% probability levels of the UKCP Probabilistic projections (black boxplots, which include some multi-model information from CMIP5). One exception is winter when the UKCP Local show some precipitation responses above the 95% level. This is understood and relates to the improved representation of winter-time convective showers in the Local 2.2km model (Kendon et al 2020). UKCP Local projections sample relatively high temperature changes, with few outcomes cooler than the median of the UKCP Probabilistic projections in winter and none in summer. Changes in summer precipitation show a considerable drying in the Local projections

(2.2km), whereas the 13 CMIP5 simulations and the UKCP Probabilistic projections indicate that outcomes with more modest reductions or small increases should also be considered.



Above: Figure 5.1 from Kendon et al. 2021. Comparison of seasonal mean changes across UKCP18 products. Projected changes for 2061-2080 relative to 1981-2000 for Scotland and England in (top) JJA and (bottom) DJF, under RCP8.5 emissions. Results are shown for surface air temperature (left, °C) and precipitation (right, %). Box and whiskers denote the 5, 10, 25, 50, 75, 90 and 95% probability levels of the UKCP probabilistic projections (Strand 1). Orange dots (with STD in red) denote members of GC3.05-PPE and blue dots those of CMIP5-13, which together comprise the UKCP Global (60km) projections (Strand 2). Pink dots (with STD in purple) show the Regional (12km) projections and green dots (with STD in dark green) those of the Local (2.2km) projections (with the original convection permitting model in fluoro-green and the new convection permitting model (used in this manuscript) in olive-green, Strand 3).

References

Kendon E J et al (2021) Update to UKCP Local (2.2km) projections, July 2021, Met Office, Exeter, UK https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp18_local_update_report_2021.pdf

Kendon, E. J., et al (2020) Greater future UK winter precipitation increase in new convection-permitting scenarios. J Climate. DOI: 10.1175/JCLI-D-20-0089.1

RC1.23 Fig 7 - I'm not sure this is the best way of showing the data. 10 lines on top of each other, plus the ensemble mean, and then for each the regression line. I had to zoom in to 500% to read the data. Maybe consider only showing with shading the min-P25-P50-P75-max across the ensemble, and the ensemble mean regression line? This would show less data, but I think more information.

We will make the change as suggested by the reviewer.