Resilience of UK crop yields to changing climate extremes

Response to Reviewer Comment 3 (RC3):
'Comment on esd-2021-92', Anonymous Referee #3, 20 Jan 2022

The authors present an interesting analysis of UK's wheat yield variability. They first explore the influence of different climatic conditions on wheat yields to then construct a scoring system for combined climate effects. In their analysis, they separate major plant development stages. Finally, they use climate model projections to estimate potential yields in a warmer climate.

Despite the confined regional focus, I would expect that the findings and the presented approach would be of interest to a wide readership. The manuscript is well written.

We thank the Reviewer for their positive assessment of our paper and we are glad they find that it is of interest to a wide readership. We describe how we propose to address each of their comments and suggestions, point-by-point, as listed in blue italic font below.

Major concerns:

RC3.1 The paper is based on statistical analysis and this analysis should be described in more detail including a description of underlying assumptions. Especially the part about the scoring system should be better introduced and potentially justified.

We agree with this comment and will provide a complete description of the statistical methods and assumptions. We will also better introduce, describe and justify the scoring system. We will ensure that a reader can reproduce the methods in full.

RC3.2 The analysis of climate effects during the plant development phases delivers interesting results. The authors argue that with their scoring system they can assess the combined effect of climatic conditions throughout the plant development. Here the question arises whether the climatic impacts during the production phase are the same irrespective of the climatic conditions throughout the earlier plant development stages. For example, Ben-Ari et al. 2018 describes a compound event where the combination of warm winter and wet spring lead to a crop failure. As I understand the analysis, it wouldn't be able to capture such compound events if it is not generally bad for wheat to have warm winters and wet springs. This is just an example, but it might help to understand a limitation that comes from splitting up events. I would find it interested to read the authors view on this concern. These reflections could also be included in the discussion.

The Reviewer raises an important point, which is that of compound "memory" effects across different plant development phases (e.g. a warm winter followed by a wet spring). We tried to capture the effect of different climatic conditions in different individual phases through our combined scoring system. However, it is correct that our approach does not capture the extent to which climatic impacts may depend on anterior climatic conditions (as this would require a different modelling approach). We will therefore add to the discussion this potential limitation of our approach, as suggested by the Reviewer. We will also try developing a multivariate regression approach as discussed in our reply to RC2.2, and will retain this approach if it provides more robust results.

RC3.3 The use of only one climate model appears problematic to me. Furthermore, for this type of analysis I don't see the benefit of high spatial resolution if in the end regional averages are used. I would find it more convincing to see a CMIP6 ensemble instead of one high-

resolution model. On the other hand, the climate model projections are not the main part of the analysis. Therefore one could also think of comparing this climate model to the CMIP6 ensemble and discussing the differences and potential biases.

We appreciate the Reviewer's concern, however, the 12 UKCP ensemble members correspond to perturbed-physics experiments (PPE) of a single forcing Earth System Model (ESM), where uncertain parameters within the physics of the driving global model are varied. Thus the 12 members of the high resolution ensemble sample uncertainty in changes in the large-scale conditions due to modelling uncertainty and internal climate variability (so it is not really 'one model'). We acknowledge that the ensemble lacks information from other international climate models, and this is something that could be addressed in future work exploiting new CMIP5 downscaled UKCP Local projections that are underway within the UKCP project.

To answer the point about the benefits of high spatial resolution, the fine-scale information may still be relevant despite the spatial aggregation. This is because the high resolution model better captures the small-scale processes (in particular convection) behind extreme weather events, and this improved process representation can have an imprint on spatially aggregated fields. We appreciate that the Reviewer notes that the projections are just one part of the analysis, and therefore as suggested, we will compare this climate model in detail to the CMIP6 ensemble, and discuss the differences and potential biases within the revised manuscript.

Minor comments:

RC3.4 The abstract could be improved. At the moment it reads a bit like a summary of different results and ideas. The aim of the study should be clarified more precisely and not all results have to be included in the abstract.

We will streamline the abstract to better highlight the aim of the study, the key outcomes, and implications, as suggested by the Reviewer.

RC3.5 L9-10: "future impacts of climate projections on wheat". I think this should be formulated differently.

Thank you for spotting this. We will rephrase the sentence so that it addresses the impacts of possible future changes in climate on crop yields.

RC3.6 L30-31: Is this due to climatic conditions only? Or does technology play a role here?

The Reviewer is referring to the statement that "the UK climate has historically been well suited to growing wheat". Technology and investment in the agricultural sector have certainly played their part in the current wheat yields seen in the UK (as can be seen from the increasing trend in Figure 1a as technological and agronomic innovations were introduced). However, wheat is a temperate species, and the UK climate is particularly well suited to its development when autumn-sown. For example, Harkness et al (2020) state:

"As a temperate species the typical weather conditions of western Europe, including the UK, are favourable for wheat production (Reynolds et al., 2010). Approximately 40% (~1.8 million hectares) of the arable cropping area in the UK is dedicated to wheat production (DEFRA, 2018). Despite the relatively small acreage, the UK produces approximately 2% of the world's wheat benefitting from a high average yield of ~8 t ha−1, compared to a world average of ~3.5 t ha−1 (FAOSTAT, 2018)"

We will add similar wording and appropriate citations to clarify this.

RC3.7 L97-101: Did you consider a different spatial aggregation methods for precipitation? While for temperature it seems reasonable to average over the regions, for precipitation there could be other meaningful choices. As an example, what would you think about area affected by extreme precipitation instead of regionally averaged precipitation?

We did consider other approaches, such as the highest rainfall event within each region, rather than the regional average. Overall, we found the regional average produced more meaningful results. We did not consider the fractional area affected by extreme precipitation, but we accept this is an approach worth testing in future work. Hence we can mention this additional potential statistic in the limitations/further work section of the revised manuscript.

RC3.8 L111: I think you should mention here, that the scientific community is not considering this scenario as a plausible future. I have seen, that you do so later on. Maybe still worth mentioning earlier.

We will mention this point earlier in the manuscript. We are constrained by the single scenario of the UKCP Local simulations (which is RCP8.5 of course). RCP8.5 was deliberately chosen as the configuration for UKCP Local simulations to maximise the signal to noise. Using a high emissions scenario has the advantage that we can infer changes for other lower emissions scenarios using scaling approaches.

RC3.9 L102: Although the UKCP Local simulations are surely great, there remains a large uncertainty with respect to forced changes in precipitation. The accurate representation of small features in these simulations does not necessarily reduce the uncertainty concerning the regional trend in precipitation. Therefore it would be good to compare the precipitation tendency from this model with climate models from other institutes. I have seen that you do so later in the manuscript.

The Reviewer makes an important point, and we agree. We will make sure that the trends from the UKCP Local model are explicitly compared with those from climate models from other institutes. As mentioned above in response to RC3.3, the driving ESM of UKCP Local is subjected to perturbed physics, so is intended to at least partially represent the range of uncertainty in climate models. Therefore, the trends of the UKCP Local simulations should at least partially cover the range of trends of the ESMs (see last bullet point of page 5 of this document: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-factsheet-local-2.2km.pdf).

RC3.10 L120: Could you add one or two sentences on the bias correction method? Is it a trend-preserving bias correction?

Yes, the bias correction preserves any trend. It is a simple scaling method, which is additive for temperature and multiplicative for precipitation (therefore it preserves an absolute or relative trend, respectively). We will describe the method in more detail in the revised text and make sure this is clear.

RC3.11 L173-175: Are these two sentences contradicting each other?

The Reviewer is referring to "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)." This is not necessarily a contradiction, as reduced growth does not always carry through to reduced yield. We will clarify this point in the revised manuscript.

RC3.12 Section 3.2 and Table 2: How would you explain that the effects of climate conditions are different between the regions? I wouldn't have expected different effects for the different

regions. If there is a reason for that it would be good to mention it. You explain this in L194-206, right?

Yes. The climate conditions and UKCP Local climate projections are not universally identical across all the UK. For example, rainfall tends to be more frontal in the north (with orographic rainfall over high ground), and more convective in the southeastern UK. The climate projections also exhibit gradients in the changes across the UK. Even in a single ensemble, there are north-south gradients in the future changes in rainfall which can be quite different to the present-day climatology and relate to regional differences in increases in moisture availability as well as changes in circulation patterns.

Additionally, the association between climate anomalies and wheat yields can be explained by combinations of i) resilience of the wheat plant; ii) husbandry practices of farmers and agronomists (lines 194-206); and iii) non-climatic biophysical conditions (e.g. soils, day length), all of which may vary regionally.

In the revised manuscript, we will more clearly explain how these factors vary regionally, and we will provide further explanation of how the climate projections might affect the crop yields in light of these regional differences.

RC3.13 L220: What is the advantage of using this "score". Couldn't you also work directly with the correlations of table 2?

The idea behind the score is that if climate conditions are very poor or very good in just one of the crop growth stages then the effects may not be sufficient to alter crop yields. This is because there are multiple factors which affect crop growth. For instance, poor conditions in one stage may be mitigated by good conditions or agronomic methods in another stage (e.g. wet weather leading to increased incidence of fungal disease can be mitigated by subsequent increased use of fungicides). In contrast, detrimental climate conditions may have a cumulative impact across multiple growth stages, and this would be reflected by our score statistic. We will ensure this point is clarified in the revised manuscript.

RC3.14 L246: Is "sample" the correct word here? I would have written "project". But I'm not a native speaker.

The Reviewer is referring to "UKCP simulations tend to sample greater future warming and drying in summer compared to the full CMIP5 ensemble". We will modify the wording to make it more explicit (e.g. "tend to project").

RC3.15 L246: Is this statement true for the UK in particular? And how did you get there? I think it would be good to spend a few more sentences on this aspect to provide a good overview of potential biases over UK.

Yes, the statement that "UKCP simulations tend to sample greater future warming and drying in summer compared to the full CMIP5 ensemble" is true for the UK.

Our response to RC1.22 is relevant here, and we will add a more detailed discussion in the manuscript of how the UKCP ensemble compares to the CMIP ensemble. The figure in RC1.22 from Kendon et al. (2021) shows that UKCP Local projections are generally within the 5-95% probability levels of the UKCP Probabilistic projections (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) used in our study. UKCP Local projections sample relatively high temperature changes. 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.

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

RC3.16 Figure 7: I think this figure could be improved a bit. What do you think about displaying the ensemble spread by a shaded area and the ensemble median by a line?

We agree the figure can be improved by displaying the ensemble spread as a shaded area and the ensemble median by a line. This will simplify and hopefully clarify the figure in the revised manuscript. We appreciate this suggestion.

RC3.17 L292: “since crop yields” instead of “since inter-annual crop yields”?

Yes, we will change this text accordingly.

Thank you for the helpful review!

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