Reviewer responses, Parry et al. HESSD eFLaG drought paper

We thank the two reviewers and the editor for their helpful comments, that have helped us improve the manuscript. We have responded to all comments below and made changes (see Tracked Changes version) in a majority of cases, and explained our reasoning where we disagree with the comments.

Please note that we have made changes to the author team. As the lead author (Simon Parry) has now left UKCEH, we have bought in two new team members, Maliko Tanguy and Eugene Magee, who have done much of the revision work, in particular re-drafting figures and adding new ones, and analysing the data to respond to Reviewer 1's request for more specifics and quantification. We have also conducted all of the revisions using funds from another project (CANARI) as the original eFLaG project is long-finished, and hence we have amended the funding acknowledgments accordingly.

Reviewer 1

The manuscript by Parry et al. presents a thorough, technical and in-depth review of new hydrological projections for a range of catchments and boreholes in England and Wales. The novelty lies in the presentation of a new dataset and its value in assessing future climate risks to UK river flows and groundwater levels, and consequently to UK water supplies. The paper addresses relevant scientific questions within the scope of HESS, reaches multiple well-reasoned conclusions, clearly describes the scientific methods used, and is well structured.

The manuscript is well written and I recommend it to be considered for publication after addressing the general comments below and specific comments given in the attached pdf.

>>>we thank the reviewer for these very positive comments on the paper

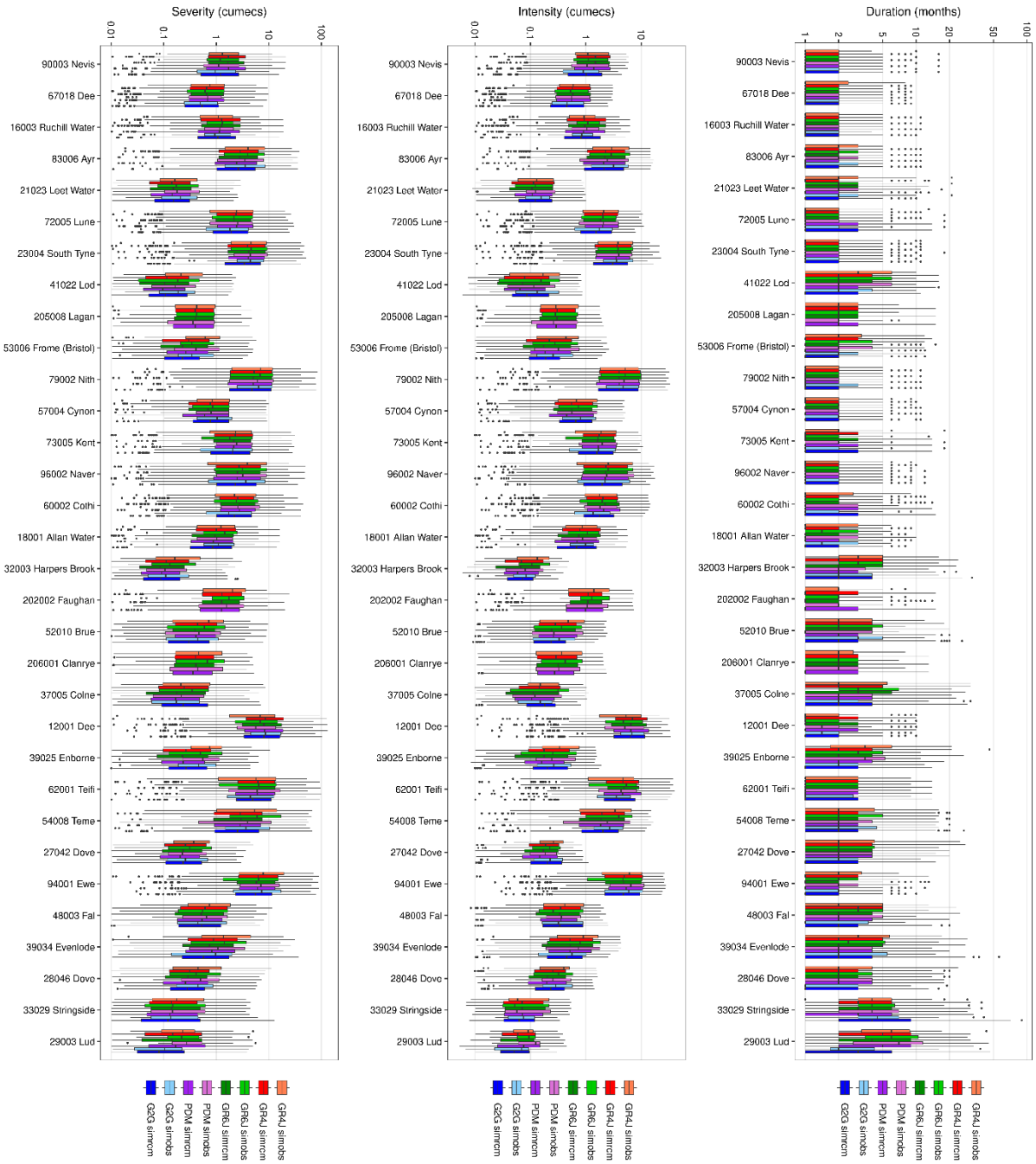
General comments:

The abstract provides a good overview of the paper, but could be strengthened by replacing descriptive language of the results with quantitative results. This same comment applies later in the manuscript when describing the changing drought characteristics of the hydrological flows.

>>We agree. We have added some clarifications and quantitative summary results in the abstract. We agree this information could be added in other locations which are currently quite descriptive, and we have amended accordingly (highlighted in the track changes version).

Overall, the quality and clarity of figures is good, however some colour schemes could be edited to improve ease of interpretation, and clarifying text needs to be added to several figures (identified in the pdf). The addition of smaller maps in several of the later figures would also help interpretation of the figures.

>>We thank the reviewer for this feedback on legibility and ease of interpretation. We have looked at the comments on individual figures and we have made some improvements on colour schemes (see below) and modified text where appropriate. We considered the idea of summary maps, but we felt it was very difficult to insert them at a meaningful scale – the location is clear to readers from Fig 1 and we don't think thumbnail maps will add anything.


Severity (cumecs)
Intensity (cumecs)
Duration (months)
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0.1
1
10
100
1
2
5
10
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50
100
90003 Nevis
67018 Dee
16003 Ruchill Water
83006 Ayr
21023 Leet Water
72005 Lune
23004 South Tyne
41022 Lod
205008 Lagan
53006 Frome (Bristol)
79002 Nith
57004 Cynon
73005 Kent
96002 Naver
60002 Cothi
18001 Allan Water
32003 Harpers Brook
202002 Faughan
52010 Brue
206001 Clanrye
37005 Colne
12001 Dee
39025 Enborne
62001 Teifi
54008 Teme
27042 Dove
94001 Ewe
48003 Fal
39034 Evenlode
28046 Dove
33029 Stringside
29003 Lud
G2G simrcm
G2G simobs
PDM simrcm
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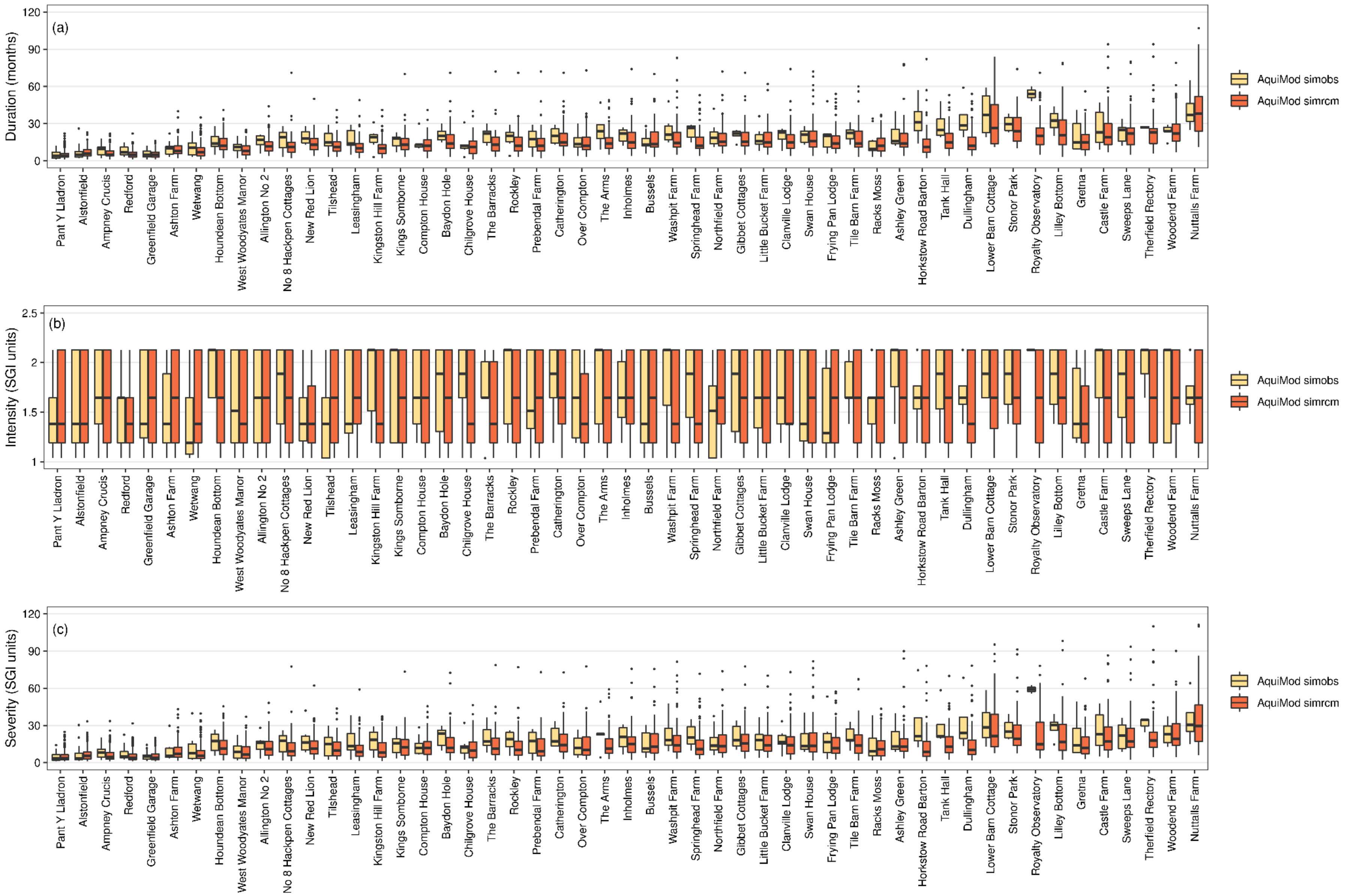

(a)
Duration (months)
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90
60
30
0
Pant Y Lladron
Alstonfield
Ampney Crucis
Redford
Greenfield Garage
Ashton Farm
Wetwang
Houndean Bottom
West Woodyates Manor
Allington No 2
No 8 Hackpen Cottages
New Red Lion
Tilshead
Leasingham
Kingston Hill Farm
Kings Somborne
Compton House
Baydon Hole
Chilgrove House
The Barracks
Rockley
Prebendal Farm
Catherington
Over Compton
The Arms
Inholmes
Bussels
Washpit Farm
Springhead Farm
Northfield Farm
Gibbet Cottages
Little Bucket Farm
Clanville Lodge
Swan House
Frying Pan Lodge
Tile Barn Farm
Racks Moss
Ashley Green
Horkstow Road Barton
Tank Hall
Dullingham
Lower Barn Cottage
Stonor Park
Royalty Observatory
Lilley Bottom
Gretna
Castle Farm
Sweeps Lane
Therfield Rectory
Woodend Farm
Nuttalls Farm
AquiMod simobs
AquiMod simrcm
(b)
Intensity (SGI units)
2.5
2
1.5
1
Pant Y Lladron
Alstonfield
Ampney Crucis
Redford
Greenfield Garage
Ashton Farm
Wetwang
Houndean Bottom
West Woodyates Manor
Allington No 2
No 8 Hackpen Cottages
New Red Lion
Tilshead
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Chilgrove House
The Barracks
Rockley
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Clanville Lodge
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Lower Barn Cottage
Stonor Park
Royalty Observatory
Lilley Bottom
Gretna
Castle Farm
Sweeps Lane
Therfield Rectory
Woodend Farm
Nuttalls Farm
AquiMod simobs
AquiMod simrcm
(c)
Severity (SGI units)
120
90
60
30
0
Pant Y Lladron
Alstonfield
Ampney Crucis
Redford
Greenfield Garage
Ashton Farm
Wetwang
Houndean Bottom
West Woodyates Manor
Allington No 2
No 8 Hackpen Cottages
New Red Lion
Tilshead
Leasingham
Kingston Hill Farm
Kings Somborne
Compton House
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Rockley
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The Arms
Inholmes
Bussels
Washpit Farm
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Clanville Lodge
Swan House
Frying Pan Lodge
Tile Barn Farm
Racks Moss
Ashley Green
Horkstow Road Barton
Tank Hall
Dullingham
Lower Barn Cottage
Stonor Park
Royalty Observatory
Lilley Bottom
Gretna
Castle Farm
Sweeps Lane
Therfield Rectory
Woodend Farm
Nuttalls Farm
AquiMod simobs
AquiMod simrcm

I commend the authors on their thorough discussion section, particularly on the consideration of the impacts of future changes in river flow and groundwater levels on the UK water supply. This narrative is timely and has considerable potential for informing future water resource assessments.

>>>Thanks, we are pleased to see this assessment of timeliness and potential impact of the work

Line 18: It would be helpful to indicate how many catchments, i.e. as a percentage of total catchments
>>>We have amended this along with the above general request for more specifics/quantification

Line 19: Again, quantifying the magnitude of this would be helpful

>>>Agreed – as above

Line 21: How many boreholes decline?

>>Agreed – as above

Lines 46-47: It might be interesting to visualise this relationship – perhaps as a supplementary map

>>>Maps of average annual rainfall and population density could theoretically have been be added, but this is additional replication of material that is well documented and accessible. Have made minor text updates and references to existing materials, namely Folland et al. 2015 who highlight these NW-SE contrasts.

Lines 52-54: For completeness, it would be good to give Wales' water supply composition

>>>We have added this (around 5% groundwater also, according to the same BGS reference)

Line 125: Is the choice of RCP8.5 significant? A sentence on why (i.e. higher likelihood of producing severe droughts) would be good

>>> It is significant and we turn to this in the discussion (and also this is well covered in the othe eFLaG papers: Hannaford et al. 2023 and Tanguy et al. 2023). We have added a small comment (and forward reference) here.

Lines 153-154: Why provide insight into the sensitivity of future projections to hydrological model but not groundwater model? It's possible that AquiMod is the only suitable model for this study, but it would be good to flag / understand the authors reasoning for the difference in motivations

>>>Fundamentally, this is just a limit of the eFLaG dataset, and is really because there is no readily-available alternative model. We have added clarification and highlighted the implications.

Line 164: Do you mean key strategic national water supply networks? Or hydrological networks? Or some other type of network? Clarification would be helpful

>>>We mean hydrometric network, so have added a line to clarify – this is all fully expanded upon in the reference to Hannaford et al. 2013.

Line 175: Clarify in the figure / caption that the number preceding the case study site refers to the NRFA gauging station number, as this may not be clear to an international reader

>>Yes, we have done this

Line 198: Why Q70? Is this decision based on existing literature?

>>It was chosen following experimentation in previous work, and because it is fairly widely-used. There is no consensus on threshold levels in literature; decisions are based on expert judgement and knowledge of typical UK droughts. It might be considered a bit of a high threshold, but from experience, this was necessary to ensure multi-year droughts naturally pooled together rather than arbitrarily split. It is lower than some studies that use Q50 (e.g. Rudd et al. 2017, 2019), and balances yielding sufficient drought in the sample while still being impactful. We have added some explanatory text.

Line 241: Consider re-ordering based on geographical region, i.e. north-east, south-east, etc. This would help the reader match descriptions in the main text to the data in the figure

>>> We considered this – this has been done in the past, using north-south (e.g. Barker et al. 2019). We chose this time to focus on the BFI and responsiveness as it is part of the story (we use this approach to sorting throughout). We feel it is better to leave as-is, for that reasons – readers can see spatial patterns better using the maps, and can select catchments using the interactive maps available (refer to the eFLaG Portal: https://eip.ceh.ac.uk/hydrology/eflag). We added references to the Portal in the main text and the 'data access' section.

Line 267: Consider re-ordering the x-axis by region (as suggested for Figure 2)

>>>>Same as above

Line 336: It would be helpful to quantify here (and throughout the manuscript) what "vast majority", "numerous", "most" and other descriptive words mean, i.e. provide a count / percentage of the number of catchments exhibiting these patterns

>>>Agreed, amended here and in other locations

Line 391: Consider adding a map alongside the figure which shows the locations of the stations visualised in the sub-plots. This would help the reader understand the geographical patterns in the results. It may also be helpful to group the sub-plots by regions

>>>Tricky to add here to a nice 4x8 grid of plots, and catchments identified in location map figure – so we prefer not to make this change

Lines 398-399: This clear quantification of change is what is missing from the flow analysis

>>> thanks, agreed

Line 435: A map showing the borehole locations could be inserted into the figure as sub-plot 8

>>>>Easier to add map here than above (because there are 7 catchments in a 4x2 grid, leaving a gap). But still the map would be small, tricky to identify locations. We prefer to leave as-is, to be consistent across all Figs.

Lines 469-470: I understand what this sentence is trying to convey, but the wording is odd. It's not the narrative of climate change that will influence the underlying hydrological processes, but the consequences / impacts of climate change. Consider re-wording

>>>> agreed. Can have re-worded. We have reframed this, rather than talking about the 'narrative' (which is often a device used to refer to these kind of simple headlines) we now talk more directly about this being the 'future changes in seasonality'. We will still refer to such

changes being a 'headline', about which there is much uncertainity and variability in future ensembles, in reality. But we have removed that the starting sentence and improved the wording.

Line 492: Figure is missing sub-plot titles (i.e. names of the 12 simrcm runs)

>>>we will add this.

>>>We have amended this figure to a new visualisation – see replies to R2.

Reviewer 2

This study presents a comprehensive overview of drought characteristics for future river flows and groundwater levels based on a newly available dataset. Results show that most of the projected future river flows decline over time and hydrological droughts show an increase in duration, intensity and severity. This general tendency towards increasing drought risk that agrees with international drought research. Projected groundwater droughts divert slightly from this overall decline with some projected increase in groundwater in specific regions. The manuscript is well-written and the discussion leads to interesting implications for UK water resource management. Overall, I would recommend this work for publication, albeit with some changes primarily to the presentation of the data.

>>>Thank you for this positive assessment of the research and the communication in our paper

It is evident from the manuscript that a lot of work has been done to generate this overview of drought characteristics. However, I would suggest a somewhat further analysis or rather further synthesis of identified droughts in the 32 catchments (river flows) and 51 boreholes (groundwater levels). This would improve the readability of the result sections and figures and thereby strengthen the Discussion.

Main comments:

Figures 2, 3, 4, 5 and 7 present a lot of data without much direction for the reader in the figures. It would be better if the figures highlight examples in the text as similar to Figure 8. This is makes the results more readable and gives more confidence in the summarised values mentioned in the text. For example, in the surface water section there is often a reference to catchments north-west and south-east (R: 279-280) and catchments further north (R 300 – 301). A more readable version of Figure 4 could display just the highlighted catchments in 2 panels with the complete figure in the supplementary material. The groundwater figures are equally busy, whilst in the text useful comparisons are summarised based on the accumulation period [R323-326]. I would suggest supporting these statements with a trimmed down version of the current figures.

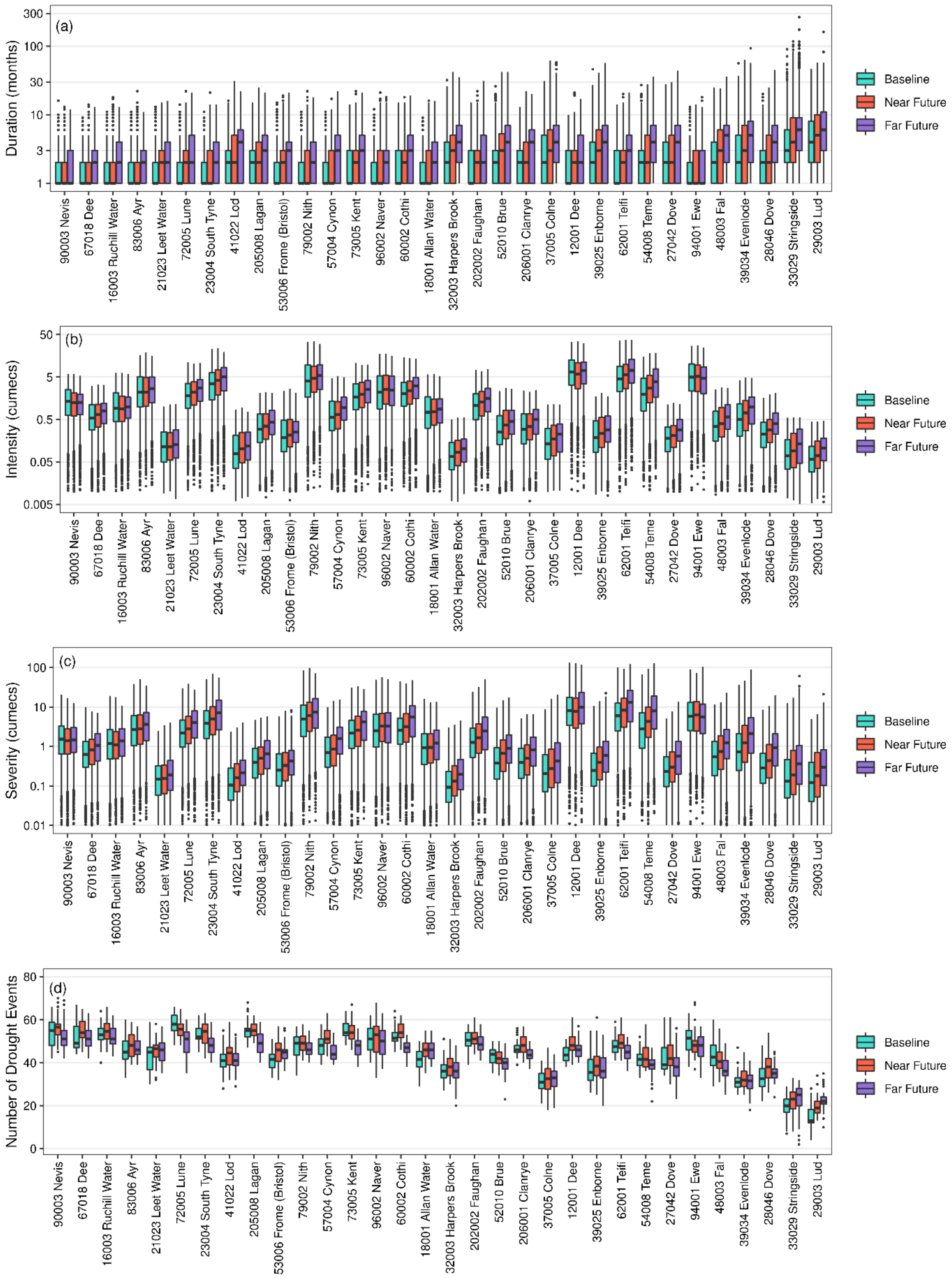
>>>We disagree with this, as we want this to be comprehensive given that (for flows), these catchments are already a subset of the 200 catchments. We feel there is an advantage to the story to show the full range of behaviours. Sub-selecting catchments would be somewhat arbitrary. We prefer to keep the whole range for flows, but have sharpened up the textual references to help the reader. We have though added another figure (see below) that helps to interpret the changes across catchments and interactions between the different drought properties

Additionally, the drought analysis could be more informative as the drought intensity and severity are fairly similar given that the drought duration is already presented. Authors may prefer to select either the maximum intensity or severity and calculate the frequency of drought events for the identified decades. This will indicate how often droughts of a certain duration & intensity/severity might be expected in which time periods, which will be valuable to add to the Discussion and invaluable information to water managers aiming to manage drought impacts.

>>> We explored frequency for river flows but have decided not to feature it as it rather confuses the picture. Frequency decreases in future (see below) in many catchments, largely because duration increases. Although the number of months 'in drought' does increase. Given that this would be a very substantial change requiring significant reframing of the methods, analysis and discussion, we feel that this should be considered 'beyond scope' and a subject for a whole follow-up study, exploring the interaction between these drought characteristics. In common with Rudd et al (2017, 2019) we have decided to stay with the current set of characteristics. Intensity and severity are different characteristics – intensity is the peak of the drought, whereas severity is integrated over the event.

However, we have added plots that help show frequency and how it interacts with duration, and these plots also help summarise future drought changes in a more accessible way, as per the above comment.

Drought frequency plots:


(a)
Duration (months)
300
100
30
10
3
1
(b)
Intensity (cumecs)
50
5
0.5
0.05
0.005
(c)
Severity (cumecs)
100
10
1
0.1
0.01
(d)
Number of Drought Events
80
60
40
20
0
Baseline
Near Future
Far Future
90003 Nevis
67018 Dee
16003 Ruchill Water
83006 Ayr
21023 Leet Water
72005 Lune
23004 South Tyne
41022 Lod
205008 Lagan
53006 Frome (Bristol)
79002 Nith
57004 Cynon
73005 Kent
96002 Naver
60002 Cothi
18001 Allan Water
32003 Harpers Brook
202002 Faughan
52010 Brue
206001 Clanrye
37005 Colne
12001 Dee
39025 Enborne
62001 Teifi
54008 Teme
27042 Dove
94001 Ewe
48003 Fal
39034 Evenlode
28046 Dove
33029 Stringside
29003 Lud

New Fig 5: Gantt chart type plots:

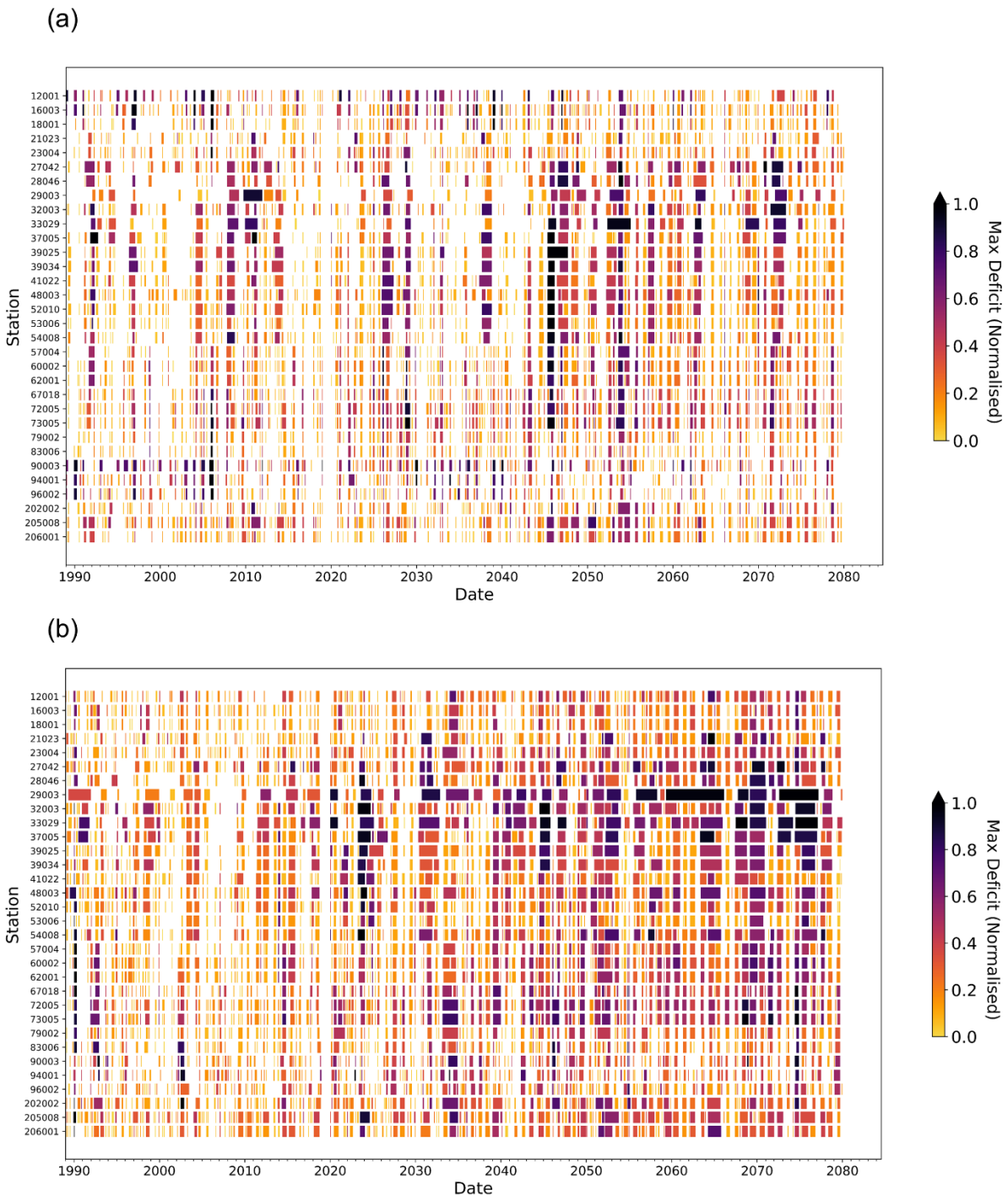


Figure X – Gantt chart of drought events extracted from streamflow simulated by PDM model for two example RCMs (a) RCM 7 and (b) RCM 13.

Lastly, the baseline period could be more informative both in terms of the uncertainty in the projections and the robustness of the dataset with 4 models in the dataset. I would suggest comparing the projections for the baseline to the observational records rather than the simulations of those models, as this includes the model bias for simulated droughts. An over/underestimation of simulated drought/low flow conditions is thereby unaccounted for, as mentioned in the Discussion [R602-604]. Part of this issue is acknowledged by the authors when discussing the value of calibration of the different models that seems crucial. Some models (i.e. G2G) might be less suitable to simulate catchments with artificial influences. However it remains unknown how this relates to the results in the baseline and if this would therefore explain the systematic higher projection results. More, detailed explanation with examples is necessary to convince the reader that there is sufficient confidence in the projections.

>>>We respectfully disagree - do not think it is a good idea to compare to observations as a baseline – this rather goes against convention in climate impact research. While we agree that there are biases in the original model vs observations, this is precisely why we compare against OBS SIM, so the comparisons are internally consistent – otherwise the model bias just becomes an uncontrollable and unsystematic noise that makes it impossible to look at climate and hydrological model uncertainty. It's important to separate these sources of error.

But, regarding the fact there are also biases in the hydrological model similations: this is an important point to address, and we thank the reviewer for raising it. But we feel best not addressed not in the analytical framework as suggested by the reviewer. We feel that this has already been very comprehensively explored in Hannaford et al. 2023, which evaluates the models in both ways - against observations (Stage 1), and then when driven by the RCM (Stage 2). We do not want to repeat that here, as the sole purpose of this was to look at how well drought properties are captured in the RCM ensemble (i.e. a further Stage 2 evaluation) relative to simobs, to add to the rigorous evaluation already conducted in Hannaford er al. 2023 based on low flows and a range of other metrics. In our discussion of caveats and limitations we have already been very detailed in referring to the inter-model differences and their likely reasons, including the point made about G2G and artificial influences. We have however added reference to the more expansive consideration of this already set out in Hannaford et al. (2023).

Minor comments:

in the abstract, I would suggest naming the database in the abstract to avoid confusion. Also, the abstract is fairly lengthy and could do with shortening.

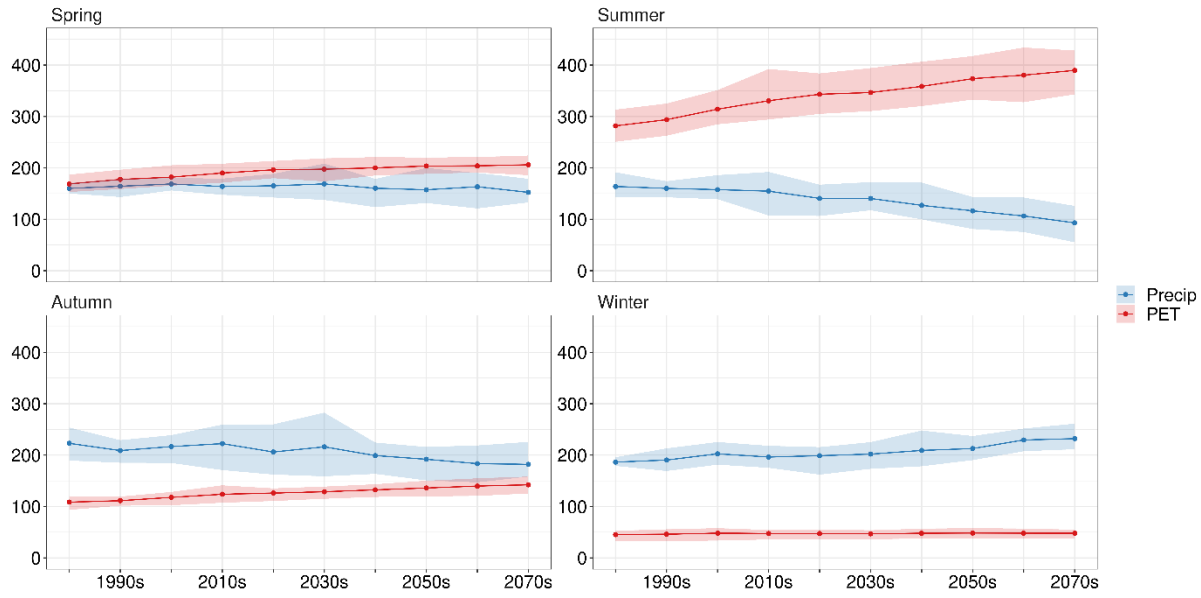
>>Agreed, we made these changes

Figures 2, 3 and 5 seem upside down in this version of the manuscript. Do check the final formatted version to avoid this prior to publication.

>>>They had to be added into the HESSD submission sideways because HESSD guidelines wouldn't allow a mix of portrait and landscape pages. We will obviously liaise with the HESS production team should the manuscript be accepted.

Figure 9 can be condensed into just 4 figures with a range showing the variation. The lines are now overlapping, which makes it hard to distinguish the individual P from PET or the estimate the range across the 12 runs.

>>>We have suggested an alternative version of these figures – see below


Spring
Summer
Autumn
Winter
400
300
200
100
0
1990s
2010s
2030s
2050s
2070s
Precip
PET