

Author's response to referee comments

Response to anonymous referee #1

Thank you for taking the time to review our paper and helping to significantly improve it, particularly with regards the way the methodology is presented. Our responses to your comments are in bold font. Where we reference pages, lines, figure and tables, this corresponds to the revised manuscript and approximately to the tracked changes manuscript.

1. The term “biased correction” is not defined thoroughly in the study. I read the article but I could not relate the biased calculations with the methodology described by the authors. It was just hard to follow. A proper explanation of what specific “biases” are the author trying to correct is missing. For instance, are the authors trying to correct the CMIP5 Q data with a Budyko-type equation (Eq. 2). If this is it, I do not understand why are there using so many ways of calculating Q and related changes (climate, human, GCM-LSM, Q_a , Q_h , below combined) in the context of this study. Please explain this clearly.

The only “conventional” bias correction performed in this study is in section 3.2, using equation 10. This is used to correct P and E_p in the CMIP5 models so that they are in the correct part of the Budyko space, prior to accounting for changes in these variables. These corrected variables (which become P' and E'_p) are then used to calculate Q^* , the Budyko corrected runoff, which is defined on page 9, line 5. We think some of the misunderstanding of this, and the other methodology that you list in your following comments, comes down to conflating methods, data and equations that are used for the historical 20th century analysis with those that are used for the projected CMIP5 analysis. The other referee has also commented that the methodological approach could be explained better. We have therefore added a flow chart (Fig. 1; Fig.3 in the manuscript) to the end of the introduction section in the revised manuscript to serve as an overview for the subsequent breakdown of the paper.

The key message from this is that the Budyko curve, or rather the updated Fu version (equation 3), can be used to both attribute past changes and help refine future changes. These two strands share common ideology but are attempting to

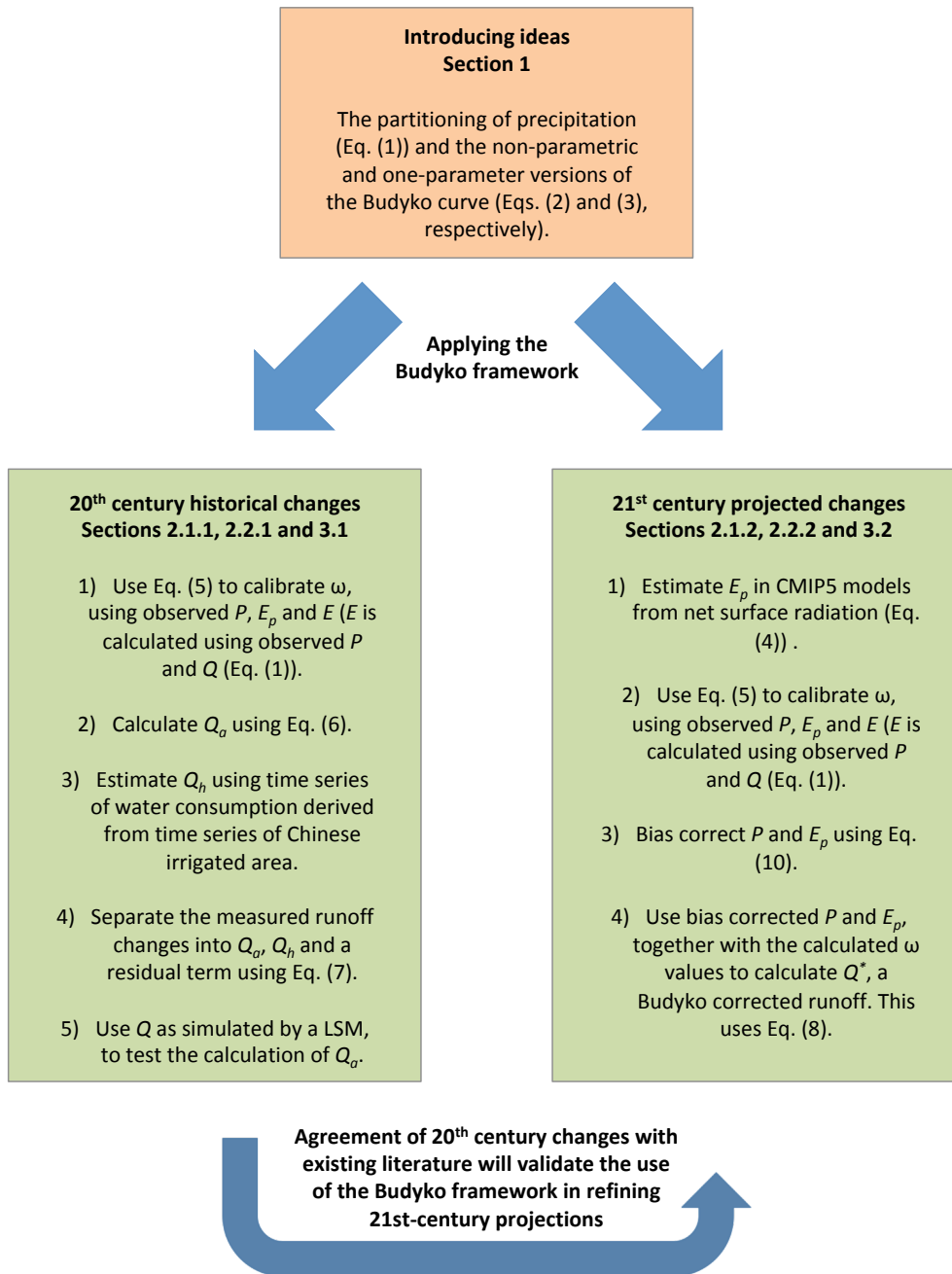


Figure 1: Schematic of how the Budyko framework is used to improve our understanding of 20th-century historical changes and 21st-century projected changes.

tackle different problems and therefore use different equations. The flow chart more clearly emphasises this and even lists the equations that are used in each application. We have also divided the Data (section 2.1) and Methods (section 2.2) subsections into further subsections to more clearly differentiate the two applications.

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Also regarding what I just mentioned, if the authors are trying to perform this bias correction of CMIP5 data, I must say that I have a feeling that CMIP5 data for Q is already biased-corrected. For bias corrected I mean that it is made at least consistent in Budyko space ($0 < ET/P < 1$ and $PET/P > 0$ and $PET/P > ET/P$) for most basins in the world. Strangely, the direct CMIP5 ET data does not comply with this (all over Budyko space), and hence I assume there has been some type of “bias correction” in this sense for CMIP5 Q data. The authors should check Q and ET data from CMIP5 data for their two basins and if so, please update.

The models are coded to avoid values that are not physically consistent, but we are almost certain that Q output from CMIP5 models is not biased corrected. It is a direct output. We check Q as directly available for 28 models with water balance-derived Q (calculated with $P - E$) and do not see any sensitivity to this, stating “These findings are not sensitive to using directly simulated runoff instead (Fig. 11 and Table 1).” Further, we do not perform direct bias correction on Q , only P and E_p . The “correction” of Q is within the Budyko framework and we do not use CMIP5 Q in this calculation. The Budyko framework ensures that calculated Q values are physically consistent.

2. The authors describe the methods partly in the introduction, partly under “Data” and partly under “methods”. This was confusing, and hard to follow in general. I would describe the methodology in chronological order and only under “Methods”. In this way, you would also clear much needed space to expand the literature review which is now limited. Please mention the several studies that use the Budyko framework to understand water changes in Chinese basins. I mention here a few. The authors say that there is little consensus on the contributions of these two components to the decrease in Q . I would say that there is plenty, mainly afforestation and/or flow regulation. And what is the Q_h have to do with the bias correction. Again, please expand on this.

We think the methodology section is clearer through incorporating the changes listed above in response to your comment 1, particularly with the inclusion of the flow chart. However, we do feel that the introduction as it is contains only information that is crucial to introduce the overarching ideas and, namely, the Budyko framework. While used in the methodology, the water balance (equation 1) is introduced here because it is critical in discussing the partitioning of P into Q and E and how the Budyko formula helps to understand this. While we refer to equations 2-3 in the methodology to derive further equations, they are not directly used in any calculations in the form presented in the introduction. The data section only contains information on the data used, with equation 4 simply stating that we calculate E_p in the CMIP5 models directly from net surface radiation (CMIP5 data that is archived). Also the methods section is currently in chronological order in the sense that one needs to determine ω (equation 5), before calculating Q_a (equation 6), before Q_a can be used in the decomposition of Q_m in equation 7 (with Q_h also detailed in the section above equation 7). In addition to the improvements to the structure of the methodology suggested above, we have added some specific additional information to make the manuscript easier to follow. For example, the following sentence has been added to the paragraph underneath equation 8:

“In Eq. (8) we use ω values calculated using observed data and Eq. (5) for the 1951–2000 period (1.77 and 2.44 for the Yangtze and Yellow, respectively).”

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And we have moved the paragraph talking of comparing directly simulated Q with Q calculated from $P - E$ from the data section 2.1.2 to the methods section 2.2.2, because it fits better under methods. We have also rewritten it to be clearer:

“We compare Q^* with the original CMIP5 model simulated Q , calculated as $P - E$. Data for Q are also directly available for 28 of the 34 GCMs. Conclusions should not be sensitive to using either direct Q output or water balance-derived Q if changes in storage are negligible. Bring et al. (2015), however, showed evidence for long-term systematic changes in water storage in some CMIP5 models. Although not a primary analysis, it is sensible to test the sensitivity of our results to the choice of Q .”

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Of the Budyko/Chinese basins studies that you list, only one is directly related to the Budyko framework. However, we agree that we should mention this study and some other high profile papers that we found. To the page 3, line 10 paragraph we have added:

“There is a wealth of literature that uses the Budyko framework to understand water changes in other Chinese basins (Yang et al., 2007; Xu et al., 2014; Liang et al., 2015).”

References:

Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., Yang, Y., Long, D., and Feng, M.: Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in Chinas Loess Plateau, *Water Resour. Res.*, 51, 6500–6519, 2015.

Xu, X., Yang, D., Yang, H., and Lei, H.: Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin, *J. Hydrol.*, 510, 530–540, 2014.

Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., and Lei, Z.: Analyzing spatial and temporal variability of annual water-energy balance in nonhumid regions of China using the Budyko hypothesis, *Water Resour. Res.*, 43, W04426, 2007.

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With regards the “little consensus on the contributions of these two components to the decrease in Q ”, you are correct. Most papers suggest that human impacts have had a significant influence on runoff. We have changed this sentence and added the useful references you provided:

“Most studies suggest a significant contribution of direct human impacts, including afforestation and land-use change (Huang et al., 2003; Liu et al., 2008; Zhang et al., 2008; Qiu et al., 2011), although methods and attributed contributions vary.”

References:

Huang, M., Zhang, L., and Gallichand, J.: Runoff responses to afforestation in a watershed of the Loess Plateau, China, *Hydrol. Processes*, **17**, 2599–2609, 2003.

Liu, M., Tian, H., Chen, G., Ren, W., Zhang, C., and Liu, J.: Effects of land use and land cover change on evapotranspiration and water yield in China during the 20th century, *J. Am. Water Resour. Assoc.*, **44**, 1193–1207, 2008.

Qiu, G. Y., Yin, J., Tian, F., and Geng, S.: Effects of the “Conversion of Cropland to Forest and Grassland Program” on the water budget of the Jinghe River catchment in China, *J. Environ. Qual.*, **40**, 1745–1755, 2011.

Zhang, X., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P.: Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China, *Water Resour. Res.*, **44**, W00A07, 2008.

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3. I tried to understand the methods:

a. You calculate historical Q from GRDC data (1951-2000) b. You calculate E as P-Q from a) (1951-2000) c. You calculate E_p from Penman-Monteith (1951-2000) d. You calculate Q from LPJ-LSM (1951-2000). Here I could not understand what is this estimate trying to represent? Is it land-use driven Q, climatic Q, combined Q, or what? It was hard to follow, the explanation of the multiple runs. e. You calculate Q from the CMIP5 data (2006-2100) as P-E. Here see my comment 1, specially regarding the statement of line 31 Page 5, Conclusions should. . . f. You calculate E_p from the CMIP5 data (2006-2100) g. Calibrate Eq. 2 to obtain w. How did you do that? I would do it as: *Wang, D. and Hejazi, M.: Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States, *Water Resources Research*, **47**(10), n/an/a, doi:10.1029/2010WR010283, 2011. h. You calculate Q_a i. You calculate Q_h , I could not understand why nor how. What does Q_h have to do with the biased correction? j. Now you calculate changes in all Q components. k. Then you compare Q_a with Q from LPJ LSM. Again, it is hard to know what this comparison should result in, since it is not clear what Q from LPJ LSM really represent. l. I got lost in what Q^* psychically means. If this is the main purpose of the study, then I cannot understand why the authors go through a to k.

a; We do not use GRDC data. The first line of section 2.1.1 states “We use the Dai et al. (2009) Global River Flow and Continental Discharge Dataset...”

b-c; Yes, for the historical 20th century analysis, which is more clearly separated in the revised manuscript.

d; We agree that this could be easier to understand. We have therefore added some clarification. You are correct in saying it is meant to represent climatic Q , or rather changes due to aridity change alone. It does also include a representation of some non-climatic factors but we expect these to be of second-order importance compared to changes in P and E_p . Therefore, it should agree with the calculation of Q using the Budyko framework, which also accounts for aridity change alone. To the page 4, line 15 paragraph in the introduction we have added:

“If these estimates reconcile it suggests that the Budyko framework is suitable for this attribution, since Q simulated by the LSM should largely reflect changes in P and E_p only.”

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In the 20th-century historical changes data section (section 2.1.1) we have highlighted that we consider a second LPJ LSM run that does not include land-use changes and we can therefore test the assumption that this specific non-climatic factor has a negligible effect on simulated Q compared to P and E_p . To the page 6, line 30 paragraph we have added clarification of how this extra run provides an extra line of evidence but does not form a main focus of the paper:

“The run used in our primary analyses was also driven by historical land-use changes, calculated from the History Database of the Global Environment (HYDE) (Klein Goldewijk and Verburg, 2013). A separate run excludes the HYDE dataset, so that we are able to test the sensitivity to land-use changes. Assuming that any sensitivity is minimal, we only comment on this separate run briefly.”

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Further, in the 20th-century historical changes methods section (section 2.2.1) we define the runoff simulated by the LPJ LSM as ΔQ_{a_i} and added extra information to

explain what this represents and how land-use changes are briefly considered:

“That is to say, ΔQ_{a_i} should be dominated by changes in P and E_p and show strong agreement with ΔQ_a . We specifically test the sensitivity to land-use changes since they are excluded in a separate run of the LPJ LSM model. This is the only change between the two runs, so we can elucidate the influence of land-use changes by simply taking the difference between them.”

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e-f; Yes, although we actually use 1951–2100 (page 9, line 5 paragraph).

g; This is explained in the page 7, line 20 paragraph and we actually use equation 5.

h-i; Yes. The calculation of Q_h is explained at the bottom of page 6/top of page 7. It has nothing to do with the bias correction, which concerns the projected CMIP5 analysis. We hope this is more clear with the inclusion of the flow chart and improved methodology section as described above.

j-k; Yes. The LJP LSM runoff should be a proxy for Q_a calculated via the Budyko framework as detailed in the text (page 8, line 30 and supplementary Sect. S3).

l; Again, this is concerning the projected 21st century CMIP5 analysis, which is much clearer in the revised manuscript.

The authors need to mention what calculations are related with the bias-correction, and which ones are related with the aim of calculating the human component of Q (Q_h). So, is this the chronological order of calculations? If not, please modify. Also, where is the correction bias coming into these methods, I could not see it, until maybe the calculation of Q^* . Please specify.

We hope the revised layout of the methodology makes this much clearer. We have included the equations that are used in each calculation and in each application in Fig. 1.

Response to anonymous referee #2

Thank you for reviewing our paper and providing suggestions that have improved it. Our responses to your comments are in bold font. Where we reference pages, lines, figure and tables, this corresponds to the revised manuscript and approximately to the tracked changes manuscript.

The manuscript is generally in a good shape, well structured and well written. The overall presentation of the results is good with concise and high-quality figures. The methodological approach seems to be technically sound, but (due to its complexity) needs to be explained better. Maybe some sort of conceptual figure or flow chart would help! Further, the obtained results depend on many assumptions which potentially not permit a robust interpretation of the results. The authors already discuss some limitations of their approach, but it is my assessment that this discussion needs to be extended before final publication. Also, some important references are missing to better outline some issues and limitations of their approach.

The other referee has also commented that the methodological approach could be explained better. We have therefore added a flow chart (Figure 1) to the end of the introduction section in the revised manuscript to serve as an overview for the subsequent breakdown of the paper.

The key message from this is that the Budyko curve, or rather the updated Fu version (equation 3), can be used to both attribute past changes and help refine future changes. These two strands share common ideology but are attempting to tackle different problems and therefore use different equations. The flow chart more clearly emphasises this and even lists the equations that are used in each application. We have also divided the Data (section 2.1) and Methods (section 2.2) subsections into further subsections to more clearly differentiate the two applications.

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Major comments:

1) I would be very careful with separating the measured change in runoff into the individual components as done in eq. 7. If you assume such a linear relationship, you also assume the individual components to be independent, which they are clearly not! Especially the separation

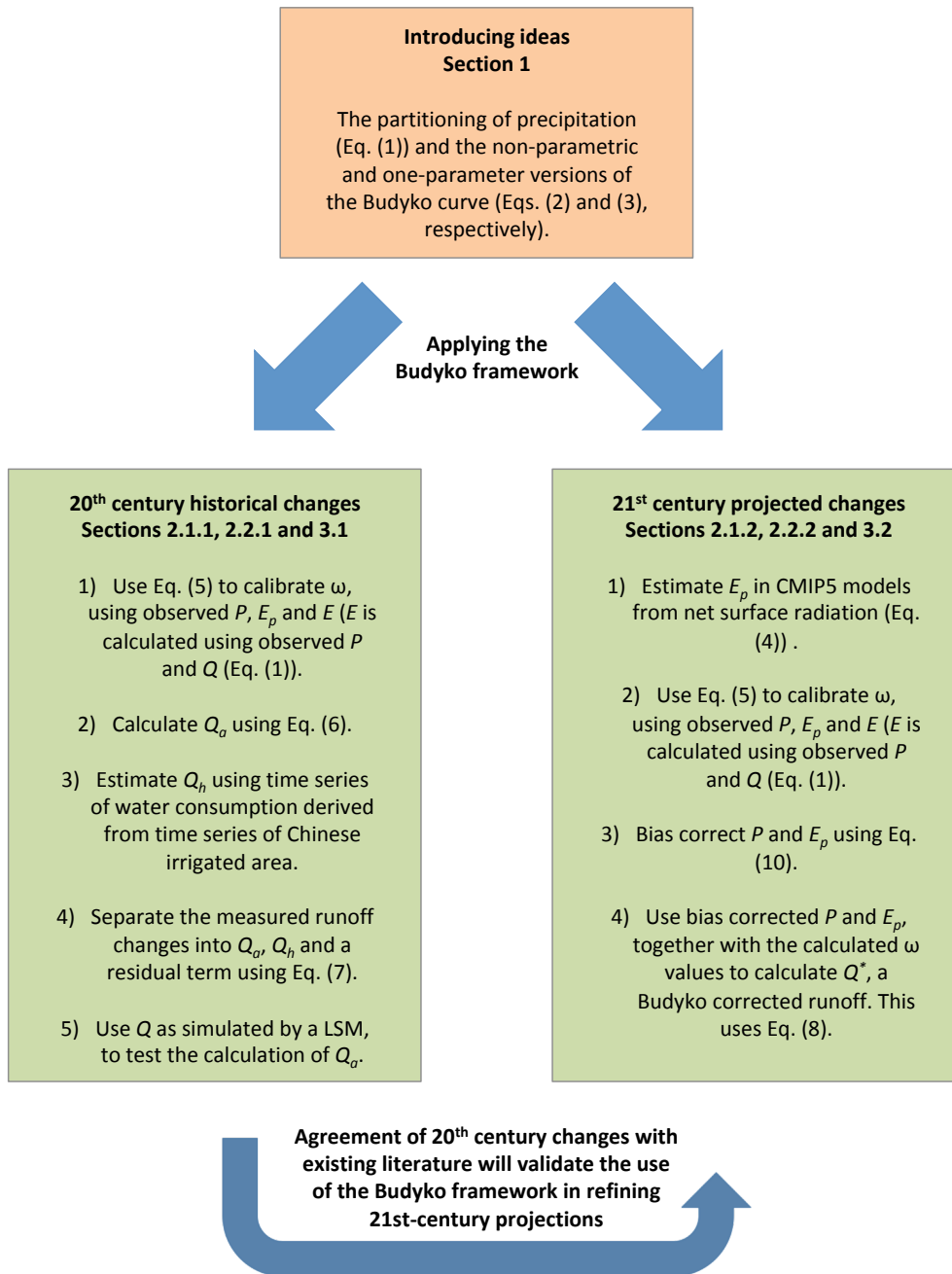


Figure 1: Schematic of how the Budyko framework is used to improve our understanding of 20th-century historical changes and 21st-century projected changes.

into Q_h and Q_o is potentially dangerous. Please also be aware that in the context of the Budyko framework, aridity is solely defined through the notional, dimensionless ratio E_p/P , which has no direct physical meaning. Everything else besides mean annual E_p/P is actually integrated into w . Also, w and E_p/P are not necessarily independent (please see Padron et al, 2017). It would be nice if you could try to determine if there are dependencies between Q_a , Q_h , and Q_o . Is it possible to plot these against each other? In case there are large dependencies and interrelationships the obtained results might be less meaningful.

This is a very good point and something that we have explored further. Unfortunately it is difficult to test for dependencies between Q_h and Q_o due to the limited temporal resolution (decadal mean values) of the irrigated area time series of Freydkank and Siebert (2008) that is used to calculate Q_h (page 13, line 10). We can, however, look at the relationship between Q_a and changes due to all other factors besides aridity change (ω), represented by the residual $\Delta Q_h + \Delta Q_o$ in equation 7. The interannual correlation is -0.35 (Figure 2).

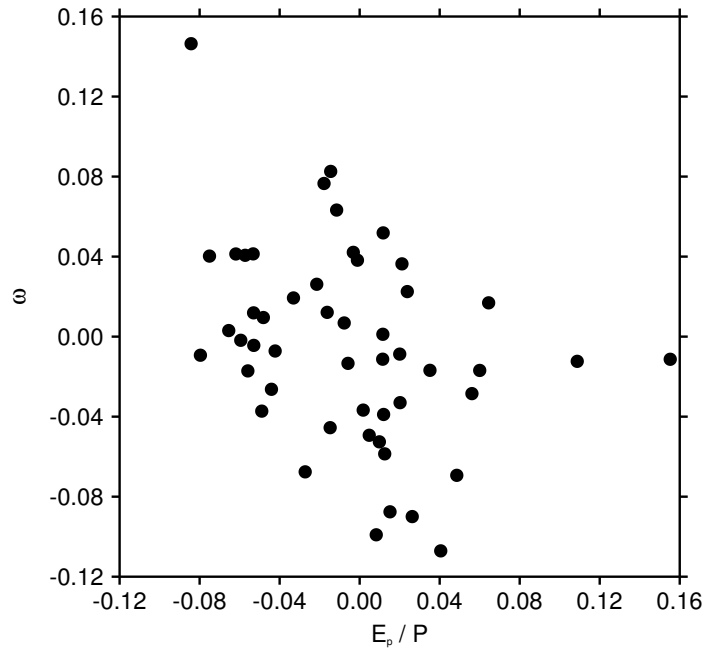


Figure 2: Interannual correlation.

However, this correlation becomes positive (0.66) when considering 5-year means (Figure 3). Although both correlations are significant, the change in sign leads us to believe that there is not strong and consistent evidence for such a relationship here. We do feel it is important to point this out as a potential limitation of decomposing changes in runoff into these separate components. We have therefore added the

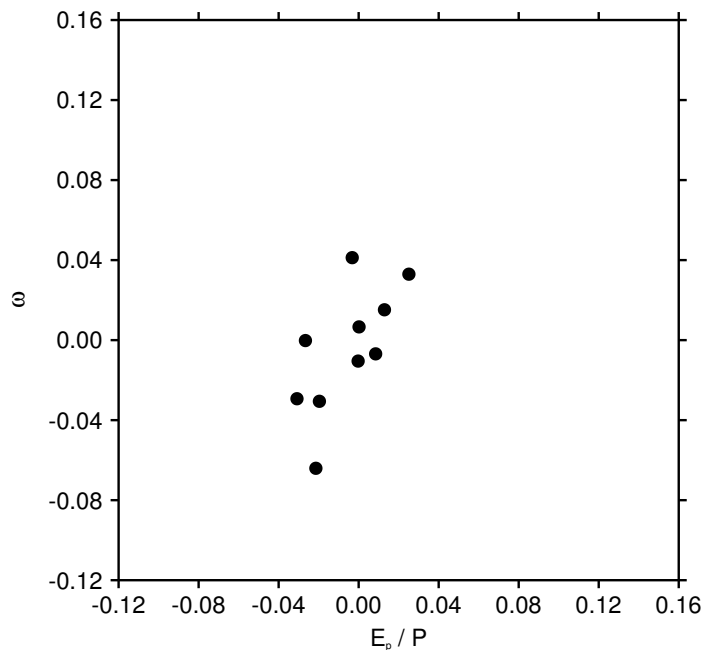


Figure 3: 5-year mean correlation.

following to the discussion (page 21, line 30):

“It is also important to note some potential limitations of using Eq. (7) to separate the measured decrease in Yellow river runoff into various components. This approach assumes a linear relationship and therefore that the individual components are independent. Padron et al. (2017) showed that cross correlations exist between many of the factors suggested to influence runoff through ω . Testing for dependencies between ΔQ_h and other components is unfortunately limited by the poor temporal resolution of the irrigated area time series of Freydank and Siebert (2008). Although we find that interannual variations in Q_a and the residual $Q_h + Q_o$ are correlated (-0.35), this correlation is weak and reverses sign when considering multi-year means. Further, our approach considers long-term trends/changes in runoff, which means that any dependencies at shorter timescales should not influence conclusions.”

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2) In the main text, the authors assume w (omega) to be constant. In the Supplementary they further present results obtained for a (time-)varying w . I actually leave this to the authors, but I would almost prefer to present the time-varying more prominently. A certain variation around the original Budyko curve and thus a variation of w is actually inherent to the Budyko framework. This was already stated by Budyko himself. Hence, the Budyko framework is not necessarily

deterministic. There is a growing body of literature interpreting the Budyko framework in a probabilistic sense (e.g. Greve et al., 2015, Singh and Kumar, 2015, Gudmundsson et al., 2016, etc.), thus accounting for the spread in w and taking into account the complex interplay of all other factors (besides the aridity index). By using the time-varying approach you basically account for these variations, which in my assessment is more realistic.

We were equally unsure during the writing of the paper whether to present the time-varying analysis in the manuscript or leave it as supplementary material. Although, as you say, using the time-varying approach allows a more complete assessment of changes within the Budyko framework, our main aim here is to illustrate the large improvements that can be made by considering CMIP5 output without the large aridity biases that are currently present. The choice of ω (constant or time-varying) actually plays a small role in shaping changes, compared to correcting for aridity biases (E_p/P). Also, many of the other factors that determine ω are not well represented in CMIP5 models so that a full consideration of ω is difficult. We understand the argument for both choices but, for the reasons given above, have decided to keep the time-varying approach in the supplementary materials.

3) In this context, please be aware and discuss that you are considering temporal variations here. Most of the referenced Budyko-based studies actually consider spatial variations. It is important to note that these are not necessarily tradable (Berghuijs and Woods, 2017).

This is an important point to make. We would like to point out that the year-to-year variability calculated through the Budyko framework and presented in Figs. 5 and 10 should not be taken at face value, since changes in storage could dominate at these timescales. The Budyko framework is more appropriately applied to study long-term mean changes, which is exactly what we do with the CMIP5 projected changes. Although we present year-to-year variability in Fig. 10, the conclusions are drawn from the differences between two 20-year means at the end of the 20th and 21st centuries. Likewise, we look at trends in the 20th century analysis. It is worth pointing out that the conclusions on historical changes, regarding the contributions of aridity change and direct human impacts, are qualitatively the same if considering differences between 10 (or 20) year means at the start and end of the 1951–2000 period. We have pointed this out in the text by adding the following to the end of

the discussion (page 22, line 25):

“Most applications of the Budyko framework consider spatial rather than temporal variations. Berghuijs and Woods (2016) demonstrate that spatial and temporal variations are not necessarily tradable. We stress that the Budyko framework is not employed here to robustly determine interannual variability in water availability, but is instead used to understand long-term trends (Sect. 3.1) or the difference between 20-year means at the end of the 20th and 21st centuries (Sect. 3.2).”

And the following to the text underneath equation 7 (page 8, line 20):

“...with changes over the historical period (1951–2000) calculated as the linear trend. We note that our conclusions are not affected by using the difference between either 10 or 20-year means at the beginning and end of the historical period.”

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4) You use the Budyko-based equation 8 to compute Q^* for each year. One of the main assumptions of the Budyko hypothesis is stationarity, i.e. storage changes are negligible. This might, however, not be the case here due to interannual variations in storage. Have you maybe tested to use longer time periods to smooth out long-term variations in water storage? How would your results look like when computing decadal Q^* ?

Because we have no information on changes in storage when we calculate Q as $P - E$ (and assume changes in storage are equal to zero) our results do not change through taking decadal means (Figure 4).

We actually check the potential impact of storage changes by considering values for a subset of 28 (from 34) CMIP5 models for which Q is directly simulated. This information is shown in Fig. 10 and Table 1 and does not affect conclusions, especially for the Yellow catchment, as pointed out in the results.

Minor comments:

These are all useful comments and we have acted on all of them.

p. 1, l. 3: I would not use “describe” here, it might be better to use something like “represent”. The Budyko framework does not mechanistically describe the relationship between the aridity

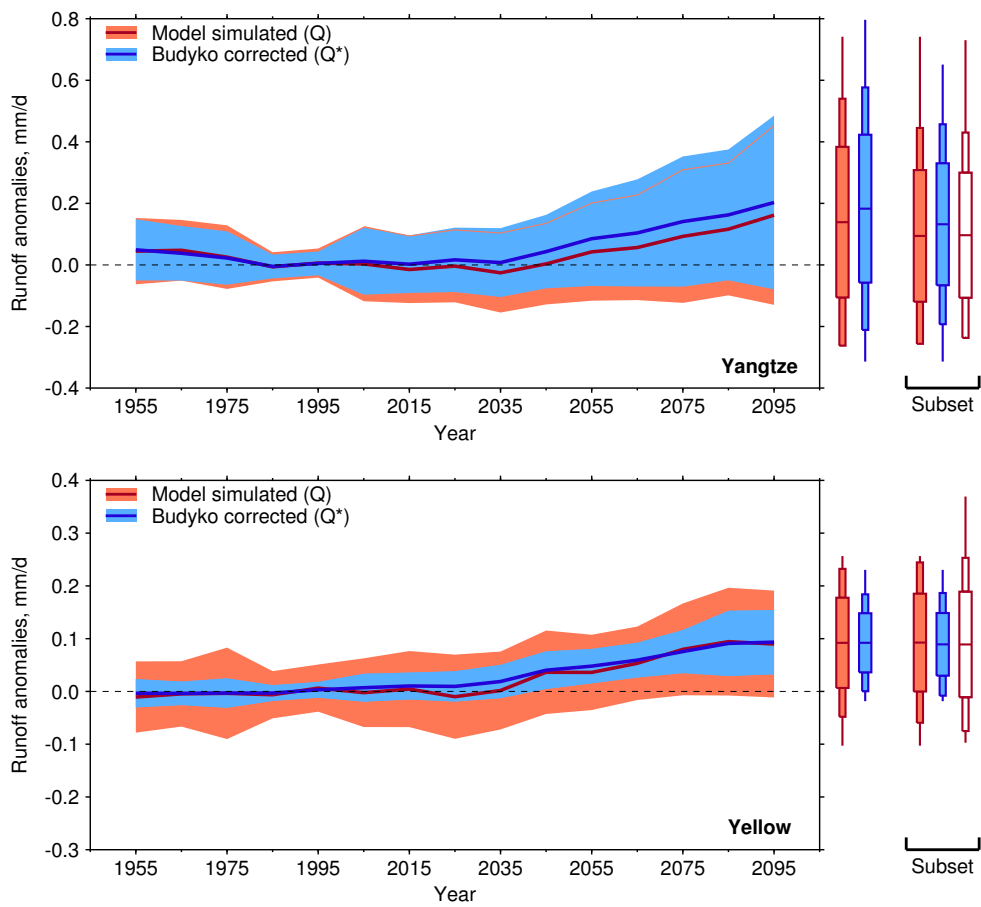


Figure 4: Using decadal means.

and the evaporative index.

Changed to “represent”.

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p. 1, l. 16-19: There is some recent literature which challenges the referenced papers and the ubiquitous increase in aridity in a warmer world (Roderick et al., 2015, Scheff et al., 2017, Greve et al., 2017, Scheff, 2018). Might be worth to mention that this is an ongoing debate.

Changed to:

“At the largest scales, the majority of literature on projected changes in aridity suggests a global land drying tendency (Dai, 2013; Cook et al., 2014; Scheff and Frierson, 2015); a consequence of ubiquitous increases in potential evapotranspiration (Ep), but mixed signals in precipitation (P). This has been challenged, however, by some recent studies (Roderick et al., 2015; Greve et al., 2017; Scheff et al., 2017).”

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p. 2, l. 1-3: It might be better to rephrase this a bit. Depending on the context, the terms “water supply” and “water demand” are interpreted differently. Water supply is not necessarily just atmospheric water supply. Water supply can also be runoff. Some people also consider groundwater or water from other, unconventional sources (water transfer, desalination, etc.) as water “supply”. Also, water stored in reservoirs is some sort of water supply. Water demand is often used in terms of human water consumption, including domestic and industrial water use as well as water used for irrigation.

We agree that this was poor wording. Rather than considering the entire problem in this context we rather meant that most studies working on water availability projections consider very specific components of supply and demand. We have rewritten the opening sentence as this (page 2, line 5):

“Literature on future water availability projections has typically been framed around the net atmospheric supply of water versus the net demand for water resulting from direct human impacts (land-use change, dam construction and reservoir operation, and surface water and groundwater consumption for irrigation)...”

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p. 3 l. 7: For $w=2.6$, please cite Yang et al, 2008.

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p. 4, Fig. 2: The basin outlines look a bit strange. I know that this is based on grid cells, but why dont you just outline the grid cells instead of interpolating the basin borders. This would also help to avoid the gap between both basins

We have changed the plots to avoid this gap between the Yellow and Yangtze basins.

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p. 4, l. 3: Among seasonality, snow dynamics and storminess it is also many other factors that are related to a hydroclimatological change. Maybe just add an “etc.”

Changed to:

“The contributions of climate change (which incorporates aridity change, but also changes in seasonality, snow dynamics, storminess and many other factors...”

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p. 5, l. 24-26: Is this shown by Sitch et al., 2013. In this case, it might be better to add the reference at the end of the sentence. Or is this based on a separate analysis? In this case, you might add something like “not shown”?

Good point. Sitch et al. (2013) referred to the TRENDY intercomparison project. The runoff coefficient comment was based on our own separate analysis, so we have added a “not shown” comment.

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p. 6, eq. 4: Milly actually proposes an ad-hoc multiplier of 0.8. Have you checked if you can maybe reduce some of the biases in E_p by adjusting the multiplier?

This does affect E_p biases. The multi-model mean bias for E_p for the Yellow catchment changes from +0.30 mm/day to -0.25 mm/day relative to the observed climatology. But since the aridity biases are largely a result of precipitation biases, this makes little

difference to the overall results (“Figure” 5; compare to Table 1 of the manuscript).

		RCP4.5	RCP8.5
Yangtze (all):	ΔQ	0.12 +/- 0.32	0.14 +/- 0.40
	ΔQ^*	0.18 +/- 0.34	0.20 +/- 0.41
Yangtze (subset):	ΔQ	0.08 +/- 0.26	0.09 +/- 0.35
	ΔQ^*	0.13 +/- 0.27	0.15 +/- 0.34
	ΔQ_{direct}	0.08 +/- 0.25	0.10 +/- 0.33
Yellow (all):	ΔQ	0.07 +/- 0.11	0.09 +/- 0.14
	ΔQ^*	0.07 +/- 0.07	0.10 +/- 0.10
Yellow (subset):	ΔQ	0.06 +/- 0.11	0.09 +/- 0.15
	ΔQ^*	0.06 +/- 0.08	0.10 +/- 0.10
	ΔQ_{direct}	0.06 +/- 0.11	0.09 +/- 0.16

Figure 5: The equivalent to Table 1 in the manuscript using the Milly and Dunne (2016) multiplier.

p. 8, l. 30: See my first major comment. This might also be due to dependencies between each factor.

We have covered this in the discussion.

p. 18, Fig. 10: Is the time series for Q^* computed annually? And is the 5yr running mean subsequently computed from the annual time series? Or is Q^* computed from the 5yr running mean time series of P and E_p ?

Yes, it is computed annually and the running mean is computed from the annual time series.

p. 19, l. 30-32: Please note here that Li et al. (2018) is potentially only valid at large catchment scales. At other scales, this might not be the case. You might also note here or somewhere else that the interpretation of w is still largely and inconclusive and sometimes also contradictory (Padron et al., 2017).

We have added the important caveat that this vegetation link may only hold for large catchments..

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A simple tool for refining GCM water availability projections, applied to Chinese catchments

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Abstract. There is a growing desire for reliable 21st-century projections of water availability at the regional scale. Global climate models (GCMs) are typically used together with global hydrological models (GHMs) to generate such projections. GCMs alone are unsuitable, especially if they have biased representations of aridity. The Budyko framework ~~describes~~ represents how water availability varies as a non-linear function of aridity and is used here to constrain projections of runoff from GCMs, without the need for computationally expensive GHMs. Considering a Chinese case study, we first apply the framework to observations to show that the contribution of direct human impacts (water consumption) to the significant decline in Yellow river runoff was greater than the contribution of aridity change by a factor of approximately 2, although we are unable to rule out a significant contribution from the net effect of all other factors. We then show that the Budyko framework can be used to narrow the range of Yellow river runoff projections by 34 %, using a multi-model ensemble and the high end RCP8.5 emissions scenario. This increases confidence that the Yellow river will see an increase in runoff due to aridity change by the end of the 21st century. Yangtze river runoff projections change little, since aridity biases in GCMs are less substantial. Our approach serves as a quick and inexpensive tool to rapidly update and correct projections from GCMs alone. This could serve as a valuable resource when determining the water management policies required to alleviate water stress for future generations.

1 Introduction

Climate change is a global problem, but the impacts and associated vulnerability are not homogeneous. There is therefore a demand for robust projections of changes in regional climate, particularly water availability. At the largest scales, the majority of literature on projected changes in aridity suggests a global land drying tendency (Dai, 2013; Cook et al., 2014; Scheff and Frierson, 2015); a consequence of ubiquitous increases in potential evapotranspiration (E_p), but mixed signals in precipitation (P). This has been challenged, however, by some recent studies (Roderick et al., 2015; Greve et al., 2017; Scheff et al., 2017). At the river catchment scale, direct human impacts (non-climatic, human interventions directly affecting the partitioning of P into runoff (Q) and evapotranspiration (E)) are already having a significant, but poorly quantified, effect on water availability (Nilsson et al., 2005; Gerten et al., 2008; Destouni et al., 2013; Haddeland et al., 2014). For the Indus river catchment Haddeland et al. (2014) showed that current direct human impacts on water availability (decreases due to water consumption for irrigation) are expected to be greater in magnitude than end-of-21st-century climatic impacts on water availability. Increasing E due to

irrigation is commonly observed in heavily populated catchments, especially across southern and eastern Asia (Gordon et al., 2005).

Projecting Literature on future water availability ~~can be thought of as a supply and demand issue;~~ projections has typically been framed around the net atmospheric supply of water versus the net demand for water resulting from direct human impacts (land-use change, dam construction and reservoir operation, and surface water and groundwater consumption for irrigation). Recent studies have considered either: 1) the projected human water demand using integrated assessment models, with water supply fixed to present conditions (Hejazi et al., 2014a); 2) the projected water supply using global climate models (GCMs) to force offline global hydrological models (GHMs), with human water demand fixed to present conditions (Cook et al., 2014; Schewe et al., 2014); or 3) both projected water supply and projected human water demand (Haddeland et al., 2014; Hejazi et al., 2014b).

Using GCM output alone in hydrological projections is not considered suitable, because GCMs have coarse resolution, simplified land surface schemes and, crucially, biases in simulating hydrological cycle components. The usual approach for generating hydrological projections is to use bias corrected and downscaled GCM output to force offline GHMs (Wood et al., 2004). Using GHMs in addition to GCMs greatly increases the computational expense of a study. Here, we propose an approach for refining projections of water availability from GCM models participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5). We use Q as a measure of water availability. The term “refine” is used in the sense that we expect to generate projections of Q on an improved physical footing, compared to using GCM output directly. The approach uses model simulated aridity and a bias correction, within the Budyko framework (Budyko, 1974). We do not consider future human water demand, only future net atmospheric supply of water, of which aridity is a key determinant.

We consider a simple water balance and assume that changes in storage are negligible:

$$P = Q + E. \tag{1}$$

GCM variables require bias correction to be of value at catchment scales (Schewe et al., 2014). Bias correcting a GCM simulated future Q or E is a complex process. To illustrate this point we introduce the Budyko framework (Budyko, 1974). Within this framework the partitioning of (annual to long-term mean) P into Q and E scales as a non-linear function of aridity. Aridity, within the Budyko framework, is the dimensionless ratio of E_p to P . The evaporative index, the dimensionless ratio of E to P , is dependent on E_p/P . The relationship is ~~described~~ represented by the non-linear Budyko curve, which is constrained by the physical limits of the atmospheric demand for water ($E < E_p$; the red dashed 1:1 line in Fig. 1) and the atmospheric supply of water ($E < P$; the blue dashed horizontal line in Fig. 1).

The original deterministic and non-parametric Budyko formula was developed using data mainly from European river catchments (Budyko, 1974):

$$\frac{E}{P} = \left\{ \frac{E_p}{P} \tanh \left(\frac{P}{E_p} \right) \left[1 - \exp \left(- \frac{E_p}{P} \right) \right] \right\}^{1/2}. \tag{2}$$

The trajectory taken in the Budyko space due to a change in P , E_p or E is dependent on the initial values of these three fluxes (the mean state) (van der Velde et al., 2014). Therefore, an accurate representation of the observed climatology is important

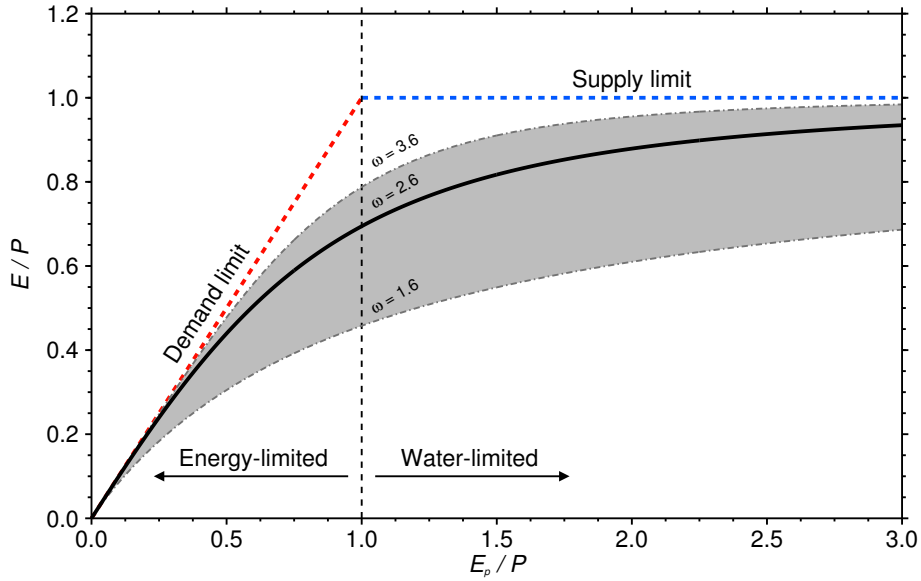


Figure 1. The traditional Budyko curve (solid black curve), corresponding to $\omega = 2.6$ in Eq. (3). The $\omega = 2.6 \pm 1$ curves are also shown (dot-dashed gray curves bounding the shaded region). The atmospheric supply limit ($E < P$; horizontal dashed blue line) and atmospheric demand limit ($E < E_p$; diagonal dashed red line) are shown. Energy-limited conditions are represented to the left of the vertical dashed black line ($E_p/P < 1$) and water-limited conditions are represented to the right ($E_p/P > 1$).

in any modelling study looking at hydrological projections, especially since changes in variables are typically small compared with climatology. If the present-day aridity is biased then the future-minus-present changes in runoff (ΔQ) and evapotranspiration (ΔE) will also be biased, even if the future-minus-present changes in precipitation (ΔP) and evapotranspiration (ΔE_p) are correctly simulated. Supplementary Sect. S1 further demonstrates this point with an example that, although arbitrary, is illustrative of the magnitude of aridity biases in CMIP5 models.

Recent work has shown that aridity can only explain part of the differences between catchments (e.g., Zhang et al., 2001). This has led to the derivation of a number of parametric forms of the Budyko curve. One of the more popular forms is the Fu equation (Fu, 1981; Zhang et al., 2004), a one-parameter function expressed as:

$$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P} \right)^\omega \right]^{1/\omega}, \quad (3)$$

where ω is an empirical parameter that is calibrated against local data. The traditional Budyko curve (Eq. (2)), corresponds to $\omega = 2.6$ in Eq. (3) (Yang et al., 2008).

Here, an attempt is made to utilize biased but plentiful GCM output without the need for GHMs. We apply our approach to two major catchments in China, the Yangtze and the Yellow. [There is a wealth of literature that uses the Budyko framework to understand water changes in other Chinese basins \(Yang et al., 2007; Xu et al., 2014; Liang et al., 2015\).](#) The Yangtze and

Yellow rivers dominate the wetter south and drier north, respectively (Fig. 2). The spatial variability in P means that the north of the country, which is poleward of the East Asian monsoon rains, is more water-stressed than the south. This is exacerbated by the fact that the north has 65 % of the total arable land in China (Piao et al., 2010).

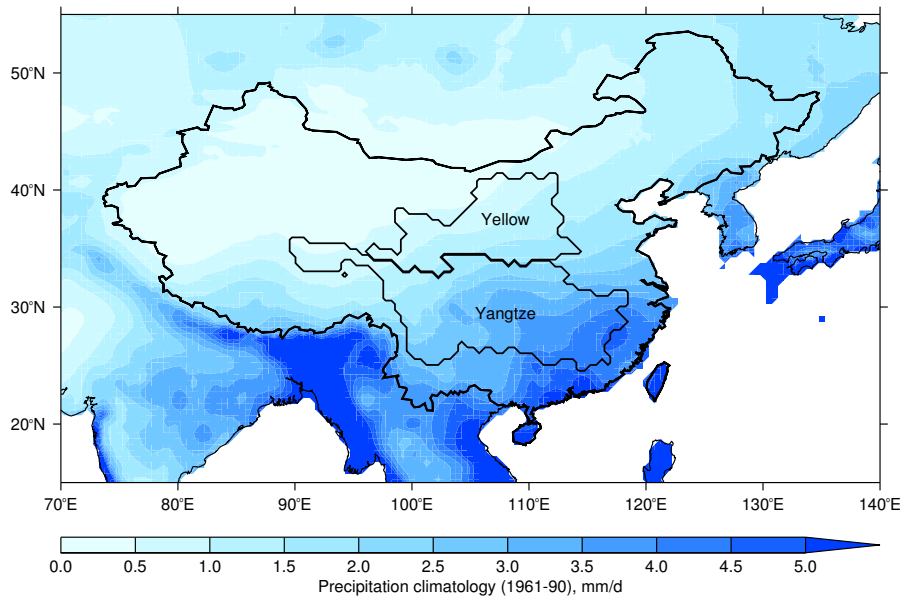


Figure 2. Precipitation climatology for 1961–1990 using the CRU precipitation dataset. This dataset is spatially interpolated, using available in situ observations, to give complete global land coverage. The location of the Yangtze and Yellow catchments within China is shown.

The mismatch in water supply versus water demand could be the reason behind the stark decline in Yellow river streamflow (the temporally lagged, spatial integral of upstream Q) seen in recent years (Yang et al., 2004). The contributions of climate change (which incorporates aridity change, but also changes in seasonality, snow dynamics and storminess, storminess and many other factors (Gudmundsson et al., 2016)) and direct human impacts to this “drying up” are widely discussed in recent literature (Wang et al., 2006; Piao et al., 2010; Miao et al., 2011). However, there is little consensus on the contributions of these two components to the decrease in Q . Therefore, we Most studies suggest a significant contribution of direct human impacts, including afforestation and land-use change (Huang et al., 2003; Liu et al., 2008; Zhang et al., 2008; Qiu et al., 2011), although methods and attributed contributions vary.

We can also use the Budyko framework to quantify the contribution of aridity change alone (changes in P and E_p only) to the 20th century decrease in Q in the Yellow catchment. We reconcile this estimate with Qualitative agreement with previous studies will serve to validate the use of the Budyko framework in refining 21st-century projections, while hopefully shedding new light on 20th-century observed changes. The 20th-century Budyko framework estimate is compared with an estimate of Q simulated by an offline land surface model (LSM) that does not include a representation of direct human impacts, with the

exception of land-use change. ~~This acts to test the suitability of the Budyko framework~~ If these estimates reconcile it suggests that the Budyko framework is suitable for this attribution, since Q simulated by the LSM should largely reflect changes in P and E_p only. Further, we ask if the difference between the total change in Q and the component attributed to aridity change, for the Yellow catchment, is in close agreement with a simple estimate of the change in Q due to direct human impacts.

5 Section 2.1 details the observed and modelled data used and Sect. 2.2 describes the methodology. Results are presented in Sect. 3, first applying the Budyko framework to the 20th century observed water availability (Sect. 3.1), before extending the approach to constrain 21st-century model projections of water availability (Sect. 3.2). We finish with a discussion (Sect. 4) and conclusions (Sect. 5) The two-pronged approach of this paper is summarised in Fig. 3. It shows how the approaches share the same theory and use many of the same equations, but are independent in their objectives. However, the 20th century application of the Budyko framework supports the suitability of the 21st century application, as indicated (Fig. 3).

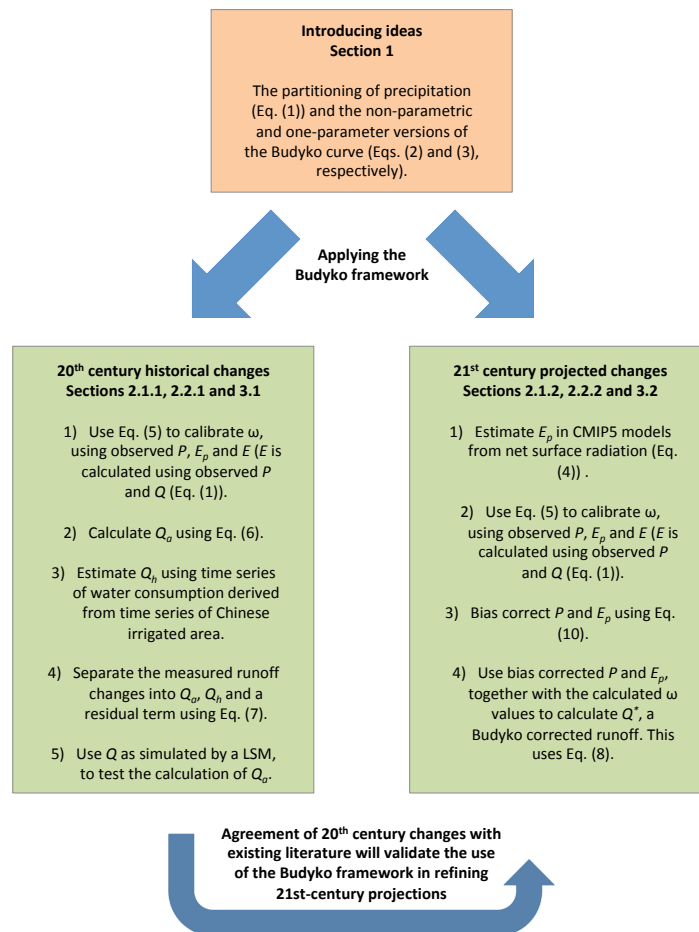


Figure 3. Schematic of how the Budyko framework is used to improve our understanding of 20th-century historical changes and 21st-century projected changes.

5 2 Data and methods

2.1 Data

2.1.1 20th-century historical changes

We use the Dai et al. (2009) Global River Flow and Continental Discharge Dataset to calculate observed Q for the Yangtze and Yellow catchments. This dataset aimed to use the farthest downstream gauging station (to maximise spatial representation) that had good temporal coverage. Q is calculated by dividing river discharge at a gauging station by the upstream catchment area. In keeping with many other hydrological studies we use annual mean values throughout, but consider the water year (October-September). Data are available for October 1950 to September 2000.

To ensure an accurate comparison between observed P and Q we produce high-resolution catchment masks on a $0.5^\circ \times 0.5^\circ$ grid to match that of the P dataset used (Fig. 2). We select the latest Climatic Research Unit (CRU) high-resolution P dataset, CRU TS3.23 (Harris et al., 2014). The interpolated version of the dataset is used, which offers complete global terrestrial coverage. This allows for direct comparison with the spatial and temporal coverage of observed Yangtze and Yellow Q . By restricting our analysis of observations to 1951–2000 we find that our conclusions are not sensitive to using either the interpolated version or raw version of the precipitation dataset (see supplementary Sect. S2 and Fig. S1). We then calculate E as $P - Q$ (Eq. (1)).

Likewise, we use the CRU TS3.23 E_p dataset ($0.5^\circ \times 0.5^\circ$ resolution), which is estimated from variables such as temperature, vapour pressure, cloud cover and wind speed, using a variant of the Penman-Monteith equation. This E_p estimator is computed from variables that are often poorly observed, both spatially and temporally. An energy-only E_p estimator would be preferable (Sheffield et al., 2012; Milly and Dunne, 2016), but required observations are not available.

We also use Q output from the Lund-Potsdam-Jena (LPJ) LSM (Sitch et al., 2003; Osborne et al., 2015). This is forced over the 1951–2000 historical period with observed CRU P , as well as other observed CRU climate variables (Harris et al., 2014) and changing CO_2 concentrations (more details are given in supplementary Sect. S3). The run considered-used in our primary analyses was also driven by historical land-use changes, calculated from the History Database of the Global Environment (HYDE) (Klein Goldewijk and Verburg, 2013). A separate run excludes the HYDE dataset, so that we are able to test the sensitivity to land-use changes. Assuming that any sensitivity is minimal, we only comment on this separate run briefly. Simulated Q is available at a monthly frequency at $0.5^\circ \times 0.5^\circ$ resolution. The LPJ LSM is chosen from a multi-model ensemble that forms the TRENDY intercomparison project (Sitch et al., 2013) because it simulates a long-term mean (1951–2000) runoff coefficient (Q/P) that is closest to that observed for both major Chinese river catchments (not shown).

2.1.2 21st-century projected changes

We use data from 34 GCMs participating in CMIP5 (Taylor et al., 2012). These are listed in supplementary Sect. S4. We consider data for historical (1951–2005) and two 21st-century RCP emissions scenarios (RCP4.5 and RCP8.5; 2006–2100)

experiments. Only one ensemble member was used for each model and experiment (the first; r1i1p1). Simulated data are
 5 regrided to $0.5^\circ \times 0.5^\circ$ resolution and masked to the two Chinese river catchments. We calculate Q as $P - E$ (Eq. (1)).

~~However, data for Q is also directly available for 28 of the 34 GCMs. Conclusions should not be sensitive to using either direct Q output or water balance-derived Q if changes in storage are negligible. Bring et al. (2015), however, showed evidence for long-term systematic changes in water storage in some CMIP5 models. It is sensible to test the sensitivity of our results to the choice of Q .~~

10 An energy-only E_p estimator is used for CMIP5 models. E_p , being a hypothetical construct, is not a standard output of CMIP5 models. We follow recent work (e.g., Greve et al., 2014; Greve and Seneviratne, 2015; Milly and Dunne, 2016) and estimate E_p directly from net surface radiation (R_n):

$$E_p = \frac{R_n}{\lambda}, \quad (4)$$

where λ is the latent heat of vapourisation ($\lambda \approx 2.45 \text{ MJ kg}^{-1}$). This simple energy-only E_p estimator has been shown to perform well compared to more complicated estimators, particularly under significant climate change (Sheffield et al., 2012).

15 2.2 Methods

2.2.1 20th-century historical changes

The Budyko framework can be used to estimate the aridity change contribution to the overall change in Q . We have to first calibrate ω against local data for each catchment. Using the observed annual mean P , E and E_p for 1951–1960, ω is calculated as the value that minimises the mean squared errors between the observed annual mean E/P ratios and those modelled using
 20 Eq. (3), for each catchment. Following Li et al. (2013) the objective function is:

$$Obj = \min \sum_i \left\{ \frac{E_i}{P_i} - \left\{ 1 + \frac{(E_p)_i}{P_i} - \left[1 + \left(\frac{(E_p)_i}{P_i} \right)^\omega \right]^{1/\omega} \right\} \right\}^2, \quad (5)$$

where i is the year. The period 1951–1960, in this context, is considered to be representative of natural Q (minimal water consumption or regulation by human activities). There will be some direct human impacts on Q at this time, with a substantial Chinese land area equipped for irrigation even in the 1950s (Freydank and Siebert, 2008), although it does pre-date major dam construction; the Sanmenxia dam was the first major dam in the Yellow catchment and was completed in 1960. In calculating
 25 the E_p/P (aridity change) contribution to the change in E/P (Eq. (3)) we take ω to be constant over the period 1951–2000. Our results are not qualitatively affected by the length of period chosen to represent natural Q (analyses are repeated with 5, 15 and ~~20-year~~ 20-year periods, all starting in 1951).

We use ω values of 1.74 and 2.29 for the Yangtze and Yellow, respectively. Combining Eq. (1) with Eq. (3) gives:

$$Q_a = -E_p + P \left\{ \left[1 + \left(\frac{E_p}{P} \right)^\omega \right]^{1/\omega} \right\}, \quad (6)$$

where Q_a is the runoff due to aridity change (changes in P and E_p only) and so ω is taken to be constant. This separates aridity change from changes in all other climatic factors besides aridity change, as well as changes in all non-climatic factors. All other

climatic and non-climatic factors are integrated by ω . This aridity change component is sometimes referred to as the natural Q in other studies (Wang et al., 2006). However, this can be misleading since changes in P and E_p include both changes due to natural variability and, potentially, human-induced changes (Zhang et al., 2007; Dai, 2013).

We also estimate the runoff due to direct human impacts (Q_h) for the Yellow catchment only, since previous work suggests that Q_h contributes significantly to the measured runoff (Q_m) here (Wang et al., 2006; Miao et al., 2011). Time series of water consumption are derived to estimate Q_h . Water consumption is defined as the water withdrawn for human use that leaves a catchment (Xu et al., 2010). Agricultural sector irrigation accounts for a large proportion of total water consumption and, in turn, Q_h . A year 2000 water consumption estimate of $0.082 \text{ mm day}^{-1}$ for the Yellow catchment (48 % of the 1951–1960 mean Q_m) (Xu et al., 2010) is scaled with a 1951–2000 time series of Chinese irrigated area (Freydank and Siebert, 2008). Irrigated area in China increased three-fold between 1951 and 2000 and we assume that Yellow catchment irrigated area has changed in proportion with national changes. Accurate quantification of past (and even present) water consumption is immensely difficult, but using estimates of past irrigated area offers a means of making pseudo-quantitative statements about Q_h .

Defining the change in runoff due to aridity change as ΔQ_a , the measured change in runoff (ΔQ_m) can be approximated as the sum of ΔQ_a , the change in runoff due to direct human impacts (ΔQ_h) and the change in runoff due to all other climatic and non-climatic factors besides aridity change and direct human impacts (ΔQ_o):

$$\Delta Q_m = \Delta Q_a + \Delta Q_h + \Delta Q_o, \quad (7)$$

with changes over the historical period (1951–2000) calculated as the linear trend. We note that our conclusions are not affected by using the difference between either 10 or 20-year means at the beginning and end of the historical period. The Budyko framework can only separate the contribution of aridity change to the measured decrease in Yellow river runoff from the contribution of all other factors besides aridity change (time-varying ω), represented by the residual $\Delta Q_h + \Delta Q_o$ in Eq. (7). The parameter ω integrates all other factors, so a significant residual represents a significant net contribution from these factors. Changes in climatic factors besides aridity, such as seasonality, snow dynamics and storminess, and non-climatic factors besides direct human impacts, such as land surface characteristics and the physiological response of plants to increasing CO_2 (CO_2 fertilization, CO_2 stomatal closure and water-use efficiency) could all play a role. However, previous literature suggests that ΔQ_h has been significant in the Yellow catchment. We therefore decompose the residual in Eq. (7) into a component due to direct human impacts and a component due to all other factors besides both aridity change and direct human impacts. Since water is being diverted from the river and heavily consumed, we expect ΔQ_h to be negative.

We reconcile Q_a with Q simulated by the LPJ LSM. Although the LSM is unable to simulate water resources with the complexity of a GHM, it does include a representation of some of the factors integrated by ω , particularly non-climatic factors such as changes in land-use and land cover, the response of stomata to rising CO_2 concentrations, CO_2 fertilization and soil moisture controls on transpiration (see supplementary Sect. S3 and Sitch et al. (2013)). ~~Different runs test the sensitivity to land-use change.~~ The representation of these other factors means that we do not truly compare like-for-like when reconciling Q_a with Q simulated by the LPJ LSM. However, we still expect aridity change to be the dominant driver of runoff in the LPJ LSM and so define the change in runoff simulated by the LPJ LSM as ΔQ_{a_1} . That is to say, ΔQ_{a_1} should be dominated by

changes in P and E_p and show strong agreement with ΔQ_a . We specifically test the sensitivity to land-use changes since they are excluded in a separate run of the LPJ LSM model. This is the only change between the two runs, so we can elucidate the influence of land-use changes by simply taking the difference between them.

2.2.2 21st-century projected changes

Equation (6) is also used to constrain projections of Q in CMIP5 models, instead substituting P with a corrected P (P') and E_p with a corrected E_p (E'_p):

$$Q^* = -E'_p + P' \left\{ \left[1 + \left(\frac{E'_p}{P'} \right)^\omega \right]^{1/\omega} \right\}, \quad (8)$$

where Q^* , the Budyko corrected runoff, is calculated for the period 1951–2100. An asterisk (rather than a prime) is used to show that Q has been corrected using the Budyko framework and not directly using a simple bias correction. The bias correction technique chosen to calculate P' and E'_p is covered in Sect. 3.2. This is because the results of exploratory data analyses on ΔP and ΔE_p , and how these relate to climatology biases across the CMIP5 models, will inform the choice of correction technique. In Eq. (8) we use ω values calculated using observed data and Eq. (5) for the 1951–2000 period (1.77 and 2.44 for the Yangtze and Yellow, respectively).

We compare Q^* with the original CMIP5 model simulated Q , calculated as $P - E$. Data for Q are also directly available for 28 of the 34 GCMs. Conclusions should not be sensitive to using either direct Q output or water balance-derived Q if changes in storage are negligible. Bring et al. (2015), however, showed evidence for long-term systematic changes in water storage in some CMIP5 models. Although not a primary analysis, it is sensible to test the sensitivity of our results to the choice of Q .

3 Results

3.1 20th-century historical changes

The drying of the Yellow river has been one of the most notable aspects of hydrological change in China over recent decades (Yang et al., 2004; Piao et al., 2010). There has been a significant negative linear trend in Yellow river Q between 1951 and 2000 ($-0.26 \pm 0.06 \text{ mm day}^{-1} \text{ century}^{-1}$, $p < 0.05$; range is the 5–95 % range, taken as ± 1.64 standard deviations), while the decrease in P over the equivalent period is not significant at the 95 % ($p = 0.05$) confidence level ($-0.17 \pm 0.21 \text{ mm day}^{-1} \text{ century}^{-1}$) (Fig. 4). The decrease in Q is particularly notable since about 1970. Despite a substantial human water demand in the second half of the 20th century there has been a slight, non-significant, increase in Q in the Yangtze catchment ($0.04 \pm 0.29 \text{ mm day}^{-1} \text{ century}^{-1}$) that is closely matched by a slight, non-significant, increase in P ($0.02 \pm 0.34 \text{ mm day}^{-1} \text{ century}^{-1}$).

The Yangtze river shows no tendency to shift towards a distinct new area of the Budyko space between 1951 and 2000 (Fig. 5). The Yellow river, however, seems to shift towards larger E/P values (smaller Q/P). Within the Budyko framework this could be expected under a shift towards greater aridity (larger E_p/P values), or increases in ω . A systematic shift towards greater aridity is not obvious in Fig. 5. There is a significant positive linear trend in Yellow river E/P between 1951 and 2000

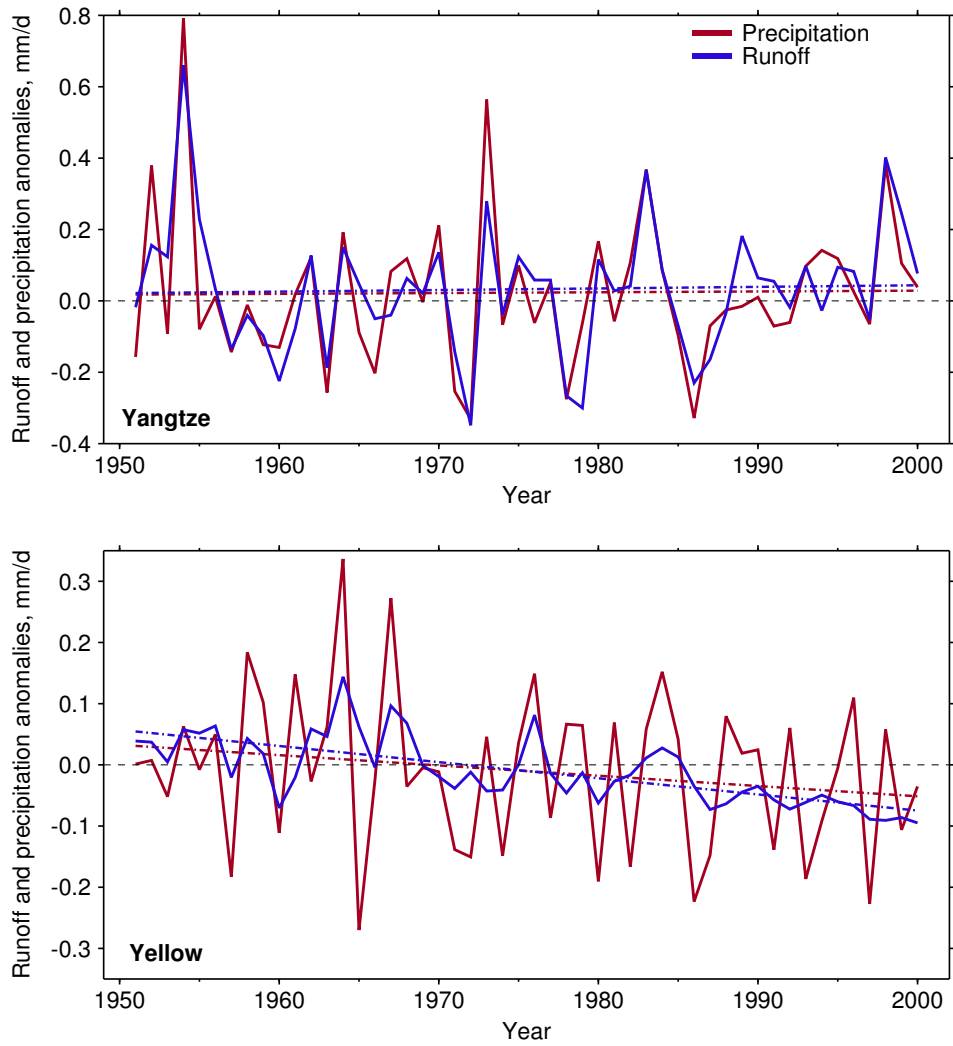


Figure 4. Observed runoff and precipitation anomalies for the Yangtze (top) and Yellow (bottom) river catchments for 1951–2000, relative to 1961–1990. The dot-dashed lines show linear fits to the time series.

(0.22 ± 0.05 per century), but the positive trend in E_p/P (0.52 ± 0.50 per century) is only significant at the 90 % ($p = 0.10$) confidence level. This suggests that all other factors (ω) may also be a key driver of changes in E/P over this time period in the Yellow catchment. Given this evidence and the significant negative linear trend in Yellow river Q , we investigate further the contributions of aridity change and all other factors to the decrease in Q .

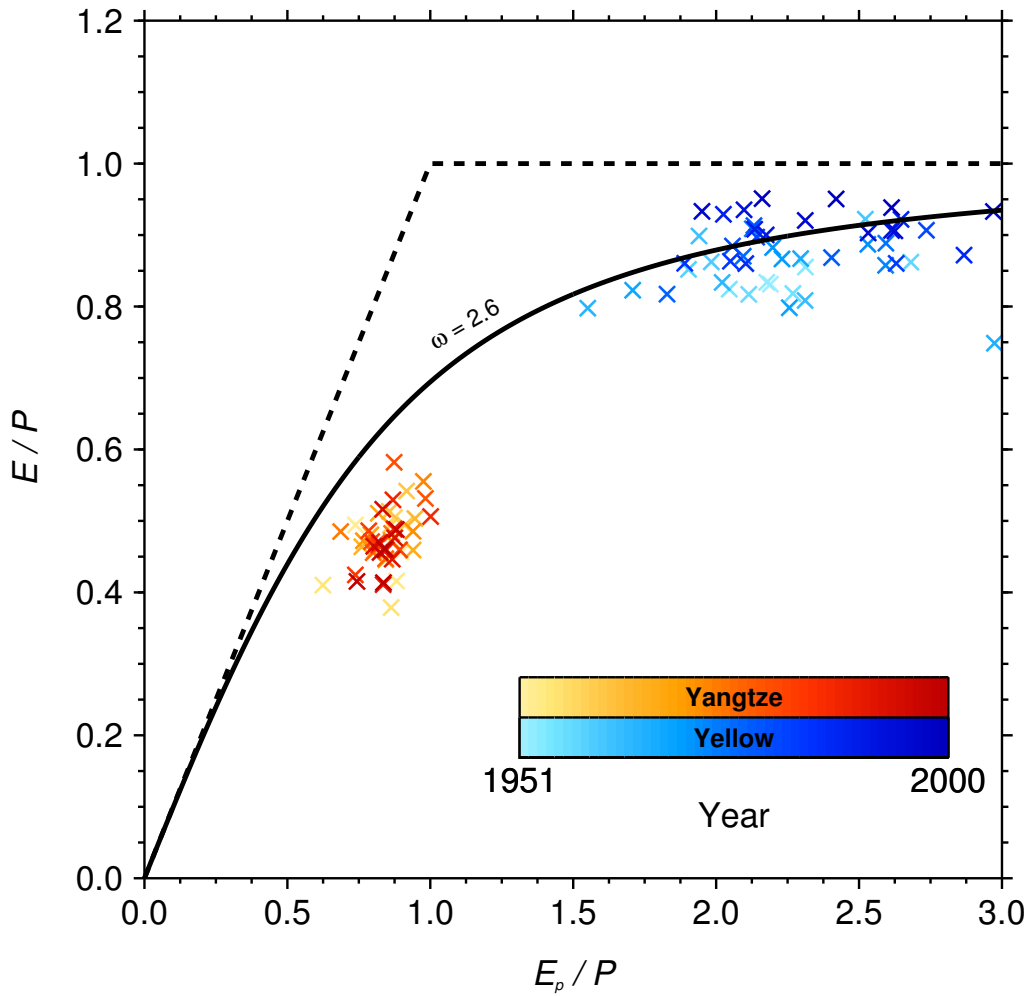


Figure 5. The evaporative index against aridity for the Yangtze (red) and Yellow (blue) river catchments. The symbols represent observed annual mean data for 1951–2000 with darker shades for the more recent years. The traditional Budyko curve is fitted, corresponding to $\omega = 2.6$ in Eq. (3).

ΔQ_a is noticeably different to ΔQ_m for the Yellow catchment ($-0.07 \pm 0.08 \text{ mm day}^{-1} \text{ century}^{-1}$ and $-0.26 \pm 0.06 \text{ mm day}^{-1} \text{ century}^{-1}$, respectively), with a significantly less negative trend ($\Delta Q_a - \Delta Q_m$ is equal to $0.19 \pm 0.07 \text{ mm day}^{-1} \text{ century}^{-1}$, $p < 0.05$) (Fig. 6). We reconcile our ΔQ_a calculations with ΔQ_{a_i} . The linear trends are statistically consistent ($-0.07 \pm 0.08 \text{ mm day}^{-1} \text{ century}^{-1}$ and $-0.05 \pm 0.06 \text{ mm day}^{-1} \text{ century}^{-1}$ for ΔQ_a and ΔQ_{a_i} , respectively). This also holds

5 when considering the LPJ LSM run without land-use changes, for which ΔQ_{a_i} is $-0.06 \pm 0.06 \text{ mm day}^{-1} \text{ century}^{-1}$. Our results are not sensitive to fixed or varying land-use.

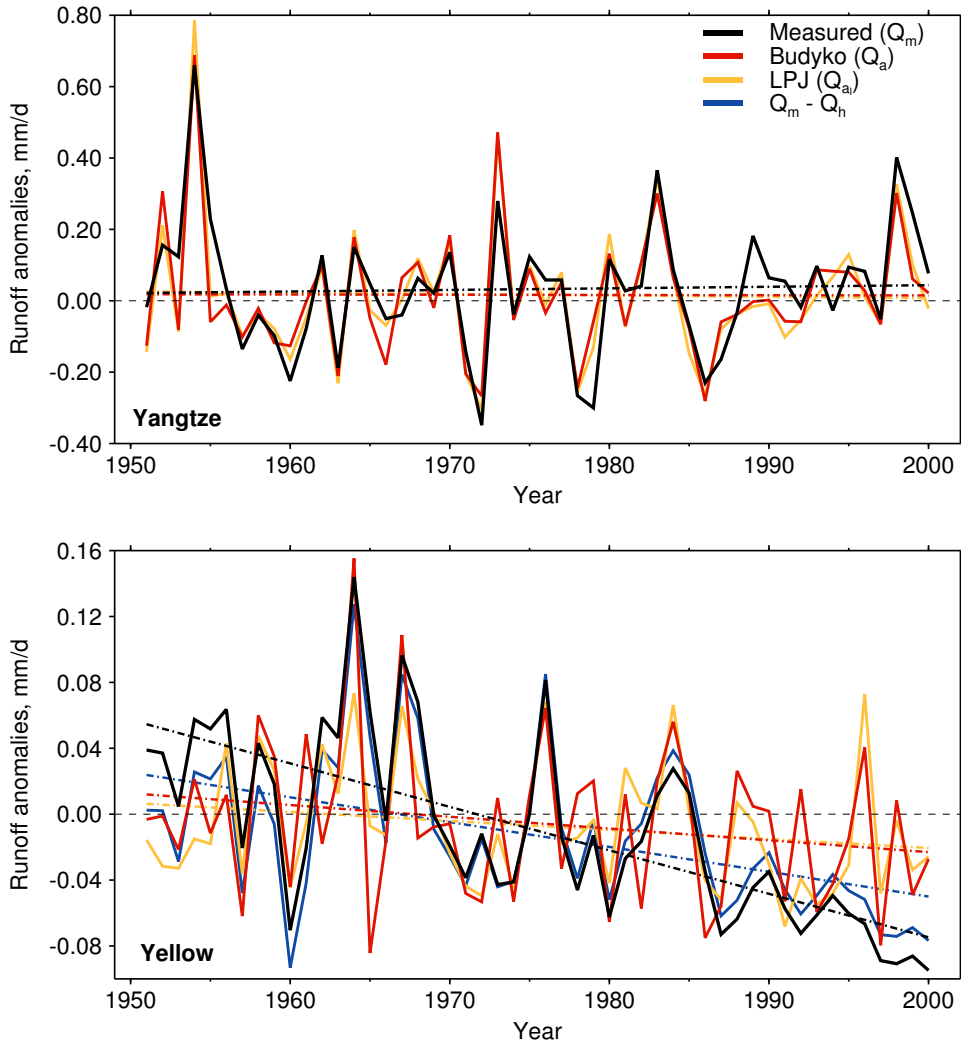


Figure 6. Runoff anomalies for the Yangtze (top) and Yellow (bottom) river catchments for 1951–2000, relative to 1961–1990. Shown are measured runoff (Q_m), runoff due to aridity change (Q_a), runoff simulated by the LPJ LSM (Q_{a_i}) and (for the Yellow river only) the difference between Q_m and runoff due to direct human impacts (Q_h). The dashed lines show linear fits to the time series.

If aridity change and direct human impacts have dominated the measured change in Yellow river runoff, so that the change in runoff due to all other factors is negligible, from Eq. (7) we get $\Delta Q_a \approx \Delta Q_m - \Delta Q_h$. We calculate ΔQ_h as -0.11 ± 0.01 mm day⁻¹ century⁻¹ for the Yellow river (note that the uncertainty range is artificially small due to the limited temporal resolution of the irrigated area time series of Freydank and Siebert (2008)). Therefore, $\Delta Q_m - \Delta Q_h$ (-0.15 ± 0.07 mm day⁻¹ century⁻¹) does not fully reconcile our estimates of ΔQ_a and ΔQ_{a_i} (-0.07 ± 0.08 mm day⁻¹ century⁻¹ and -0.05 ± 0.06 mm day⁻¹ century⁻¹, respectively). ΔQ_h only accounts for 59 % and 54 % of $\Delta Q_m - \Delta Q_a$ and $\Delta Q_m - \Delta Q_{a_i}$, respectively. This imbalance could suggest a significant contribution from ΔQ_o , or be explained by an underestimate of the year 2000 water consumption. We calculate the year 2000 water consumption that balances $\Delta Q_a = \Delta Q_m - \Delta Q_h$ to be 0.140 mm day⁻¹, a 70 % increase on the estimate of Xu et al. (2010). This closely matches a year 2000 water consumption estimate by Zhu et al. (2003) of 0.137 mm day⁻¹. Calculating the relative contribution of aridity change to the measured decrease in Yellow river runoff as $(\Delta Q_a / \Delta Q_m) \times 100\%$ returns a value of 27 %. Using the two estimates of year 2000 water consumption of 0.082 mm day⁻¹ and 0.137 mm day⁻¹, the relative contribution of direct human impacts to the measured decrease in Yellow river runoff $((\Delta Q_h / \Delta Q_m) \times 100\%)$ is 43 % and 71 %, respectively.

We account for between 70 % and 98 % of ΔQ_m with $\Delta Q_a + \Delta Q_h$, using the low and high water consumption estimates, respectively. Using this information with Eq. (7), we could suggest that the contribution from ΔQ_o is either negligible (using the high water consumption estimate) or significant (using the low water consumption estimate). Instead, it shows that there is considerable uncertainty in quantifying water consumption and, in turn, the contribution of ΔQ_h to ΔQ_m . Nevertheless, the close agreement of ΔQ_a and ΔQ_{a_i} suggests that direct human impacts have played a larger role than aridity change in causing the water availability crisis in the Yellow catchment. The contribution of direct human impacts would appear to be greater, by a factor of approximately 2, than the contribution of aridity change. It is worth remembering that ΔQ_a will not only reflect natural variability, but also human-induced changes; E_p has increased due to human-induced warming (Dai, 2013) and P has changed due to various anthropogenic forcings (Osborne and Lambert, 2014; Burke and Stott, 2017).

3.2 21st-century projected changes

From the Budyko framework, changes in Q are not only dependent on changes in P , E_p and E , but also the initial values of these three fluxes. This means that we should view Q projections cautiously if there are biases in key hydrological cycle variables in CMIP5 models. Consistent with previous work (Chen and Frauenfeld, 2014), we find that the spatial pattern of P over China is reproduced by CMIP5 models but annual mean P is overestimated in most regions, compared to CRU climatology. This is evident in the multi-model mean P bias (Fig. 7), with the greatest wet biases seen in the the western parts of the Yangtze and Yellow catchments (the eastern Tibetan Plateau).

As a result of these P biases most CMIP5 models do not fall in the same region of the Budyko space as observations for the Yellow catchment (Fig. 8). Although P is overestimated in the Yangtze catchment for 1951–2000 (3.78 ± 0.97 mm day⁻¹ and 2.74 mm day⁻¹ for CMIP5 and observations, respectively), there is little multi-model mean bias in E_p/P (0.88 ± 0.28 and 0.85 for CMIP5 and observations, respectively), implying that E_p is also overestimated (3.24 ± 0.47 mm day⁻¹ and 2.30 mm day⁻¹ for CMIP5 and observations, respectively). In contrast, there is considerable multi-model mean bias in E_p/P in the

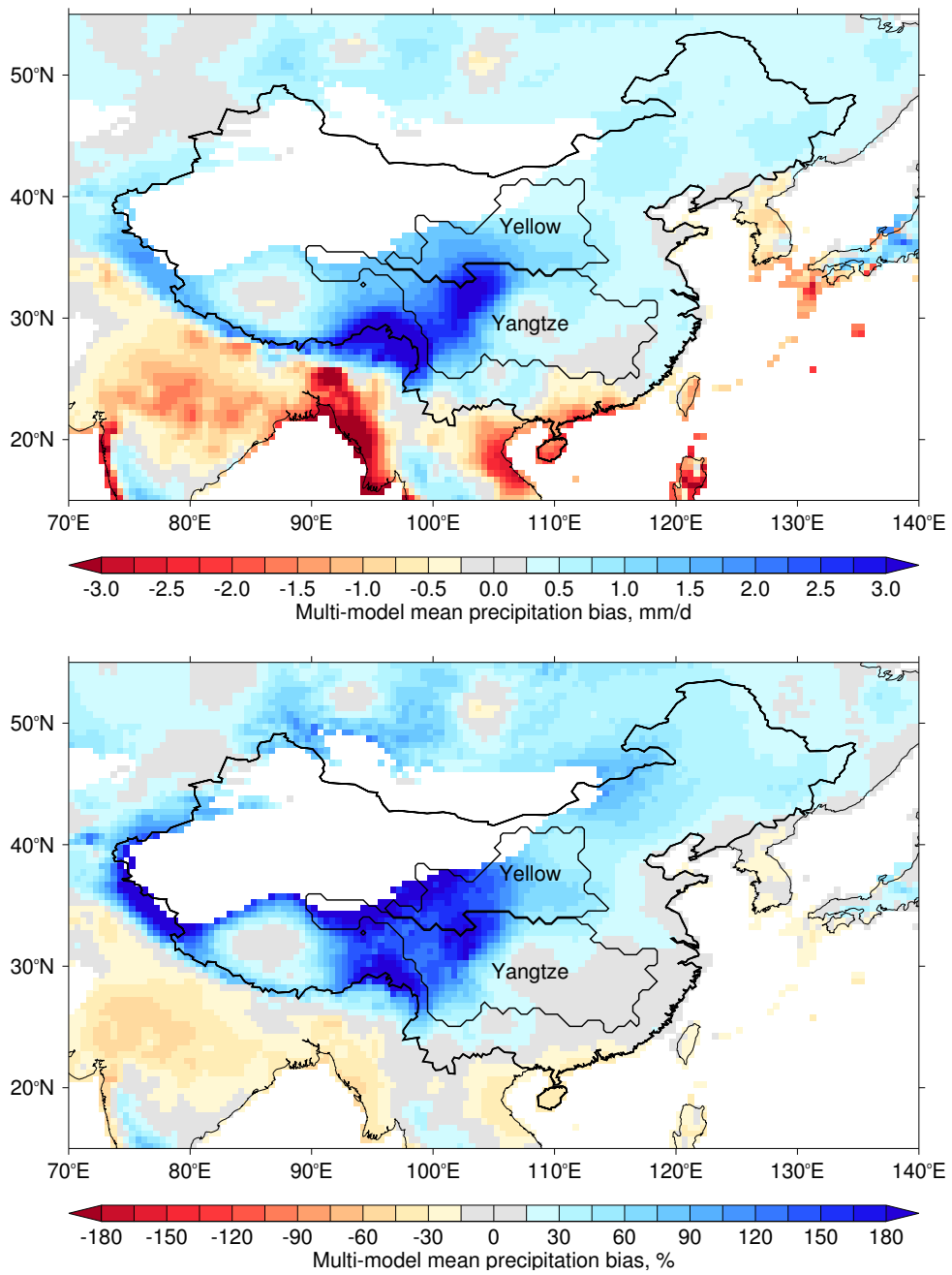


Figure 7. Absolute (top) and relative (bottom) multi-model mean precipitation climatology bias for 1961–1990. The location of the Yangtze and Yellow catchments within China is shown. Desert regions ($<200 \text{ mm year}^{-1}$), as determined from CRU climatology (1961–1990), are masked in white.

Yellow catchment (1.35 ± 0.52 and 2.27 for CMIP5 and observations, respectively), with models (on average) simulating a humid rather than a semi-arid climate zone, according to a widely-used aridity classification (Middleton and Thomas, 1997). In fact, only one of 34 models considered simulates an aridity greater than 2.0 (MRI-CGCM3). This misrepresentation is a result of a significant overestimate of P for 1951–2000 (2.18 ± 0.91 mm day⁻¹ and 1.10 mm day⁻¹ for CMIP5 and observations, respectively) and a less biased simulation of E_p (2.75 ± 0.43 mm day⁻¹ and 2.45 mm day⁻¹ for CMIP5 and observations, respectively).

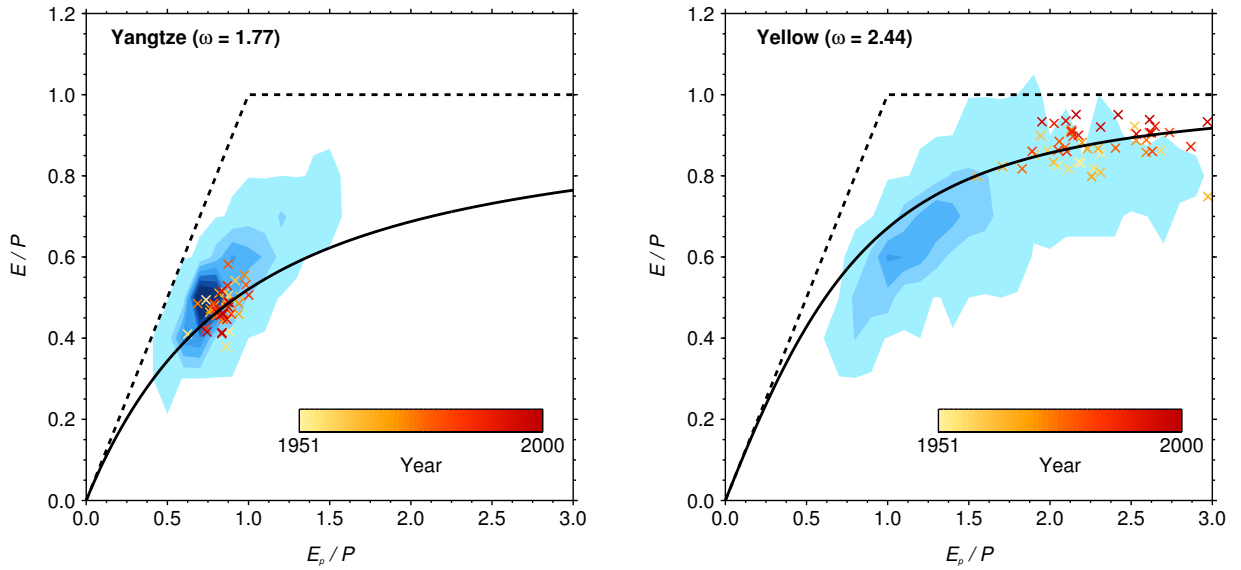


Figure 8. The evaporative index against aridity for the Yangtze (left) and Yellow (right) river catchments. The shaded blue regions represent the density of CMIP5 annual mean data for the 1951–2000 period, with darker shades meaning more data in a given region of the Budyko space. The symbols represent observed data with darker shades for the more recent years. ω values are calculated for the 1951–2000 period using Eq. (5).

Figure 9 shows the multi-model mean ΔP and ΔE_p (using 1980–1999 and 2080–2099 as present-day and future climates, respectively) in RCP8.5. Consistent with previous literature (Chen and Frauenfeld, 2014), P increases in CMIP5 projections throughout China, with significant increases across most of the Yellow catchment. P also increases across the Yangtze catchment, although fewer models simulate significant increases here. As discussed by Greve and Seneviratne (2015), significant E_p increases are ubiquitous. CMIP5 multi-model mean ΔP is 0.36 ± 0.56 mm day⁻¹ and 0.35 ± 0.30 mm day⁻¹ for the Yangtze and Yellow, respectively. Respective values for ΔE_p are 0.33 ± 0.23 mm day⁻¹ and 0.25 ± 0.19 mm day⁻¹.

Although we expect model simulated ΔQ and ΔE to be erroneous due to climatology biases (as highlighted in the hypothetical example in supplementary Sect. S1), we assume that ΔP and ΔE_p in the CMIP5 multi-model ensemble are not dependent on the biases in climatology described above (Fig. 7). Figure 10 shows how ΔP and ΔE_p relate to the climatology of P (\bar{P})

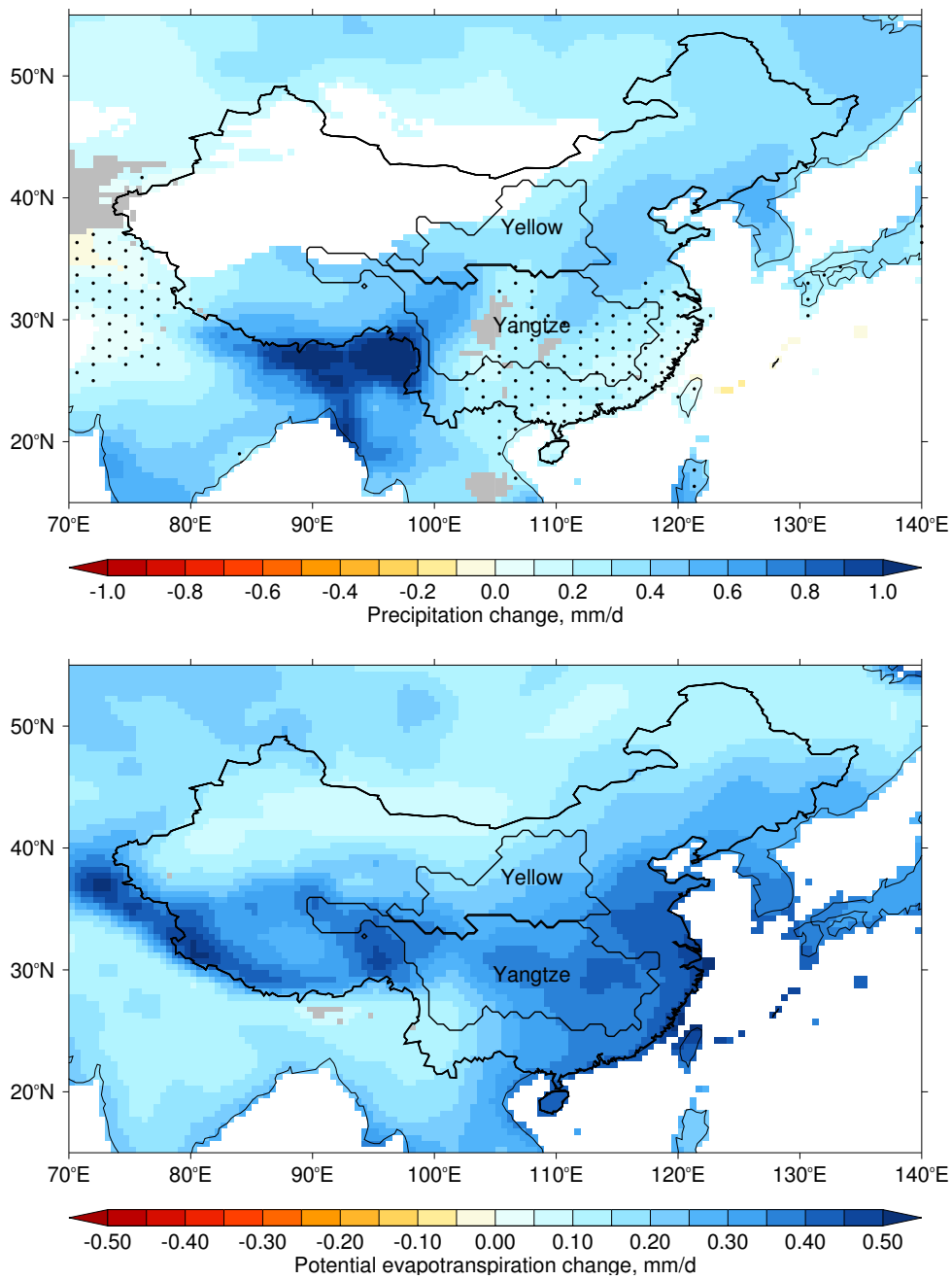


Figure 9. Multi-model mean future-minus-present changes (2080–2099 minus 1980–1999) in P (top) and E_p (bottom) in RCP8.5. Stippling indicates where less than 50 % of the CMIP5 models show significant change, as determined with a t -test comparing present-day and future climates. Absence of stippling indicates where more than 50 % of the models show significant change and more than 80 % of the significant models agree on the sign. Gray indicates where more than 50 % of the models show significant change but less than 80 % of the significant models agree on the sign. This method follows (Tebaldi et al., 2011). Desert regions ($< 200 \text{ mm year}^{-1}$), as determined from CRU climatology (1961–1990), are masked in white for P .

and E_p ($\overline{E_p}$), respectively, across the 34 CMIP5 models. There are weak but significant correlations between ΔP and \overline{P} in RCP8.5 for both the Yangtze and Yellow catchments, but significance is lost with the exclusion of an outlying model in each case. The weak but significant correlation between ΔP and \overline{P} in RCP4.5 for the Yangtze catchment is also dependent on an outlying model. There is little evidence for significant correlations between ΔE_p and $\overline{E_p}$.

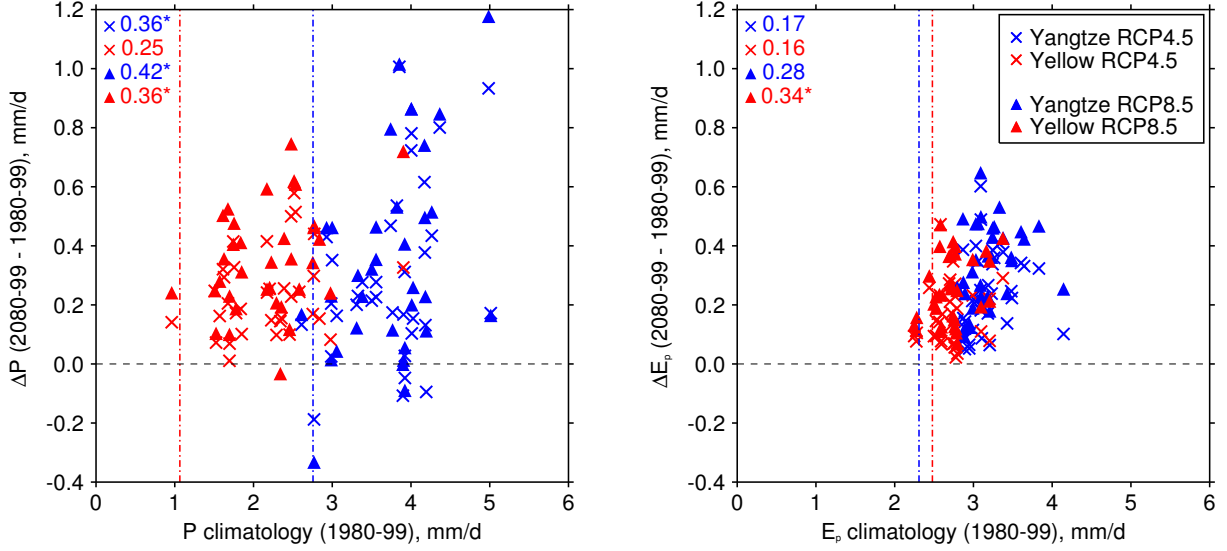


Figure 10. Future-minus-present changes (2080–2099 minus 1980–1999) in P (left) and E_p (right) against P and E_p climatologies (1980–1999), respectively, for 34 CMIP5 models. The dashed vertical lines show the observed climatologies for the Yellow (red) and Yangtze (blue) catchments. The values in the top left of each panel refer to correlation coefficients for the catchment and RCP emissions scenario listed in the legend. Those with asterisks are significant at the 95 % ($p = 0.05$) confidence level.

If there was strong evidence for relationships between ΔP and \overline{P} and/or ΔE_p and $\overline{E_p}$ then a simple multiplicative correction, applied to catchment annual mean P and E_p , would be appropriate (Hempel et al., 2013). For P :

$$P'_{GCM} = P_{GCM} \times \frac{\overline{P}_{CRU}}{\overline{P}_{GCM}}, \quad (9)$$

where the subscript GCM is an individual model from the CMIP5 ensemble, the subscript CRU is the observed data and P' is the corrected P . The period 1980–1999 is used to calculate the climatologies. Using a multiplicative correction factor preserves the relative rather than absolute trends in model simulated P and E_p .

CMIP5 P and E_p biases for the Yangtze and Yellow catchments are, on average, positive and substantial (Fig. 10). As such, the correction factor in Eq. (9) is, on average, less than unity. A multiplicative correction factor would therefore narrow the ranges of ΔP and ΔE_p across the CMIP5 ensemble. The assumption that we can use absolute ΔP and ΔE_p from CMIP5 models seems valid in the absence of strong evidence for relationships between ΔP and \overline{P} and/or ΔE_p and $\overline{E_p}$. We instead use a simple additive correction (Hempel et al., 2013). Temporally constant offsets (the absolute differences between observed

and simulated climatologies) are added to model simulated P and E_p . For P :

$$P'_{GCM} = P_{GCM} + (\bar{P}_{CRU} - \bar{P}_{GCM}). \quad (10)$$

We adjust P and E_p in the 34 CMIP5 models for 1951–2100 to eliminate the biases in simulating the observed CRU climatologies, while retaining absolute ΔP and ΔE_p . Positivity constraints on P and E_p can render additive corrections inappropriate, but this is not a problem at the spatial (catchment) and temporal (annual) resolutions considered here.

Q (as simulated by the CMIP5 models and calculated using $P - E$) differs considerably from Q^* (Fig. 11) as calculated with Eq. (8), particularly for the Yellow catchment. The Budyko corrected future-minus-present change in runoff (ΔQ^* ; recall that the future-minus-present change is the mean of 2080–2099 minus the mean of 1980–1999) is similar to ΔQ for the Yangtze catchment in both RCP4.5 and RCP8.5 across the CMIP5 ensemble (Table 1). In the Yellow catchment (RCP8.5) the multi-model mean ΔQ^* matches that of the multi-model mean ΔQ (both 0.09 mm day^{-1}). The 5–95 % range, however, is reduced by 34 % ($\pm 0.14 \text{ mm day}^{-1}$ to $\pm 0.09 \text{ mm day}^{-1}$). Similar results are found with RCP4.5, with little change in the multi-model mean from 0.07 mm day^{-1} to 0.06 mm day^{-1} but a decrease of 35 % in the 5–95 % range from $\pm 0.11 \text{ mm day}^{-1}$ to $\pm 0.07 \text{ mm day}^{-1}$ for ΔQ and ΔQ^* , respectively. These findings are not sensitive to using directly simulated runoff instead (Fig. 11 and Table 1). The small differences between Q and Q^* , and ΔQ and ΔQ^* , for the Yangtze catchment are expected given that CMIP5 models broadly fall in the correct region of the Budyko space (Fig. 8). For the Yellow catchment, the uncertainties in runoff projections have been reduced considerably. The CMIP5 multi-model mean ΔQ^* in RCP8.5 is significantly different from zero at the 90 % confidence level. Such a level of confidence is not achieved for ΔQ .

4 Discussion

Before using the Budyko framework in tandem with CMIP5 output, we considered whether it could be used to quantify the contribution of aridity change to the measured decrease in Yellow river runoff between 1951 and 2000. Encouragingly, for both the Yangtze and Yellow catchments, the Q trend due to aridity change was found to be near-identical to that simulated using the LPJ LSM (which is forced by observed P and E_p). This suggests that the Budyko framework is suitable for determining the relative contribution of aridity change to the measured decrease in Yellow river runoff, calculated as 27 %. Therefore, the relative contribution of all other factors besides aridity to the measured decrease in Yellow river runoff is expected to equal 73 %.

Deriving time series of water consumption using low and high year 2000 water consumption estimates, the component due to direct human impacts is calculated as 43 % and 71 %, respectively. Therefore, we can account for nearly all of the measured decrease in Yellow river runoff (98 %) using aridity change and the high consumption estimate alone, but stress that such estimates are highly uncertain. We are not able to dismiss a significant contribution from the net effect of all other factors (besides aridity and direct human impacts), which ranges from 2 % to 30 %. Given that the estimate of the contribution of aridity change appears to be the most robust result, we can instead state that the majority of the measured decrease in Yellow river runoff appears to be due to direct human impacts and all other factors. Also, despite the uncertain water consumption

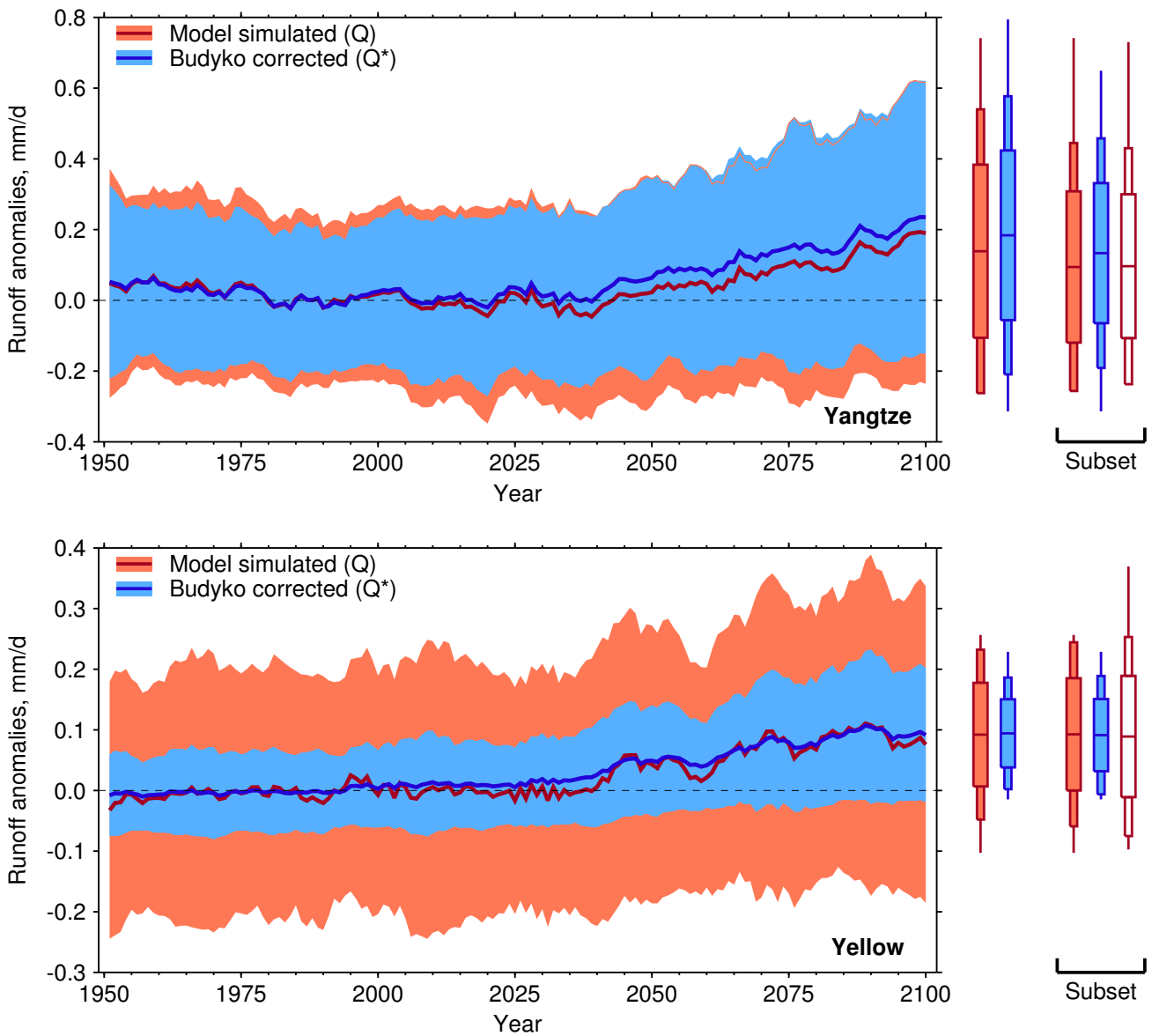


Figure 11. CMIP5 model simulated (Q ; orange) and CMIP5 Budyko corrected (Q^* ; blue) runoff anomalies for 1951–2100, relative to 1980–1999, for the Yangtze (top) and Yellow (bottom) river catchments in the historical and RCP8.5 experiments. Shown are the 5-year running multi-model mean (thick line) and 5–95 % ranges (shading) across the CMIP5 ensemble. The box plots (mean, \pm one standard deviation ranges, 5–95 % ranges, and minimum to maximum ranges) are given for 2080–2099 (Table 1). Also shown, for comparison, are box plots for a subset of 28 (from 34) CMIP5 models for which Q is directly simulated (not limited to being calculated as $P - E$). The unfilled box plot shows CMIP5 model directly simulated runoff for 2080–2099.

Table 1. CMIP5 model simulated (ΔQ) and CMIP5 Budyko corrected (ΔQ^*) future-minus-present runoff changes (mm day^{-1}) for 2080–2099, relative to 1980–1999. The multi-model mean and 5–95 % ranges across the individual models are listed (based on a Gaussian assumption). For comparison, values for a subset of 28 (from 34) CMIP5 models for which Q is directly simulated are also shown. CMIP5 model directly simulated future-minus-present runoff changes (ΔQ_{direct}) are used to verify the suitability of calculating ΔQ as $\Delta P - \Delta E$ (water balance-derived).

		RCP4.5	RCP8.5
Yangtze (all):	ΔQ	0.12 ± 0.32	0.14 ± 0.40
	ΔQ^*	0.16 ± 0.33	0.18 ± 0.39
Yangtze (subset):	ΔQ	0.08 ± 0.26	0.09 ± 0.35
	ΔQ^*	0.12 ± 0.26	0.13 ± 0.32
	ΔQ_{direct}	0.08 ± 0.25	0.10 ± 0.33
Yellow (all):	ΔQ	0.07 ± 0.11	0.09 ± 0.14
	ΔQ^*	0.06 ± 0.07	0.09 ± 0.09
Yellow (subset):	ΔQ	0.06 ± 0.11	0.09 ± 0.15
	ΔQ^*	0.06 ± 0.07	0.09 ± 0.10
	ΔQ_{direct}	0.06 ± 0.11	0.09 ± 0.16

estimates, the contribution from direct human impacts is approximately 2 times greater than the contribution from aridity
 25 change. Other studies have estimated the climate change (all non-human) and human components. Miao et al. (2011) attribute
 55 % of the reduction in Yellow river water discharge to humans, with Wang et al. (2006) giving a value of 49 %, compared to
 our range of 43 % to 71 %. Note that these studies use different methods and periods to estimate the contributions of the two
 components, but focus on the second half of the 20th century. Our estimate of the component due to direct human impacts is
 consistent with these previous estimates, although we add detail by finding that this contribution is markedly greater than the
 30 contribution from aridity change alone.

Although estimates of water consumption are highly uncertain there are also uncertainties in our estimate of the aridity
 change contribution to Q change. This estimate, as well as runoff simulated by the LPJ LSM, rely on an uncertain observed
 E_p dataset (see Sect. 2.1). An energy-only E_P estimator is expected to be more appropriate (Milly and Dunne, 2016), but
 is not available because of insufficient observed data. Meanwhile, the observed P dataset is likely to contain biases and
 inhomogeneities (Osborne and Lambert, 2014). Many grid boxes in China are poorly gauged (some not at all) in the period
 investigated (see supplementary Fig. S1), especially in the mountainous Tibetan Plateau region, where P is scarce but highly
 variable (Adam et al., 2006). These are largely insurmountable obstacles facing all hydroclimatological studies.

Within the Budyko framework all climatic and non-climatic factors besides aridity are integrated by the ω parameter. In Eq.
 5 (7) we separate this “residual” into a component due to direct human impacts and a component due to all other climatic and

non-climatic factors besides aridity change and direct human impacts. The low water consumption estimate means that we are not able to dismiss a significant contribution from the net effect of all other factors. Support for a negligible contribution from all other factors comes from the strength of agreement between Q_a and Q_{ai} . This is because the LPJ LSM includes a realistic representation of vegetation, which ~~is known~~ has been shown to be a useful ~~integrated~~ indicator of these other factors that are integrated by ω (although this may only hold for larger catchments) (Li et al., 2013) (see supplementary Sect. S3). Further, supplementary Fig. S3 shows that CMIP5 models simulate no obvious changes in ω over the second half of the 20th century.

In estimating direct human impacts from just water consumption there remains the possibility that other direct human impacts could account for a significant contribution to the decrease in Yellow river runoff. We present evidence that the contribution from land-use change is negligible. On the other hand, catchment runoff can abruptly decrease during the filling of large reservoirs following dam construction, causing anomalously low annual runoff. Following filling, runoff should return to pre-dam levels and such projects are only thought to affect seasonal water storage and not introduce trends in long-term runoff. Rather, dam and reservoir construction facilitates access to water resources and leads to more water withdrawal and consumption. The influence of dams and reservoirs are likely accounted for in the water consumption estimates (Biemans et al., 2011).

The agreement between the Budyko framework and the LPJ LSM for the observed period also increases our confidence in using the Budyko framework for projections. The CMIP5 Budyko corrected projected changes in runoff rely on the assumption that 21st-century changes in P and E_p are not dependent on existing climatology biases in CMIP5 models. Across the CMIP5 multi-model ensemble we did not find compelling evidence for relationships, supporting this assumption (Fig. 10). This is broadly consistent with expectations, given recent research showing that the “wet gets wetter, dry gets drier” paradigm (Held and Soden, 2006) does not hold over global land surfaces (Greve et al., 2014; Greve and Seneviratne, 2015). However, the mean state can undoubtedly have some influence on the simulated changes in P and E_p due to land-atmosphere feedbacks (Berg et al., 2016). We note that when correcting E_p (Eq. (10); with P replaced with E_p) we calculate the correction offset as the observed climatology (Penman-Monteith estimator) minus the model simulated climatology (energy-only estimator). Using these different estimators will likely introduce some error in the calculation.

It is also important to note some potential limitations of using Eq. (7) to separate the measured decrease in Yellow river runoff into various components. This approach assumes a linear relationship and therefore that the individual components are independent. Padrón et al. (2017) showed that cross correlations exist between many of the factors suggested to influence runoff through ω . Testing for dependencies between ΔQ_h and other components is unfortunately limited by the poor temporal resolution of the irrigated area time series of Freydank and Siebert (2008). Although we find that interannual variations in Q_a and the residual $Q_h + Q_a$ are correlated (-0.35), this correlation is weak and reverses sign when considering multi-year means. Further, our approach considers long-term trends/changes in runoff, which means that any dependencies at shorter timescales should not influence conclusions.

In calculating Q^* (Eq. (8)) ω values are calculated for the 1951–2000 period, using Eq. (5), then taken to be constant for the period 1951–2100. While the relationships of variations in Q with variations in such catchment-specific parameters are understood (Roderick and Farquhar, 2011; Gudmundsson et al., 2016), the full complexity of the influence of changes in catchment properties on these parameters is not. However, Li et al. (2013) showed that, for large catchments, the long-term

averaged annual vegetation coverage explains as much as 63 % of the variance in the catchment-specific ω . With 21st-century increases in total vegetation coverage projected (Schneck et al., 2015), we expect this parameter will increase in magnitude. This is found to be the case in the CMIP5 multi-model ensemble and these increases in ω need to be included when verifying the Budyko framework on the CMIP5 models themselves (see supplementary Sect. S3 and Figs. S2-4). The influence of changes in ω on projected changes in Q is small compared to the influence of correcting E_p and P (see supplementary Sect. S3 and Fig. S5). Demonstrating this, the CMIP5 multi-model mean ΔQ^* for the Yellow catchment in RCP8.5 with constant ω (0.09 ± 0.09 mm day⁻¹) is not significantly different to the CMIP5 multi-model mean ΔQ^* for the Yellow catchment in RCP8.5 with time-varying ω (0.07 ± 0.08 mm day⁻¹). Therefore, our conclusions are not sensitive to the choice of ω (constant or time-varying).

We show that aridity change (changes in P and E_p only) is of greatest importance in shaping projected changes in runoff in CMIP5 models and all other factors (ω) play a secondary role. We expect our CMIP5 Budyko corrected Q projections to be substantially more reliable than the original CMIP5 model simulated Q projections. In the case of the Yellow catchment, the future-minus-present (2080–2099 minus 1980–1999) change in Q 5–95 % range is reduced by 34 % and 35 % in RCP8.5 and RCP4.5, respectively. Importantly, constraining Q projections using the Budyko framework increases confidence that the Yellow catchment will see increases in Q by the end of the 21st century – the best guess (CMIP5 multi-model mean) change of 0.09 mm day⁻¹ is significantly different from zero at the 90 % confidence level. Greater confidence in the range of Yellow catchment water availability projections could be of great value to policy-makers. More generally, the Budyko framework serves as an inexpensive tool to rapidly update projections from biased GCM simulations without the need for offline GHMs. However, further research is needed. Specifically, we believe that an ensemble of GHMs, driven by at least one set of bias corrected and downscaled GCM projections, should be used as a means of verification.

Most applications of the Budyko framework consider spatial rather than temporal variations. Berghuijs and Woods (2016) demonstrate that spatial and temporal variations are not necessarily tradable. We stress that the Budyko framework is not employed here to robustly determine interannual variability in water availability, but is instead used to understand long-term trends (Sect. 3.1) or the difference between 20-year means at the end of the 20th and 21st centuries (Sect. 3.2).

5 Conclusions

We have demonstrated how the Budyko framework can be used to place water availability projections from readily-available GCM output onto a more physical basis by correcting for biases in aridity, using the example of the Yangtze and Yellow river catchments in China. The approach is inexpensive, does not need the use of offline GHMs, and could be used to provide rapid updates on water availability projections for new GCM scenarios. Wherever GCMs simulate significant biases in representing observed aridity, we expect to generate significantly altered projections. In the Yellow catchment, considerable negative biases in simulated aridity lead to a substantial narrowing of the range of future GCM projections. In catchments where GCMs simulate positive biases, we would expect to see broadening of the range of GCM projections. Meanwhile, in the Yangtze catchment, simulated aridity biases are small, meaning that projections are little changed by our approach.

We stress again that these refined water availability projections account for aridity change only. In the hypothetical case where future aridity change is known, the projected Q will not be realised due to the effect of all other factors, especially highly uncertain future changes in direct human impacts (these are not represented in CMIP5 models). Current human impacts on Q are possibly greater than end-of-21st-century aridity change impacts on Q in the Yellow catchment (Haddeland et al., 2014). Therefore, the current water shortages are not likely to be alleviated without improved agricultural practices and water management. Importantly though, reducing the range of water availability projections gives planners an improved idea of what needs to be done to reduce water stress in the Yellow catchment for future generations. Moreover, our conclusions underline the need for imminent action and highlight the fact that increases in Q due to aridity change will not offer much relief in the absence of serious and concerted action to minimize direct human impacts.

Chinese authorities have recently attempted to alleviate the drying in the north of China, by diverting water there from the wetter south (the South-to-North Water Diversion Project). It remains to be seen whether this will reduce the imbalance in atmospheric water supply and human water demand across China and whether it could even place additional water stress on the more resilient south (Barnett et al., 2015). Generating refined water availability projections in these two key river catchments should underpin decisions made on future engineering projects.

Data availability. The CMIP5 data can be accessed via the web portal <https://esgf-node.llnl.gov/projects/esgf-llnl/>. Sources for the observed datasets are: CRU TS3.23 P and E_p (Harris et al., 2014) <http://www.cru.uea.ac.uk/data/>; Global River Flow and Continental Discharge Dataset Q (Dai et al., 2009) <http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/>. Data from the LPJ LSM experiments are available from the authors upon request.

5 *Competing interests.* The authors declare that they have no conflict of interest.

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