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Hydrology and Earth System Sciences
Discussions

Interactive comment on "A simple tool for refining GCM water availability projections, applied to Chinese catchments" *by* Joe M. Osborne and F. Hugo Lambert

Joe M. Osborne and F. Hugo Lambert

j.m.osborne@exeter.ac.uk

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Thank you for reviewing our paper and providing suggestions that have improved it. Our responses to your comments are in bold font.

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 second referee has also commented that the methodological approach could be explained better. We will therefore add 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 will also divide 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 into Qh and Qo is potentially dangerous. Please also be aware that in the context of the Budyko framework, aridity is solely defined through the notional, dimensionless ratio Ep/P, which has no direct physical meaning. Everything else besides mean annual Ep/P is actually integrated into w. Also, w and Ep/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 Qa, Qh, and Qo. 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 Freydank and Siebert (2008) that is used to calculate Q_h (page 8, line 25). We can however look at the relationship between Q_a and changes dues 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).

However, this correlation becomes positive (0.66) when considering 5 year means (Figure 3). Therefore, we do not believe there is 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 will therefore add the following to the discussion:

"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 proposed 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 not robust to using multi-year means. Further, our approach considers long-term trends/changes in runoff, which means that any dependencies at interannual timescales should not influence conclusions."

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2) In the main text, the authors assume w (omega) to be constant. In the Supplemen-

tary 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 this paper whether to present the time-varying analysis in the manuscript or whether to 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. Ultimately, we understand the argument for both choices and would even welcome an extra opinion on this subject!

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 20th century analysis. It is worth pointing out however that the conclusions on historical changes regarding the contributions of aridity change and direct human impacts are qualitatively the same if considering difference between 10 (or 20) year means at the start and beginning of the 1951–2000 period. We will point this out in the text by adding the following to the end of the discussion:

"Most applications of the Budyko framework consider spatial rather than temporal variations. Berghuijs and Woods (2017) 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. 3.2) 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:

"...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 will act on all of them. We discuss below the comments that require a little more attention to show how we will act on them:

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:

"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. 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 Ep 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).

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 Ep?

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

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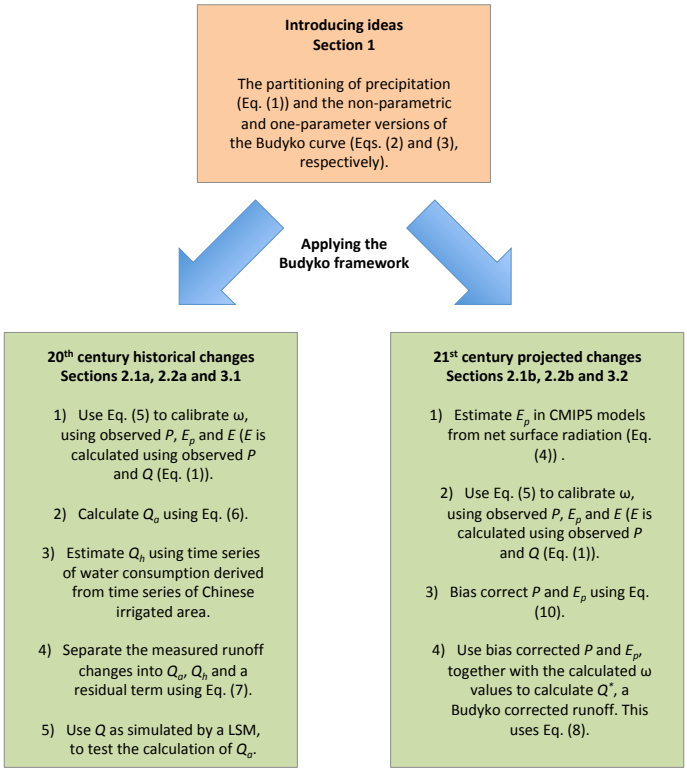

Fig. 1. Schematic of how the Budyko framework is used to improve our understanding of 20th-century historical changes and 21st-century projected changes.

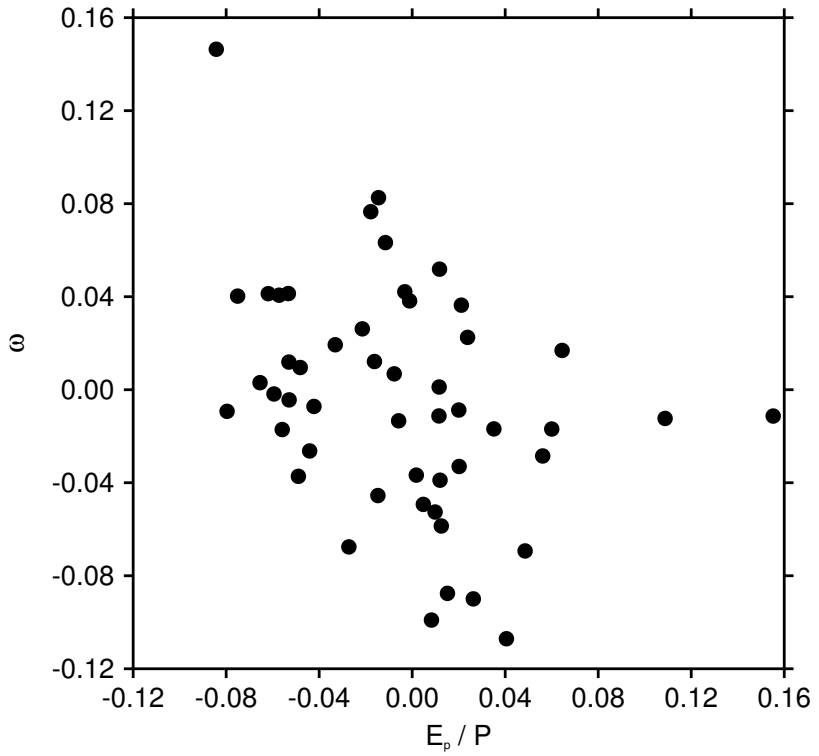

Fig. 2. Interannual correlation.

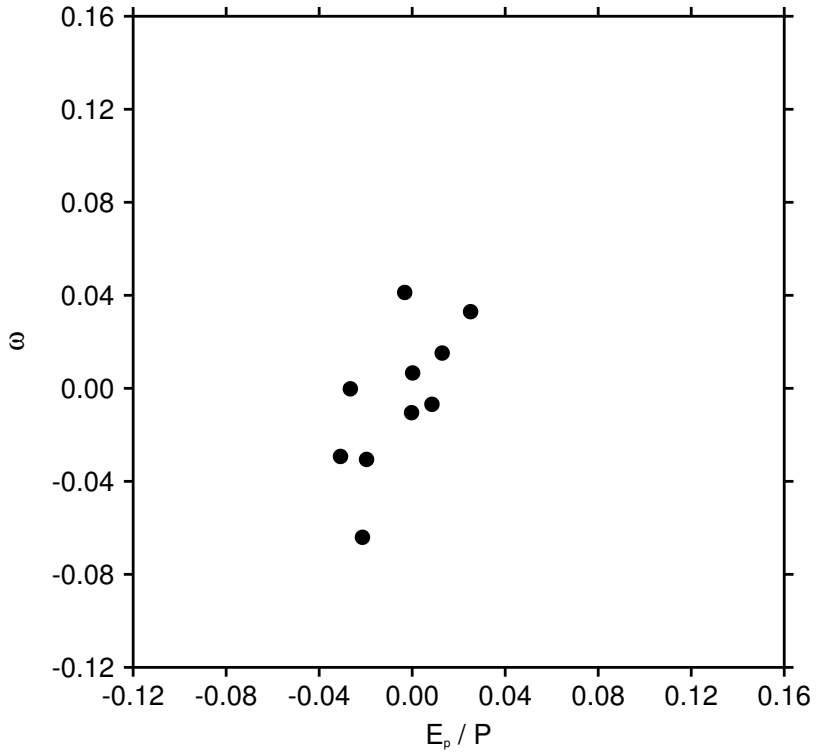

Fig. 3. 5 year mean correlation.

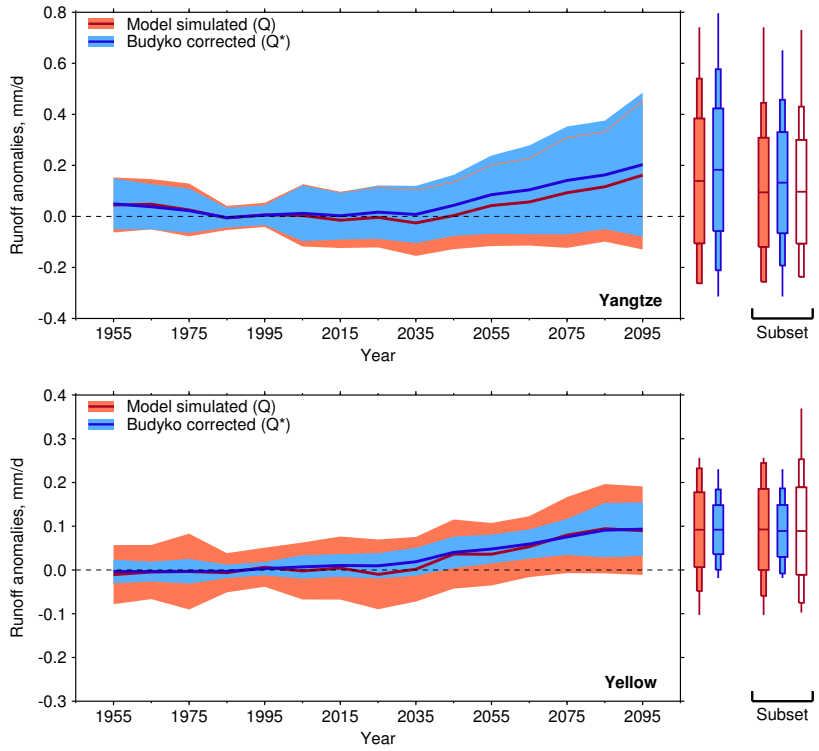

Fig. 4. Using decadal means.

		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

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