We thank the reviewer for these helpful comments. Reviewer comments are listed below, along with our response to each. In some cases, we describe the proposed revisions to the manuscript (with line numbers) or refer to proposed revisions described in our responses to the other reviewers, but we recognize that the revised manuscript is requested in a subsequent step.

Comment 1:

This paper presents interesting tests and perspectives on the Budyko framework. It first argues that there is no theoretical or empirical basis for typical key assumptions in the use of the framework (i.e (i) catchments follow parametric Budyko curves under aridity change, and (ii) the catchment-specific parameter (i.e. n or w) is determined by catchment biophysical properties. Subsequently, the paper aims to test these assumptions using outcomes of the Porporato 2004 model, and empirical data.

Response 1:

We appreciate the reviewer's interest the topics covered in our manuscript. The description provided is accurate, however another outcome of this work is to illustrate that the non-uniqueness of the parametric Budyko equations (i.e., there are several equally valid single parameter equations with different functional forms) fundamentally contradicts many recent interpretations of the parametric Budyko framework.

Comment 2:

While the paper addresses two very relevant aspects of the Budyko framework, there seem to be several conceptual limitations that make the results only weakly support the main inferences of the paper, because:

*** The approach using the models is that: "We tested the catchment trajectory conjecture by varying the model climatic parameters while holding the landscape parameter constant. If the resulting trajectories are not Budyko curves, the conjecture should be rejected." This approach assumes that the only relevant climate variable is aridity, but in reality as earlier work has shown (and as the model shows) other climate variables (such as seasonal cycles and P intermittency) also strongly controls water balances. Thus, the observation that the model diverges from the Budyko curves only shows that climate also matters (as is already known) and does not show that catchments do not follow the Budyko trajectory conjecture.**

Response 2:

We thank the reviewer for acknowledging the relevance of the topic, however it is incorrect to state that our theoretical approach assumes that aridity is the only relevant climate variable. Clearly, many different climate properties control the water balance, and our theoretical approach did not seek to test how climatic properties affect the water balance (which is already well described). Rather, we tested the commonly accepted catchment trajectory conjecture, which states that individual catchments undergoing changes in aridity index will follow explicit Budyko curve trajectories. We acknowledge, however, that our description of the catchment trajectory conjecture, Porporato model, and model variables may have caused some confusion and can be improved. We have proposed edits to address these potential issues in our responses to **Reviewer 1 Comment 9** and we also propose additional edits at the end of this response. While we hope that these edits improve the manuscript's clarity, we maintain that the results and conclusions from the current theoretical tests are sound. Further, we expect that the reviewer's comment may be due to discrepancies in the conceptualizations of the aridity index and catchment trajectory conjecture, which we seek to rectify in the remainder of our response.

First, as we state in the manuscript (page 3, lines 21-23), the catchment trajectory conjecture suggests that individual catchments undergoing ***only*** changes in aridity index will follow an explicit Budyko curve trajectory. While this is the common interpretation (as the reviewer suggests), it is actually an ill-posed conjecture since it is not possible to ***only*** change the aridity index independent of other climatic variables. The aridity index is a derived quantity ($\phi = \frac{\overline{E_0}}{\overline{P}}$), with its value dependent on measurements of fundamental climatic processes. This means it is mathematically impossible to change the value of ϕ without changing some aspect of "other climate variables", specifically, either the precipitation time series (e.g., event intermittency or depth) or the potential evaporation time series (see test cases 1-4 in the manuscript). While it is possible for ϕ to remain constant while "other" climate properties change (see test case 5) the inverse is impossible. Therefore, it does not make sense to conceptualize ϕ as an independent or isolated climate variable, even though this is often done in the Budyko framework.

Second, the catchment trajectory conjecture suggests that catchments should follow very specific parametric curves when undergoing changes in ϕ, but it doesn't specify the mechanism for how ϕ changes (e.g., changes in precipitation properties vs changes in potential evaporation properties). Different mechanisms of ϕ change will impact the evaporative index in different ways, almost all of which lead to catchments not following the particular parametric (i.e., Eq. (5) and (6) of main text) or non-parametric (i.e., Eq. (3) of main text) curve trajectories (as illustrated by the theoretical tests in the manuscript). This implies that individual catchments typically do not follow Budyko curve trajectories.

Finally, the Porporato model we use in our tests illustrates the dependency of ϕ on "other" climate variables explicitly (even with its simplified dynamics). Within the model, $\phi = \frac{\psi}{\eta} = \frac{\overline{E_0}}{\overline{P}} = \frac{\overline{E_0}}{\alpha\lambda}$. To change the value of ϕ, one must change either the average storm depth, α, the average storm frequency, λ, or the average potential evaporation, $\overline{E_0}$. Choosing one or another variable to change produces markedly different trajectories in Budyko space (see test cases in manuscript). The only way a catchment can follow a specific Budyko curve trajectory (parametric or non-parametric) would be for these three climate variables to vary together in a very specific way, which is not specified in the "the catchment trajectory conjecture". We note that for real catchments, there are vastly more ways for ϕ to change than the simple Porporato model allows (since it only has three climate parameters). As such, it is even less likely for individual real catchments to follow specific explicit Budyko curve trajectories; a statement with is supported by the results of our empirical test.

To represent these conceptualizations better in the main text, we propose the following edits:

1) Change the sentences on page 3 lines 21-26:

"This concept is typically articulated through the suggestion that an individual catchment undergoing only changes in aridity index will follow an explicit Budyko curve trajectory ("the catchment trajectory conjecture"). However, we note that it is mathematically impossible for the aridity index to vary independently of other climate variables impacting $\overline{E_0}$ or $\overline{P}$, meaning that the catchment trajectory conjecture, as typically stated, is ill-posed and untestable. Generalizing the conjecture to state that individual catchments with stable basin characteristics that undergo changes

in aridity index will follow an explicit Budyko curve trajectory (as is almost always done in practice), makes it well-posed and testable. Here we examine the support for the well-posed conjecture and test it explicitly, the results of which suggest that specific functional forms of explicit Budyko curves do not have intrinsic physical meaning, but are instead semi-empirical conceptual tools that describe the general aggregate behaviour of multiple catchments—but do not predict the specific behaviour of individual catchments."

2) Change the sentences on page 15 lines 15-16:
   "The main conclusion of this theoretical test is that a catchment undergoing changes in aridity does not have to follow a Budyko curve, contrary to the the catchment trajectory conjecture."

<u>**Comment 3:**</u>

*** The approach using the data: It is stated that "this prediction can be tested by comparing actual Budyko space trajectories of reference catchments computed from empirical observations against the expectation from the catchment trajectory conjecture. If the observed reference catchment trajectories are distinct from the expected Budyko curve trajectories, the conjecture should be rejected.". However, there are many other reasons why the trajectories do not follow the Budyko curves. For example, the water balance may not be closed, measurements may be off, climate variables (other than aridity) may also change (since land-cover is the only variable which is controlled for). Therefore it seems somewhat unfair to attribute any anomaly from the curve to solely the Budyko trajectory being wrong, rather than that is also could be caused by any of the other factors.**

<u>Response 3:</u>

We agree that there are many reasons why reference catchments may not follow Budyko curve trajectories over time. However, it is problematic that the default assumption is that catchments would follow specific trajectories under "only" changes in aridity. There are two primary reasons this default assumption is problematic: 1) There is not previous evidence to suggest that individual catchments should follow specific Budyko curves over time (i.e., it is an untested conjecture); and 2) The catchment trajectory conjecture is ill-posed (see response to **Comment 2** above) since it is mathematically impossible for the aridity index change independent of other climate properties. Part of our motivation for testing the catchment trajectory conjecture was that widespread default assumptions about catchments' long-term hydrological behavior was based on an untested and ill-posed assertion.

Still, as the reviewer points out, certain conditions (e.g., closed water balance) must be accounted or controlled for when conducting a rigorous test of the catchment trajectory conjecture. The reviewer's first example about potential issues with the closure of the water balance and its implications for estimating $\bar{E}$ via $\bar{P} - \bar{Q}$ was also raised in the **Short Comment 1 (SC1)** by Randall Donohue. Our methodology for the empirical test (see page 11 lines 26-29, page 12 lines 1-3, and Section S2 of the Supplemental Information) was specifically chosen to robustly address catchment water balance closure and storage dynamics that can impact the estimation of $\bar{E}$. As such, the results and conclusions from the test (i.e., rejection of catchment trajectory conjecture) are robust as long as some of the 728 reference catchments used have a closed water balance for some averaging time interval (which is a safe assumption or $\bar{E} = \bar{P} - \bar{Q}$ would never be true). We detail these specific arguments in our response to **SC1 Comment 3**, where we propose edits to the manuscript to make this point clearer. However, we also provide an abridged version of the response here.

The actual trajectories that catchments take in Budyko space are paired time series of the aridity and evaporative indices, the latter of which is computed from the catchment water balance, $\bar{E} = \bar{P} - \bar{Q} - \overline{\Delta S}$. While time series of P and Q were available for our 728 reference catchments, direct estimates of ΔS were not (which is most often the case). As detailed on page 11 line 29, page 12 lines 1-2 (and in the proposed edits in our response to **SC1 Comment 3**), we address the lack of information about ΔS by testing the catchment trajectory conjecture for all possible realizations of each catchment's actual trajectory through Budyko space by adjusting the size of the moving average window in annual steps from 1 year to the full length of record (resulting in 24,501 trajectories). If the catchment trajectory conjecture is correct and if $\overline{\Delta S} \sim 0$ for some catchments for some averaging windows, the frequency at which actual and expected Budyko space trajectories are statistically indistinguishable would be higher than expected at random (i.e., more than 5% of all actual vs. expected trajectories would be statistically indistinguishable at a significance level of 0.05). However, our results showed that 23,231 (95%) actual and expected trajectories were distinct while only 1270 (5%) were found to be statistically similar, which is exactly what would be expected due to random chance if the catchment trajectory conjecture was false (see page 17 lines 21-25 and the proposed edits in our response to **SC1 Comment 3**).

The reviewer's second example of potential misattribution was that empirical measurements of E_0, P, and Q may have error. We agree that this is possible for hydrological and meteorological data in any hydro-climatological study and could impact results, dependent on which variables had errors and at what magnitude. The data used in this study are from peer-reviewed datasets and were produced using standardized methodologies by the governments of the US (e.g., USGS, NASA, and NOAA) and UK (e.g., NRFA and Met Office). If the errors present in these data are sufficient to obscure catchments' "true" Budyko curve trajectories, it is unlikely that any current continental-scale catchment datasets would have sufficient accuracy to apply the parametric Budyko equations in a meaningful way. Given that individual catchments have not been shown to follow specific Budyko curve trajectories previously (see page 7 lines 26-31 and page 8 lines 1-17), and our study reaffirms this finding for 95% of realizations over 728 rigorously measured catchments (see page 17 lines 19-25), we contend that is reasonable to conclude that trajectory anomalies we observed are more likely due to a failure of the previously untested catchment trajectory theory rather than errors in data or methods. To make this point clearer in the manuscript, we propose edit the sentence on page 12 line 14 to:

"The catchments used in our empirical test were UK and US reference catchments identified from well-accepted peer-reviewed datasets. The data contained in these datasets were produced using standardized methodologies with well-documented quality control standards and therefore are comparable to similar state-of-the-art hydrological datasets."

The final example the reviewer gives as a possible cause of non-Budyko curve behavior is that climate variables other than aridity could be changing and were not controlled for. We have largely addressed this comment in our response to **Comment 2** by noting the ill-posed nature of the catchment trajectory conjecture and the conceptualization of the aridity index. In short, we agree with the reviewer that climate variables other than aridity are changing, since it is impossible for the aridity index to change without changes to the times series of P (e.g., storm return interval) or E_0 (e.g., seasonality).

<u>Comment 4:</u>

*** To what extent are the methods sensitive to the use of the Hargreaves potential evaporation over any other PET estimate? In theory it seems that the ambiguity of the PET estimate has similar problems as that of catchment specific parameter in the Budyko framework (e.g. suffering from non-uniqueness and potentially crossing trajectories).**

<u>Response 4:</u>

The conclusions obtained from our empirical test methodology are insensitive to the choice of E_0 method (e.g., Hargreaves vs. others); therefore, they provide a robust test of the catchment trajectory conjecture. To make this point clearer in the manuscript, we propose to edit the sentence on page 12 lines 24-26 to:

"Daily E_0 time series were computed from the daily T_{max} and T_{min} values using the Hargreaves potential evaporation equation (Hargreaves and Allen, 2003;Lu et al., 2005;Allen et al., 1998), though we note our empirical test methodology is insensitive to the specific choice of E_0 method (see Supplemental Information Sect. S2.6)."

Additionally, we propose to add the section references above (i.e., Section S2.6) to the Supplementary Information, the specifics of which are given at the end of this response.

Here we summarize four lines of support for our conclusion that the empirical test methodology is insensitive to the choice of E_0 method: (1) empirical evidence of insensitivity - we used two different E_0 methods in the test of the catchment trajectory conjecture (Hargreaves for US catchments and Penman-Monteith for UK catchments), and both produced the same conclusion: rejection of the conjecture (see page 12 lines 19-26 and page 17 lines 19-25); (2) the various possible E_0 methods that could be used in this analysis are highly correlated, so the choice of method will not alter the basic shape of the actual Budyko space trajectories (see proposed Section S2.6 at end of response); (3) for all averaging periods, catchments' trajectories are overwhelmingly driven by changes in $\bar{P}$ rather than changes in $\overline{E_0}$ (see proposed Section S2.6 at end of response); and (4) the non-parametric sign test used to determine consistent differences between actual and expected trajectories will provide near-identical results for each possible E_0 method if the basic shape of the actual Budyko space trajectories are generally preserved (see page 12 lines 4-7, support 2 above, and Sections S2.4 and proposed Section S2.6) We explain each support in detail below.

Support 1:

Hargreaves E_0 was used only for the US catchments since the CAMELS dataset did not include daily estimates of E_0 (page 12 lines 23-26). The CAMELS-GB had daily estimates of E_0 for the UK catchments (calculated using the Penman-Monteith equation), which were used in our analysis (page 12 lines 19-20). We note that the use of different E_0 methods did not produce differing results or conclusions for the UK and US catchments. Neither the US nor UK catchments' actual trajectories followed the expected trajectories (see Figure 3 in the main manuscript) at a higher rate than expected from random chance (i.e. 5% of actual trajectory realizations).

Our preferred choice of E_0 method was Penman-Monteith, however, this method could not be used for the US catchments since the dataset lacked wind speed. The Hargreaves method was chosen since it utilized the most information from the available data (i.e., daily average temperature and daily temperature range) compared to other E_0 methods based on temperature (e.g., Thornthwaite, Blaney–Criddle, etc.) or radiation (e.g., Priestley–Taylor, Jensen–Haise, McGuinness and Bordne, etc.). Most radiation- and temperature-based E_0 methods are unable to account for the impact of humidity and wind on E_0. However, the Hargreaves method implicitly accounts both of these effects as well as the effect of cloudiness through its use of the daily temperature range (Hargreaves and Allen, 2003).

Support 2:

While various E_0 methods may differ in magnitude, most methods (e.g., pan-, temperature-, radiation-, and mass transfer-based) are highly correlated. For example, Tabari et al. (2011) tested 31 different E_0 methods against the Penman-Monteith method and found them all to be highly correlated (R^2 ranged from 0.65 to 0.99, with all of the temperature-based methods having $R^2 > 0.82$). This high degree of correlation means that any one particular method can be well approximated as a linear function of any other (i.e., $E_0^1 = \alpha E_0^2 + \beta$). Different choices of E_0 methods can thus only do two things to a catchment's actual Budyko space trajectory, translate the entire trajectory along the ϕ axis and/or symmetrically expand or contract the trajectory around its average value in the ϕ dimension (see Figure R1). Neither of these operations changes the basic shape of the trajectory for different E_0 methods, making the conclusions obtained from our catchment trajectory conjecture test largely insensitive to the choice of E_0 method.

Support 3:

A catchment's actual trajectory through Budyko space is overwhelmingly driven by changes in $\overline{P}$ rather than changes in $\overline{E_0}$. This is because annual average E_0 is very consistent from year to year regardless of E_0 method used. In our analysis, we used all possible averaging windows, ranging from 1 to 45 years, to compute time varying values of $\overline{E_0}$ and $\overline{P}$, which were used to produce all possible actual catchment trajectory realizations (see also responses to **SC1 Comment 3**, **Comment 3**, and **Comment 17**). In Figure R2 below, we show the corresponding standard deviations of $\overline{E_0}$ and $\overline{P}$ for each of these realizations. In almost all realizations, the variation in $\overline{P}$ is far greater than the variation in $\overline{E_0}$. This implies that changes in a catchment's ϕ (i.e., the ϕ axis the component of its Budyko space trajectory) is primarily driven by changes in $\overline{P}$. Since the temporal dynamics of $\overline{E_0}$ are much less important than those of $\overline{P}$ in determining actual trajectories, the choice of E_0 method has little impact on shape of actual trajectories.

Reason 4:

The non-parametric sign test used in our analyses tests for consistent over- or under-estimation between paired observations (i.e., actual and expected trajectories in this analysis). If the catchment trajectory conjecture is correct, it would be expected that a catchment's actual trajectory would not be consistently greater than or less than the expected trajectory (i.e., it would be statistically indistinguishable). If we assume that a catchment's actual and expected trajectories are statistically similar when one particular E_0 method is used, then based on Reasons 2 and 3 above, this statistical similarity will almost always be maintained for any E_0 method, as detailed further below.

First, we note that the basic shape of an actual trajectory determines whether or not it is consistently above or below the expected trajectory. Second, since $\overline{E_0}$ does not vary much over time (Support 3) and because the various E_0 methods are highly correlated (Support 2), changing the E_0 method will not alter the basic shape of the actual trajectory. The actual trajectory could expand or contract in the ϕ dimension (Support 2), however, because these operations are symmetric, they will not alter the frequency at which the trajectory is above or below the expected trajectory. Finally, changing the E_0 method can cause the entire trajectory to be translated along the ϕ axis. The operation does not change the shape of the actual trajectory, but it does change the expected trajectory since the long-term mean values of ϕ and the evaporative index fall on a new parametric Budyko curve. The new expected trajectory will be slightly rotated with respect to actual trajectory as compared to the trajectories with original E_0 method. This rotation will cause the actual trajectory to be above and below the expected trajectory slightly more frequently, but the relative frequency of over- and under-estimation will be nearly unchanged (see Figure R1).

Thus, for any particular choice of E_0 method, the relative frequency of over- and under-estimation remains almost constant for all potential alterations of the actual or expected trajectories. The outcome of the non-parametric sign test is dependent on this relative frequency, meaning its results are robust against the choice of different E_0 methods.

The specific content of the proposed additional Section S2.6 is provided below:

Section S2.6 The insensitivity of the empirical test methodology to the choice of E_0

"The methodology for the empirical test of the catchment trajectory conjecture is insensitive to the choice of E_0 method. There are three primary reasons for this: (1) the various possible E_0 methods that could be used in this analysis are highly correlated, so the choice of method will not alter the basic shape of the actual Budyko space trajectories; (2) for all averaging periods, catchments' trajectories are overwhelmingly driven by changes in $\overline{P}$ rather than changes in $\overline{E_0}$, so the choice of E_0 method will not alter the basic shape of the actual Budyko space trajectories; and (3) the non-parametric sign test used to determine consistent differences between actual and expected trajectories will provide near-identical results for each possible E_0 method if the basic shape of the actual Budyko space trajectories are generally preserved. We summarize each of these below.

1. *While various E_0 methods may differ in magnitude, most methods (e.g., pan-, temperature-, radiation-, and mass transfer-based) are highly correlated. This high degree of correlation means that any one particular method can be well approximated as a linear function of any other (i.e., $E_0^1 = \alpha E_0^2 + \beta$). Different choices of E_0 methods can thus only do two things to a catchment's actual Budyko space trajectory, translate the entire trajectory along the ϕ axis and/or symmetrically expand or contract the trajectory around its average value in the ϕ dimension. Neither of these operations changes the basic shape of the trajectory for different E_0 methods, making the conclusions obtained from our catchment trajectory conjecture test largely insensitive to the choice of E_0 method.*
2. *A catchment's actual trajectory through Budyko space is overwhelmingly driven by changes in $\overline{P}$ rather than changes in $\overline{E_0}$. This is because annual average E_0 is very consistent from year to year regardless of E_0 method used. In our analysis, we used all possible averaging windows, ranging from 1 to 45 years, to compute time varying values of $\overline{E_0}$ and $\overline{P}$, which were used to produce all possible actual catchment trajectory realizations. For almost possible all realizations, the variation in $\overline{P}$ will be far greater than the variation in $\overline{E_0}$. This implies that changes in a catchment's ϕ (i.e., the ϕ axis the component of its Budyko space trajectory) is primarily driven*

by changes in $\bar{P}$. Since the temporal dynamics of $\overline{E_0}$ are much less important than those of $\bar{P}$ in determining actual trajectories, the choice of E_0 method has little impact on shape of actual trajectories.

(3) *The non-parametric sign test used in the empirical analysis (see Sect. S2.4) tests for consistent over- or under-estimation between paired observations (i.e., the actual and expected trajectories). If the catchment trajectory conjecture is correct, the catchment's actual trajectory would not be consistently greater than or less than the expected trajectory (i.e., they would be statistically indistinguishable). If a catchment's actual and expected trajectories are statistically similar when one particular E_0 method is used, then based on the previous two reasons above, this statistical similarity will almost always be maintained for any E_0 method.*
The basic shape of an actual trajectory determines whether or not it is consistently above or below the expected trajectory. Since $\overline{E_0}$ does not vary much over time and because the various E_0 methods are highly correlated, changing the E_0 method will not alter the basic shape of the actual trajectory. The actual trajectory could expand or contract in the ϕ dimension, however, because these operations are symmetric, they will not alter the frequency at which the trajectory is above or below the expected trajectory. Changing the E_0 method could cause the actual and expected trajectories to be translated along the ϕ axis. While this operation would not change the shape of the actual trajectory, it would change the expected trajectory since the long-term mean values of ϕ and the evaporative index fall on a new parametric Budyko curve. The new expected trajectory will be slightly rotated with respect to actual trajectory as compared to the trajectories with original E_0 method. This slight rotation will cause the actual trajectory to be above and below the expected trajectory slightly more frequently, but the relative frequency of over- and under-estimation will be unchanged in most cases.

Thus for any particular choice of E_0 method, the relative frequency of over- and under-estimation remains almost constant for all potential alterations of the actual or expected trajectories. The outcome of the non-parametric sign test is dependent on this relative frequency, meaning its results are robust against the choice of different E_0 methods."

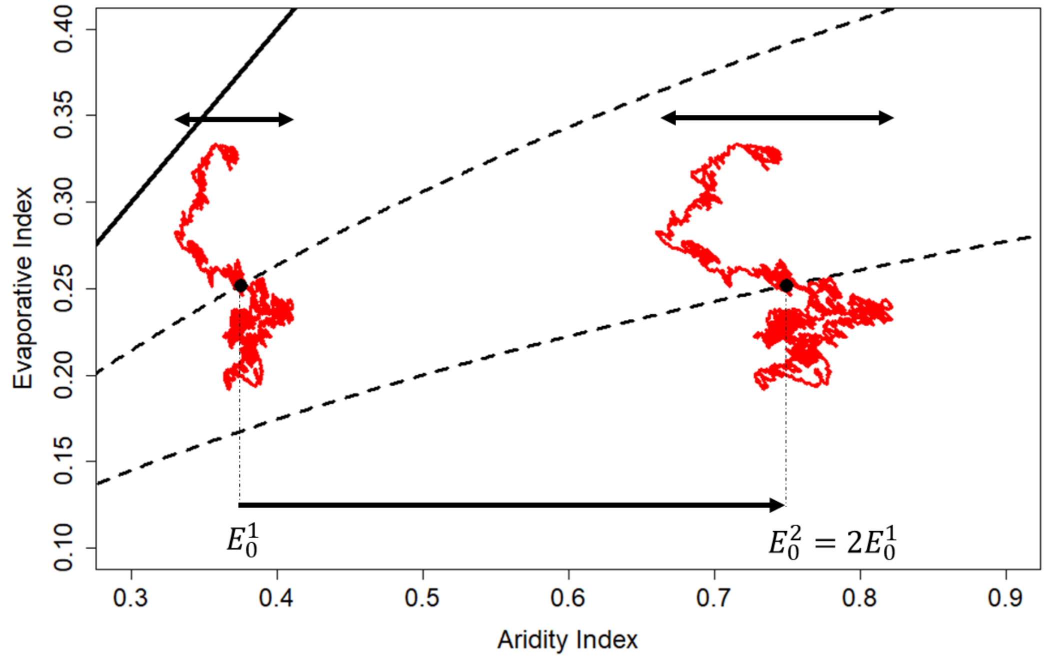

Figure R1: Illustration of the potential effects of the choice of E_0 method on the empirical test of the catchment trajectory conjecture. The actual (red solid curves) and expected trajectories (black dashed curves) of a catchment calculated using one particular potential evapotranspiration method, E_0^1, are given on the left side of the figure. If a different method, E_0^2, gives estimates of E_0 twice that of E_0^1, (i.e., $E_0^2 = 2E_0^1$), then the catchment's actual trajectory translates along the ϕ axis and symmetrically expands around its average value in the ϕ dimension. The expected trajectory changes to a new parametric Budyko curve. This new expected trajectory for E_0^2 will be slightly rotated with respect to actual trajectory as compared to the trajectories computed with E_0^1. However, the relative frequency of over- and under-estimation of the expected trajectory compared to the actual trajectory remains essentially unchanged. Thus, outcome of the non-parametric sign test is the same for both E_0 methods.

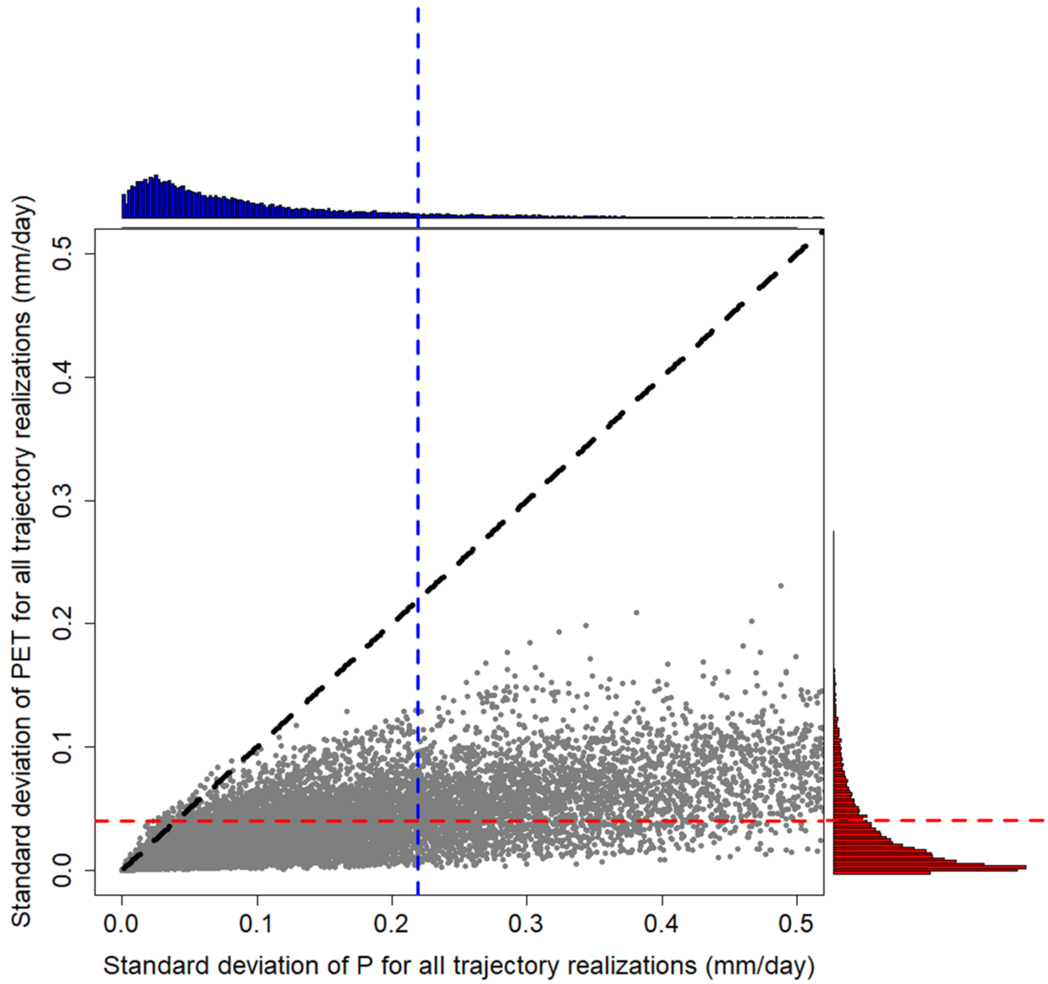

Figure R2: Corresponding standard deviations of $\overline{E_0}$ and $\bar{P}$ for all possible actual Budyko space trajectory realizations used in the empirical test of the catchment trajectory conjecture (gray dots). Histograms of the marginal distributions for $\overline{E_0}$ and $\bar{P}$ realizations are shown in red and blue, respectively. Nearly all points fall below the 1 to 1 line (black dashed line) meaning changes in $\bar{P}$ dominate the temporal dynamics of catchments' trajectories. The mean standard deviation of $\bar{P}$ is 0.22 mm/day (blue dashed line), 5.5 times larger than the value for $\overline{E_0}$, 0.04 mm/day (red dashed line).

Comment 5:

Beside these limitations, the paper nicely contrasts the large number of of Budyko studies that "blindly apply Budyko equations", and emphasizes some shortcomings of the framework that are too often ignored. Once the above issues are addressed (and the detailed comments below) I think this paper could make an excellent contribution to the literature.

Response 5:

We thank the reviewer for the positive evaluation of the manuscript's contribution to the literature. We believe that we have addressed the reviewers concerns in our responses to the comments and with our suggested edits to the manuscript.

Comment 6:

Detailed comments

Page 1 L18: “components” or “assumptions”?

Response 6:

We agree that “assumptions” is a more accurate word and propose to change this wording throughout the manuscript.

Specifically: (page 1 line 18), (page 3 line 11), and (page 3 line 14).

Comment 7:

Page 2 L3: “rainfall” should be changed into “precipitation” (as it also includes snow). This change is also recommended at other places where rainfall is stated, but precipitation may be more appropriate.

Response 7:

We agree with the reviewer and propose to make this change at all places where “rainfall” was used inappropriately in the manuscript.

Specifically: (page 2 line 2), (page 2 line 6), (page 2 line 18), (page 7 line 19), (page 7 line 28), (page 8 line 2), (page 10, line 8), (page 10 line 10), (page 10 line 18), (page 21 line 4), (page 22 line 24), and (page 22 line 27).

Comment 8:

Page 2 L30: Note that the Gentine et al. (2012) study excluded most US catchments with loads of snow or out of phase precipitation regimes (i.e. Mediterranean). As a consequence, most scatter was removed, resulting in this interpretation.

Response 8:

We thank the reviewer for calling this to our attention. Based on our reading Gentine et al. (2012), we do not believe their interpretation was completely dependent on the amount of scatter removed in their methodology. However, while they did not explicitly exclude Mediterranean and snowy climates, their exclusion methodology was biased against these types of catchments within the MOPEX dataset. Therefore, we propose to retain the citation but also add context to their interpretation by editing the sentence on pages 2 line 30 and page 3 lines 1-2 to:

“For example, Gentine et al. (2012) suggested that the aggregate Budyko curve behaviour already reflects the interdependence among vegetation, soil, and climate, and therefore, the inclusion of catchment-specific parameter into the Budyko framework is unnecessary. However, this interpretation was partially based on catchment data with limited scatter in Budyko space.”

<u>Comment 9:</u>

Page 3 L13: It is stated that "we critically reinterpret two key and interrelated components of the current framework:". I am unsure these two things can be called "components". They are rather typical assumptions that people make, but as past authors acknowledge (as referenced by this paper, or as stated above in this review) these assumptions appear largely unfounded, untested, or premature.

<u>Response 9:</u>

We agree that "assumptions" is a more accurate word and propose to change this wording throughout the manuscript (also see response to **Comment 6**).

<u>Comment 10:</u>

Page 3 L15-17: I appreciate the paper is trying to be gentle towards past research by saying "However, we stress that the aim of this reinterpretation is not to discard the voluminous efforts put forth using current interpretations of the Budyko framework, but rather to recontextualize the conclusions obtained from them". However, your work suggests that all attributions and sensitivity applications will have substantially wrong numbers. This obviously is important "context" but I'd rather say they also cast doubt on many of the past conclusions.

<u>Response 10:</u>

We thank the reviewer for recognizing our attempt to treat previous work fairly. Additionally, we agree that that our work implies that our results do cast doubt on some of the conclusions of previous work (e.g., causal attributions and sensitivity applications). However, we also stress that, with an appropriate interpretation of the parametric Budyko framework, both the intent and much of the effort of previous work can be maintained. For example, as we write in the manuscript (page 21 lines 9-14) any study that has related n or w to catchment biophysical features can easily drop the parametric framework from their analysis and use their same analytical tools to relate $\bar{E}$ or $\frac{\bar{E}}{\bar{P}}$ to biophysical features directly. This would preserve most of the analyses of such studies (i.e., same analytical methods) as well as the intent (i.e., understanding the interactions between $\bar{E}$ and catchment biophysical features). We attempt to improve our treatment of the recontextualization of prior work in out proposed edits in response to **Reviewer 1 Comment 3**.

<u>Comment 11:</u>

Page 5 L14: Schreiber, 1904 was not aware yet of the concept of potential evapotranspiration, so I am unsure it is appropriate to cite this work here.

<u>Response 11:</u>

We agree that Schreiber (1904) did not specifically use the concept of potential evapotranspiration, however, he did use a functionally equivalent constant "k" in its place (see explanation below), and he also seems to be the first to propose a functional form of what we now call the Budyko equations. Additionally, others, such as Ol'Dekop (1911), used and expanded upon his work to improve our understanding of the catchment water balance. Therefore, we think it is appropriate that his work is cited in reference early work on the catchment water balance.

Schreiber (1904) constant “k”:

We revisited the text of Schreiber (1904), and while the concept of potential evapotranspiration is not explicitly stated, Schreiber (1904) has a functionally equivalent constant “k” in its place. He refers to “k” as the limiting value that the difference between mean annual precipitation and runoff ($\bar{P} - \bar{Q}$, referred to as “die Rückstandshöhe” or the catchment’s residue/hold-back height) approaches as precipitation becomes large (i.e., $\bar{P} \rightarrow \infty$). Quoting the specific passage:

> *Je größer x [der jährichen Niederschlagschöhe] wird, um so kleiner wird $\frac{k}{x}$, so daß man für sehr große x*
>
> $$y = x - k$$
>
> *[die jähriche Abflußhöhe] setzen kann. Heiraus ergibt sich sofort die physikalische Bedeutung des Exponenten k als die Größe, der sich die Differenz zwischen Niederschlag und Abfluß [y] um so mehr nähert, je größer der Niederschlag selbst wird. Dieses Verhältnis scheint mir in der Natur des Problemes begründet zu sein. Die Differenz*
>
> $$z = x - y$$
>
> *kann man als die Rückstandshöhe bezeichen.* Schreiber (1904), page 3.

In our current language, the constant k would be the mean annual value of evapotranspiration under energy-limited conditions, i.e., the mean annual potential evapotranspiration, $\overline{E_0}$. However, while constant k is functionally equivalent to $\overline{E_0}$, Schreiber (1904) does not discuss or specify how the water that does not become discharge is being “held back” (i.e., does not discuss it as being evaporated) and therefore does not explicitly introduce the concept of potential evapotranspiration. Subsequent investigations by Ol’Dekop (1911) ascribed the concept of maximum possible evaporation (i.e., potential evapotranspiration) to “K”, as detailed in Andréassian et al. (2016).

Comment 12:

Page 5 L18: identical $\bar{P}$ and $\overline{E_0}$ seems somewhat inaccurate, as it is about the ratio of the two.

Response 12:

We agree that this statement is inaccurate and propose to change the sentence on page 5 lines 17-18 to:

“However, Eq. (3) and other forms of Eq. (2) are unable to explain differences in $\bar{E}$ between catchments with identical $\frac{\overline{E_0}}{\bar{P}}$.”

Comment 13:

Methods

Page 10 L6: “(e.g., (“ the second layer of brackets seems redundant

Response 13:

We agree and propose to change this formatting to remove the second layer of parentheses throughout the manuscript.

Comment 14:

Page 11 Section 3.1.1: This test seems inappropriate for its cause, because climate characteristics other than aridity are varied.

(Also, see main comment above).

Response 14:

We have addressed this concern in our responses to **Comment 2** and **Comment 3**. The key idea from these responses is that it is mathematically impossible to only change the aridity index independent of other climatic characteristics.

Comment 15:

Page 11 Section 3.1.2: Note that similar types of test have been done in https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.9949 and https://www.nature.com/articles/ncomms11603

Response 15:

We thank the reviewer for highlighting these two additional references. We agree that the nature of the test conducted by Berghuijs and Woods (2016) is comparable to our approach (though it doesn't explicitly control for land use stability, i.e., using only reference catchments). We acknowledge Berghuijs and Woods (2016) in the proposed edits in our response to **Comment 22**. While van der Velde et al. (2014) does track temporally changing Budyko space trajectories for individual catchments using a method somewhat similar to our approach, they do not focus on the behavior or individual catchments. Rather, they use trajectories to understand how groups of catchments have behaved and how they might do so in the future. As such, we propose to acknowledge van der Velde et al. (2014) in reference to the methodologies of calculating Budyko space trajectories.

Specifically, we propose to change the sentence on page 11 lines 27-29 to:

"Since $\bar{P}$, $\overline{E_0}$ and $\bar{E}$ represent temporal averages, and we were also interested in temporal trajectories of those magnitudes, we computed time series of moving averages for each of the three variables, similar to the method employed by van der Velde et al. (2014)."

Comment 16:

Page 11 L18-20: selecting catchments with stable land-use makes the assumption that all other time-varying factors controlling the catchment's water balance (besides aridity) are irrelevant, but this is inaccurate as, for example, seasonal cycles of P can strongly vary between years (and strongly influence the precipitation partitioning).

Page 11 L20: as a consequence, it is hard to agree with "must be attributed to climatic factors and the catchment trajectory conjecture predicts that their expected trajectories through Budyko space must be Budyko curves". Are the ways to address this critical limitation (given its purpose) to your test?

Response 16:

We agree that other climatic factors (e.g., varying seasonal cycles of P) can strongly impact a catchment's water balance. We have largely addressed the points brought up in this comment in our responses to **Comment 2**, **Comment 3**, and **Comment 14** above, but we provide a brief summary here.

The key idea from these responses is that it is mathematically impossible to only change the aridity index independent of other climatic characteristics, making the typical catchment trajectory conjecture ill-posed. In its original form, the conjecture is untestable since it does not specify the mechanism by which the aridity index should change over time (e.g., varying seasonal cycles of P) to produce specific parametric Budyko curve trajectories. We believe we have clarified these points in our proposed edits in the responses **Comment 2** and **Comment 3** and contend that our empirical test provides a well-formed and robust test of the catchment trajectory conjecture.

Comment 17:

Page 11 L27: "$\overline{E}$ were calculated from the catchment water balance, $\overline{E} = \overline{P} - \overline{Q}$. " is an obvious way to approach the problem, but also known to have issues: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020WR027392. What are the potential effects of storage changes (even over 10-y time-scales).

Response 17:

We thank the reviewer for highlighting Han et al. (2020), as their work supports the validity of our empirical test methodology as described in our response to **Comment 3** and **SC1 Comment 3**. Specifically, if $\overline{\Delta S}\sim 0$ for some of the references catchments used for some averaging windows, then the results of our empirical methodology provide a robust test of the validity of the catchment trajectory conjecture. Han et al. (2020) found that under their tightest restrictions, 71% of the 1057 catchments they tested had $\overline{\Delta S}\sim 0$ for an averaging window of 10 years. Furthermore, 94% of their tested catchments had $\overline{\Delta S}\sim 0$ for an averaging window of 30 years. We note that our empirical methodology tested actual and expected trajectory realizations for all 728 reference catchments for all possible averaging windows, ranging from 1 to 45 years (see page 11 lines 26-29, page 12 lines 1-2, and page 12 lines 19-26). Therefore, based on the results of Han et al. (2020), we would expect nearly all of the reference used to have $\overline{\Delta S}\sim 0$ for at least one of the averaging windows used, with the significant majority of catchments having $\overline{\Delta S}\sim 0$ for many of the averaging windows. Thus, if the catchment trajectory conjecture were correct, the frequency of statistical similarity for actual and expected trajectories would be ***substantially*** higher than expected at random. However, our results were exactly what would be expected due to random chance if the catchment trajectory conjecture was false, with only 5% (1270 realization) of actual and expected trajectories being statistically similar and 95% (23,231 realizations) statistically distinct.

We propose to acknowledge Han et al. (2020) with the edits described in our response to **SC1 Comment 3**.

<u>Comment 18:</u>

Page 12: "applying moving-average window sizes ranging in annual steps from 1 year to the full length of record." How is it justified to use 1-year windows as these clearly can violate the delta S =~0 assumption?

<u>Response 18:</u>

The conclusions from our empirical methodology leverage expected trajectory realizations for all 728 reference catchments for all possible averaging windows and are unaffected by whether certain catchments under certain averaging windows violate steady state conditions (see responses to **Comment 3**, **Comment 17**, and **SC1 Comment 3**).

<u>Comment 19:</u>

Page 12 L25: Why Hargreaves PET, and are there any changes to the results when other PET estimates would be used?

<u>Response 19:</u>

We have addressed this comment in our response to **Comment 4**.

<u>Comment 20:</u>

Page 14: It remains unclear to me what the purpose is of section 3.2.2. (Yes I see WHAT is done, but it seems not really explained WHY this is done).

<u>Response 20:</u>

The purpose of Section 3.2.2 (and Section 4.2.2) is to illustrate that single-parameter Budyko equations are non-unique, making the various different functional forms contradictory under commonly held interpretations of the framework. While this motivation was introduced in the Abstract (page 1 lines 25-26) and Introduction (page 4 lines 4-7), upon reviewing Section 3.2.2 we agree that its purpose could be better contextualized and motivated. We propose to do so by editing Section 3.2.2 to:

"Equations (5) and (6) are the most widely accepted and frequently used single-parameter Budyko equations. The following properties of these equations are used either as foundational constraints in their derivation or to justify their validity in describing Budyko space: (1) they describe a family of concave down non-intersecting curves; (2) these curves satisfy conservation of mass and energy; (3) every point within Budyko space belongs to only one curve (i.e., the uniqueness requirement); (4) the values and first derivatives of all curves approach 0 and 1, respectively, in the humid limit (i.e., $\phi \rightarrow 0$); (5) the values and first derivatives of all curves 1 and 0, respectively, in the arid limit (i.e., $\phi \rightarrow \infty$); (6) the curves asymptotically approach the energy and water limits as the parameter approaches infinity; and (7) the curves asymptotically approach zero as the parameter approaches its lower bound. Many previously proposed single-parameter equations violate at least one of these properties (e.g., Zhang et al. (2001) violates property (2), Wang and Tang (2014) violates property (3), and Milly (1993) violates property (5)). However, any other single-parameter equation that has these same properties is a single-parameter Budyko equation is as equally valid as Eqs. (5) and (6). In this sense, neither Eqs. (5) and (6) nor any other possible single-parameter Budyko equation has a particular claim of being the "correct" equation for representing Budyko space.

Commonly held interpretations about the parametric Budyko equations, such as the catchment trajectory conjecture, explicitly or implicitly ascribe physical meaning to the functional form of specific single-parameter curves (e.g., individual catchment trajectories). However, different valid single-parameter Budyko equation have non-equivalent functional forms. Thus, under this interpretation, when used in proposed hydrological applications (e.g., causal attributions and sensitivity applications), each distinct and valid Budyko equation version will produce results that contradict those obtained from other versions. Such results suggest the physical interpretation ascribed to explicit functional curves are unfounded.

To illustrate the contradictory nature of the parametric Budyko equations explicitly, we compare behaviors of Eqs. (5) and (6) to that of two new completely analogous relationships (i.e., they conform to all of the properties of Eqs. (5) and (6) and have analogous parameters):

$$\frac{\bar{E}}{\bar{P}} = 1 - \left[\frac{\gamma\left(q_n, \frac{q_n}{\phi}\right)}{\Gamma(q_n)}\right] + \left[\frac{\gamma\left(q_n+1, \frac{q_n}{\phi}\right)}{\Gamma(q_n+1)}\phi\right], \qquad (9)$$

and

$$\frac{\bar{E}}{\bar{P}} = 1 - \left[\frac{\gamma\left(q_w-1, \frac{\Gamma\left(q_w-\frac{1}{2}\right)}{\phi^2\Gamma(q_w-1)}\right)}{\Gamma(q_w-1)}\right] + \left[\frac{\gamma\left(q_w-\frac{1}{2}, \frac{\Gamma\left(q_w-\frac{1}{2}\right)}{\phi^2\Gamma(q_w-1)}\right)}{\Gamma\left(q_w-\frac{1}{2}\right)}\phi\right], \qquad (10)$$

where q_n and q_w are the catchment-specific parameters and $\Gamma(\ )$ is the gamma function. The parameter q_n is analogous to n of Eq. (5), taking values ranging between 0 and ∞, and q_w is analogous to w in Eq. (6), taking values ranging between 1 and ∞ (Eqs. (9) and (10) are developed fully in Sect. S3 in the Supplemental Information)."

<u>**Comment 21:**</u>

Results and Discussion

Section 4.1.1.

All these results seem to show that climate variables other than aridity also affect the partitioning of P into Q and E. This seems to be a strange way to test the catchment trajectory conjecture because if the resulting trajectories are not Budyko curves, it just means that climate (other than aridity) also influences the water balances, rather than being a test of the catchment trajectory conjecture. (See main comments).

<u>Response 21:</u>

We have addressed this comment in our responses to **Comment 2**, **Comment 3**, **Comment 14**, and **Comment 16**. We reiterate the following points: 1) The aridity index cannot vary independent of other climate features. 2) The catchment trajectory conjecture makes no claim about which climate properties vary to vary the aridity and evaporation indices in a way which will produce a specific Budyko curve trajectory (climate properties controlling $\overline{E_0}$ or $\bar{P}$ or both?). 3) Because of points 1 and 2, the catchment trajectory conjecture is ill-posed. Despite the ill-posed and previously untested nature of the catchment trajectory conjecture, we believe that this work provides a fair assessment of its validity.

<u>Comment 22:</u>

Section 4.1.2

L6: "their global behaviour". Can this be made more specific (i.e. does it refer only to the long-term mean water balances (e.g. black markers)?). Questioning that the prevailing interpretations of Budyko curves suggest that the explicit functional forms represent trajectories through Budyko space for individual catchments undergoing changes in aridity index has also been discussed in https://onlinelibrary.wiley.com/doi/10.1002/hyp.13958 and tested in https://www.nature.com/articles/ncomms11603. This may be worth acknowledging.

<u>Response 22:</u>

Yes, by global behavior we mean the long-term mean water balance (the black markers in Figure 2). To make this clearer we propose to edit the sentence on page 17 lines 5-7 to:

"The catchments investigated span a wide range of aridity indices, climate zones, latitudes, longitudes, and vegetation types, and the global behavior of their long-term mean water balances is in agreement with the non-parametric Budyko curve (Fig. 2)."

We thank the reviewer for highlighting the two additional references in relation to our empirical test of the catchment trajectory conjecture. We also agree that Berghuijs et al. (2020) and Berghuijs and Woods (2016) should be acknowledged. As such, we propose the following edits:

1) Change the sentences on page 8 lines 14-17 to:

   "Additionally, the interpretations typically given for such relationships implicitly assume that the functional forms of either Eq. (5) or Eq. (6) a represent physically meaningful relationship between the aridity and evaporative indices, an assumption which has not been empirically validated, as previously noted by Berghuijs et al. (2020)"

2) Change the sentences on page 18 lines 3-7:

   "The full range of evaporative index errors spanned from 0.4% to 1991%, with an average value of 26%. We note that the average value of this error closely agrees with the value (27.9%) found by Berghuijs and Woods (2016), when they conducted a comparable test of the catchment trajectory conjecture using Eq. (6) and 420 catchments from the MOPEX dataset (Schaake et al., 2006). Importantly, the average relative error for the parametric Budyko framework (26%) is actually larger than that for Eq. (3) (23%), which suggests that the non-parametric Budyko curve is in better agreement with the global behaviour of catchments than the ensemble of parametric curves specifically fit to the individual catchments.

<u>Comment 23:</u>

Figure 2: is there any way to better visualise what is going on here? One minor change (that will not resolve all issues) may be to make the x-axis on a log-scale. This avoids that humid catchments are all condensed in a tiny part of the left side of the figure (whereas arid catchments are spread out at the right-hand side).

<u>Response 23:</u>

We agree that we can likely make Figure 2 clearer. Reviewer 1 had similar concerns about this figure. We believe our proposed edits detailed in the response to **Reviewer 1 Comment 13** address these issues.

<u>Comment 23:</u>

Section 4.2.2.

L7-8: please specify that it is the common interpretation not ALL interpretations in "should cast doubt on the current interpretations of parametric Budyko equations,"

<u>Response 23:</u>

We agree we should be clearer on this point. We propose to change the sentence on page 22 lines 7-9 to:

"The contradiction between Eq. (5) and (6) alone should cast doubt on current commonly held interpretations of parametric Budyko equations, particularly regarding the physical meaning of explicit curves and the provenance and meaning of the catchment-specific parameter."

<u>Comment 24:</u>

Conclusions

"We suggest that process-based evapotranspiration models be used" Note that this is consistent with earlier works: e.g. https://doi.org/10.1029/94WR00586, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005WR004606, etc).

<u>Response 24:</u>

We agree that our suggestion has been recognized and implemented many times in previous work and propose to edit the sentence on page 25 lines 12-14 to:

"Therefore, as an alternative to using explicit Budyko curves to understand catchment trajectories, we suggest that process-based evapotranspiration models be used, as has been previously done (e.g., Eagleson (1978);Milly (1994);Daly and Porporato (2006);Rodriguez-Iturbe et al. (1999);Feng et al. (2015), etc.)."

<u>Comment 25:</u>

Conclusions

"The general Budyko curve behavior can and should be utilized as a global constraint". The "should" seems a bit odd as there will be many instances in which there will be better/more data available than the Budyko curve to constrain models.

<u>Response 25:</u>

As is described in the remainder of the quoted sentence, we used the word "should" since any valid process-based evapotranspiration model must be able to reproduce the general Budyko curve behaviour when applied to multiple catchments across a range of climates since that behaviour is what is observed in nature. We completely agree that in many cases (e.g., for individual catchments) there will be better/more data to constrain evapotranspiration models (e.g., evapotranspiration from eddy covariance). However, it is still important to test that a specific model's structure is able to produce the general Budyko curve behavior when applied across a wide range of climates. To reflect this concept better in the manuscript, we propose to edit the sentence on page 25 lines 14-16 to the following:

"Additionally, to be a valid representation of catchment evapotranspiration, process-based models need to able to reproduce the empirically established general Budyko curve behavior (i.e., nonparametric) when applied to multiple catchments across a range of climates. As such, the general Budyko curve behavior can serve as a global constraint (i.e., calibration or validation) in the application of such models, e.g., Greve et al. (2020)."

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