Impacts of Climate Seasonality on Water Availability and Long-Term Water Balance - A Aridity-Seasonality Index (ASI)

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Abstract

This study investigates the impacts of climate seasonality, i.e., the seasonal cycle of precipitation (P) relative to that of potential evaporation (PET), on surface water supply and the long-term water partitioning and proposes an augmented aridity index considering climate seasonality in addition to climatic mean. Evaporation tends to be favored over streamflow at long-term timescales when both cycles occur in tandem (in-phase seasonality), while the opposite occurs (less evaporation, more streamflow) when the two cycles are out-of-phase. This study proposes a straightforward approach to incorporating the seasonality effects on the mean annual water balance into the Budyko framework, by revising the water availability (A) in the formulation of the aridity index (Φ). We hypothesize the Budyko curve represents catchments with uniform monthly values of P, leading to a mathematical formulation of A that better represents the coupled, land-atmosphere nature of the water availability. Our results also provide a simple mathematical framework for incorporating the seasonality into the aridity index, thus reducing the dimensionality of the long-term water balance problem through an aridity-seasonality index (Φ'). The formulation used here was able to improve the explanatory power of the Budyko framework for 328 catchments within the continental US, being proved as a useful strategy for the incorporating climate variations into its formulation in addition to climatic mean.

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Key points

1. The relative seasonal variations of precipitation (P) and potential evaporation (PET) modify the actual surface water availability.
2. We propose a new aridity index augmented with the corrected surface water availability due to seasonality.
3. The new aridity index extends the explanatory power of the Budyko framework.

ABSTRACT

This study investigates the impacts of climate seasonality, i.e., the seasonal cycle of precipitation (P) relative to that of potential evaporation (PET), on surface water supply and the long-term water partitioning and proposes an augmented aridity index considering climate seasonality in addition to climatic mean. Evaporation tends to be favored over streamflow at long-term timescales when both cycles occur in tandem (in-phase seasonality), while the opposite occurs (less evaporation, more streamflow) when the two cycles are out-of-phase. We propose a straightforward approach to incorporating the seasonality effects on the mean annual water balance into the Budyko framework, by revising the water availability (A) in the formulation of the aridity index (ϕ). We hypothesize the Budyko curve represents catchments with uniform monthly values of P, leading to a mathematical formulation of A that better represents the coupled, land-atmosphere nature of the water availability. Our results also provide a simple mathematical framework for incorporating the seasonality into the aridity index, thus reducing the dimensionality of the long-term water balance problem through an aridity-seasonality index (ϕ'). The formulation used here was able to improve the explanatory power of the Budyko framework for 328 catchments within the continental US, being proved as a useful strategy for the incorporating climate variations into its formulation in addition to climatic mean.

1. Introduction

Climate seasonality (or simply seasonality) refers to how the seasonal cycles of precipitation and potential evaporation (PET), which is controlled by radiation, temperature, humidity, and wind speed, are related to each other. An "in-phase" seasonality refers to a climate when precipitation falls in the boreal summer and thus in phase with PET, while an "out-of-phase" refers to when precipitation falls in the boreal winter (Hickel and Zhang, 2006; Yokoo et al., 2008; Potter et al., 2005; Yao et al., 2020). Seasonality influences not only the water balance at shorter, intra-annual timescales but also the long-term fluxes of streamflow and evapotranspiration (Budyko 1974; Milly, 1994a; Milly 1994b; Potter et al., 2005; Berghuijs et al., 2014; Padron et al., 2017; Yao et al., 2020). Additionally, the interest in seasonality and its controls on the water balance go beyond improving our ability to explain the spatial differences in how freshwater resources are distributed, as shifts in seasonality have been reported to be both currently occurring (Feng et al., 2013) as well as associated with future climate scenarios (Konapala et al., 2020; Montaldo and Oren, 2018).

How does seasonality affect the mean annual water balance? In a broader sense, most hydrologists would regard this as a quite straightforward question. By using a terminology that will be followed along this manuscript, it can be argued that the monthly march of potential evaporation (or evapotranspiration) represents how the atmospheric demand to evaporate the water available at the land surface progresses throughout the year. On the other hand, the monthly march of precipitation would resemble that of the water available for evaporation. Thus, for climates in which both cycles occur in tandem (or in-phase), evaporation would be relatively favored over infiltration (and ultimately streamflow generation) while for climates where both cycles are offset (or off-phase), a lower atmospheric demand would be present during the months with higher surface water availability, leading, therefore, to more water being infiltrated and consequently being released into the streams.

Many studies on the impacts of seasonality versus climate mean on the long-term water balance have confirmed this simple explanation both theoretically via models (Milly, 1994a; Milly, 1994b; Woods, 2003; Potter et al., 2005; Yokoo et al., 2008; Gerrits et al., 2009) and through empirical evidence associated or not with modelling efforts (Hickel and Zhang, 2006; Berghuijs et al., 2014; Beck et al., 2015; Tang and Wang, 2017). Most authors agree that the mechanisms mediating the effects of seasonality on the long-term water balance are associated with the soil storage capacity and its spatial variability, making it necessary to incorporate the knowledge of soil storage capacity for a meaningful representation of the long-term water balance across catchments. There seems, however, to be exceptions for the rationale above. Potter et al., (2005) suggests that for catchments with significantly lower soil moisture capacity, higher (mainly infiltration-excess) runoff rates would still occur for in-phase climates, as seen in Australian catchments.

The Budyko (1974) framework (or hypothesis) is arguably the most widely used analytical tool for investigating the mean annual water balance. In it, the long-term water balance partitioning, represented as the ratio of mean annual evapotranspiration over the mean annual precipitation (E/P), is considered to be solely a function of climate aridity ϕ, which conceptually represents the competition between atmospheric water demand and water availability, and is written as the ratio of the mean annual potential evaporation to precipitation ($\phi = PET/P$). The Budyko framework has received in the last decades a great deal of attention due to its empirical nature and mathematical simplicity (Berghuijs et al., 2020), with applications ranging from prediction of water fluxes in ungauged basins (Bloeschl et al., 2013), global-scale assessments of water availability under climate change scenarios (Milly and Dunne, 2016; Yang et al., 2019), and investigations on how other factors aside from aridity control the long-term water balance (Donohue et al., 2012; Berghuijs et al., 2014; Abatzoglou and Ficklin, 2017; Padrón et al., 2017). The effects of secondary climatic and landscape factors on the long-term water balance can be seen through the existence of systematic deviation from the Budyko curve (Berghuijs et al 2020). **Figure 1** illustrates the systematic deviations for the case of seasonality: a catchment with in-phase seasonality is assumed to be plotted above the empirical Budyko curve, meaning its evaporative fraction (E/P) is higher than expected, whereas catchments with off-phase seasonality are plotted below the curve, meaning that less water is evaporated into the atmosphere.

The uses of the Budyko framework in exploring the role of seasonality are diverse (Milly., 1994; Sankarasubramanian and Vogel, 2001; Potter et al., 2005; Hickel and Zhang., 2006; Yokoo et al., 2008; Shao et al., 2012; Fu and Wang, 2019). On one hand, hydrologic model outputs can be investigated in the $\phi - E/P$ space, by casting their modeling results as "Budyko-like" curves (Milly, 1994; Yokoo et al., 2008; Gerrits et al., 2009; Tang and Wang., 2017). For instance, Milly (1994) developed an analytical bucket-type soil-water model, showing how off-phase seasonality tends to increase runoff. Yokoo et al., (2008) uses a lumped, physically based model, arriving at similar conclusions as in Milly (1994). A strategy that has received much attention consists of improving the explanatory power of the Budyko hypothesis by fitting parametric versions of the Budyko equation to additional factors, which often include some measures of seasonality (Shao et al., 2012; Abatzoglou and Ficklin, 2017). While complex models that reproduce the shape of the Budyko curve might shed light on the underlying mechanisms controlling the mean annual water balance, the multitude of modelling assumptions together with their parameterizations limits their use and universality. Alternatively, parameterized Budyko-type equations cannot be used at ungaged basins and fail in providing the necessary understanding as to why those factors play such roles (Berghuijs et al., 2020).

This paper proposes a way forward to incorporate climatic seasonality into the Budyko framework with no need of parameterization. We pose a novel hypothesis within the Budyko framework and explore its implications through a revised aridity index. The aridity-seasonality index (ASI) accounts for the effects of long-term means and seasonality of P and PET, thus reducing the dimensionality of the long-term water balance problem through the Budyko framework and providing a higher explanatory power over long-term evaporation and runoff partitioning. Additionally, this revised index leads to a redefinition of the concept of water supply/availability within the Budyko framework. We used observations from 328 catchments distributed within the conterminous United States. This paper is organized as follows: *First*, we briefly introduce the catchment dataset and some quality control criteria leading to the final catchment selection, along with some basic computations. *Second*, we provide a formal introduction to the long-term water balance and the Budyko framework, as well as a metric of seasonality. *Third*, we revise the seasonality issue through the Budyko equation by investigating an alternative hypothesis about its origin that leads to alternative formulation of the aridity index. *Fourth*, an assessment of the implications of the proposed changes is shown. *Last*, we discuss the meaning of the implemented changes.

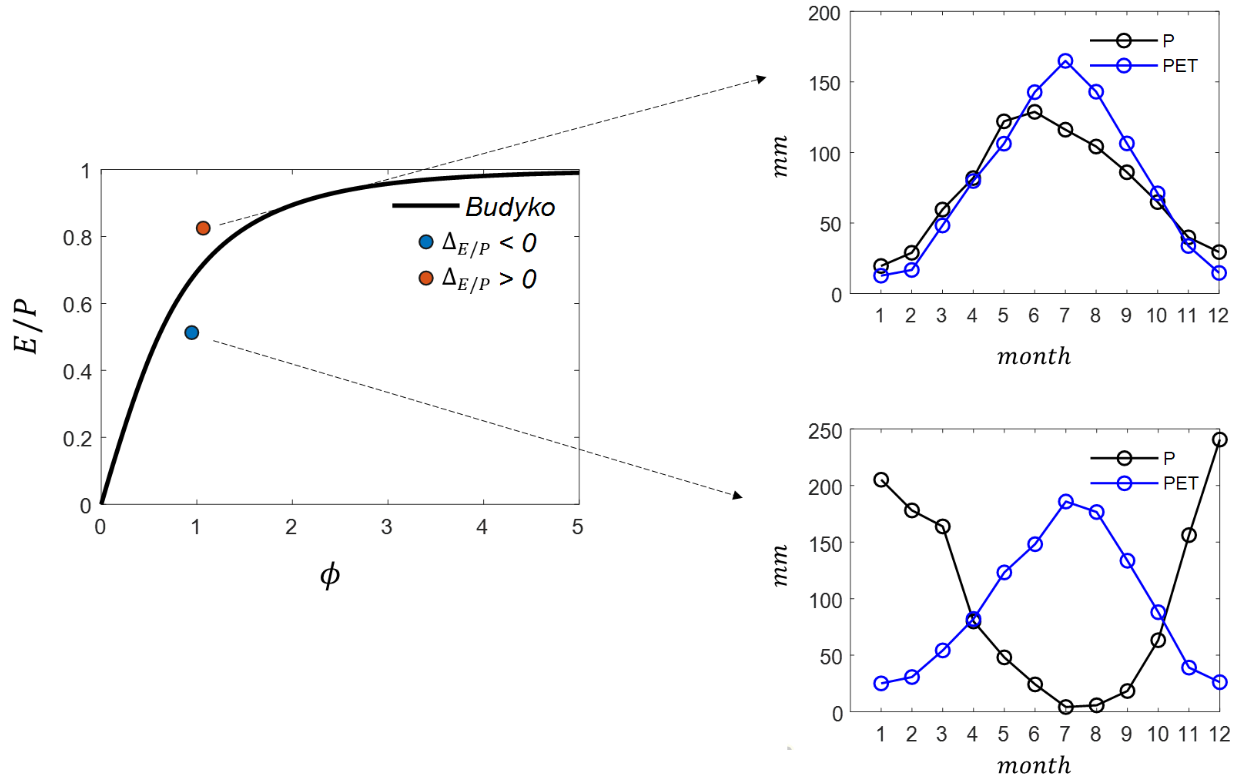

Figure 1. Schematic diagram showing the influence of seasonality on the long-term water partitioning within the Budyko framework for US catchments. For similar values of aridity, a catchment with an in-phase seasonality shows a higher E/P ratio than a catchment with an off-phase seasonality. $\boldsymbol{\Delta_{E/P}}$ represents the deviation between observed E/P versus Budyko's predicted values.

2. Methodology

2.1. Data sources and Computed Hydrological Variables

We used the catchment hydrologic data from the CAMELS (Addor et al., 2017) dataset in our analysis. The CAMELS dataset contains daily time-series of streamflow, precipitation, and several other meteorological variables as well as landscape properties for a total of 671 catchments within the conterminous USA. We have analyzed 34 hydrologic years (October 1st through September 30st, between 1980 and 2013) and used the following criteria for removing catchments in our analysis: (i) catchments with missing values of streamflow, (ii) catchments with negative values of mean annual evaporation (E< 0), (iii) catchments with a fraction of precipitation falling as snow higher than 30%, and (iv) catchments with area smaller than 20 km^2. The resulting subset contained 328 catchments (**Figure S1)**.

We used the Reference-crop Penman-Monteith formulation for calculating daily values of PET (in mm) as:

$$PET = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u(es - e)}{\Delta + \gamma(1 + 0.34u)}, \qquad (1)$$

where Rn is the net radiation at the surface $(MJ.m^{-2}.day^{-1})$, G is the heat flux into the subsurface in $(MJ.m^{-2}.day^{-1})$, e and e_S are respectively the actual and saturated vapor pressure $(kPa.K^{-1})$, u is the wind speed at 2 m $(m.s^{-1})$, T is the air temperature at 2 m (K), Δ is the slope of the relationship between saturation vapor pressure and temperature $(kPa.K^{-1})$ and γ is the psychrometric constant $(kPa.K^{-1})$. Rn is calculated as:

$$Rn = Rs(1 - \alpha) + Rnl\,, \qquad (2)$$

where Rs is the incoming solar radiation $(MJ.m^{-2}.day^{-1})$, α is the surface albedo of the reference crop ($\alpha = 0.23$), and Rnl is the net longwave radiation $(MJ.m^{-2}.day^{-1})$. Briefly, we computed equations (1) and (2) based on the procedure described in Zotarelli et al., (2009). All atmospheric inputs were obtained from the North American Land Data Assimilation System phase 2 (NLDAS-2), Xia et al., (2012).

2.2. The Budyko Framework and Seasonality.

At sufficiently long timescales, the interannual changes in storage can be negligible, allowing us to write the long-term water balance as:

$$P = Q + E, \qquad (3)$$

where Q is the mean annual streamflow (mm). Budyko (1974) proposed an analytical solution for the above equation, based on the physical reasoning that at very humid sites ($\phi \to 0$) the evaporative fraction must tend to zero ($E/P \to 0$), while at very arid sites ($\phi \to \infty$), E/P should tend to 1:

$$E/P = \sqrt{\phi \tanh(\phi)\,(1 - \exp(-\phi))}. \qquad (4)$$

In this study, we define both E/P and ϕ in terms of mean monthly values, i.e., ϕ as the ratio of mean monthly potential evapotranspiration to precipitation ($\phi = \overline{PET}/\bar{P}$) and the evaporative fraction as $\bar{E}/\bar{P}$. This modification brings no mathematical change in the values of the computed variables, since both numerators and denominators are simply being divided by 12.

Several methods for quantifying seasonality exist in the literature, with metrics considering only the progression of monthly values of precipitation throughout the year (Markham, 1970; Walsh & Lawler, 1981), as well as methods considering monthly marches of both P and PET (Milly, 1994; Woods, 2009; Feng et al., 2013; Feng et al., 2019). A common way to represent the seasonal (monthly) progression of P and PET is achieved using sinusoidal functions (Milly, 1994; Woods, 2009; Yokoo et al., 2008):

$$P(t) = \bar{P}\left[1 + \delta_P \sin\left(\frac{2\pi(t - s_P)}{12}\right)\right]; \quad (5)$$

$$PET(t) = \overline{PET}\left[1 + \delta_{PET} \sin\left(\frac{2\pi(t - s_{PET})}{12}\right)\right], \qquad (6)$$

where t is the time (months), δ_P and δ_{PET} are normalized (dimensionless) seasonal amplitudes, and s_P and s_{PET} are phase shifts (in months). The seasonality metric chosen for this study following Woods (2009) uses the sinusoidal approximations to quantify the extent to which the seasonal cycles of precipitation and PET are in-phase or out-of-phase:

$$SI = \delta_P sgn(\delta_{PET})\, cos\left(\frac{2\pi(s_P - s_{PET})}{12}\right). \, (7)$$

SI values range from -1 for a strong off-phase climate, with predominant winter precipitation, 0 for precipitation uniformly distributed throughout the year, and +1 for a strong in-phase seasonality, or with predominant summer precipitation. **Figure S2** presents the geographical distribution of SI values for the selected US catchments.

Figure 2a displays the selected US catchments within the Budyko space, where the catchments are labelled with respect to their SI values, along with the Budyko curve (equation 4). The effects of seasonality on the location of a catchment within the $\phi - E/P$ space as suggested from previous studies seem to be supported by visual inspection of **Figure 2a**. A more rigorous assessment of such a pattern is shown in **Figure 2b**, in which the deviations from the Budyko curve ($\Delta_{E/P}$), computed as the difference between the observed evaporative fractions $\left(\frac{E}{P}\right)_{obs}$ and the evaporative fractions predicted by equation (4), $\left(\frac{E}{P}\right)_{Budyko}$, are shown to be significantly correlated with SI (correlation coefficient r = 0.65, p = 10^{-30}-3). This significant positive correlation supports the hypothesis that catchments under in-phase climates tend to have higher evaporation rates and less runoff ($\Delta_{E/P}$>0, or a general tendency to be located above the Budyko's curve), with catchments under off-phase climates suggesting the opposite lower E/P or, $\Delta_{E/P} > 0$ and a tendency to be located below Budyko's curve).

We also show in **Figure 2c** and **Figure 2d**, the predictability of the Budyko equation (equation (4)) with respect to the evaporative fraction and the long-term streamflow, which will be used later in this manuscript for comparison. The performances shown here exemplify the ability of the Budyko equation to explain the spatial variability of the long-term water balance partitioning for the selected US catchments.

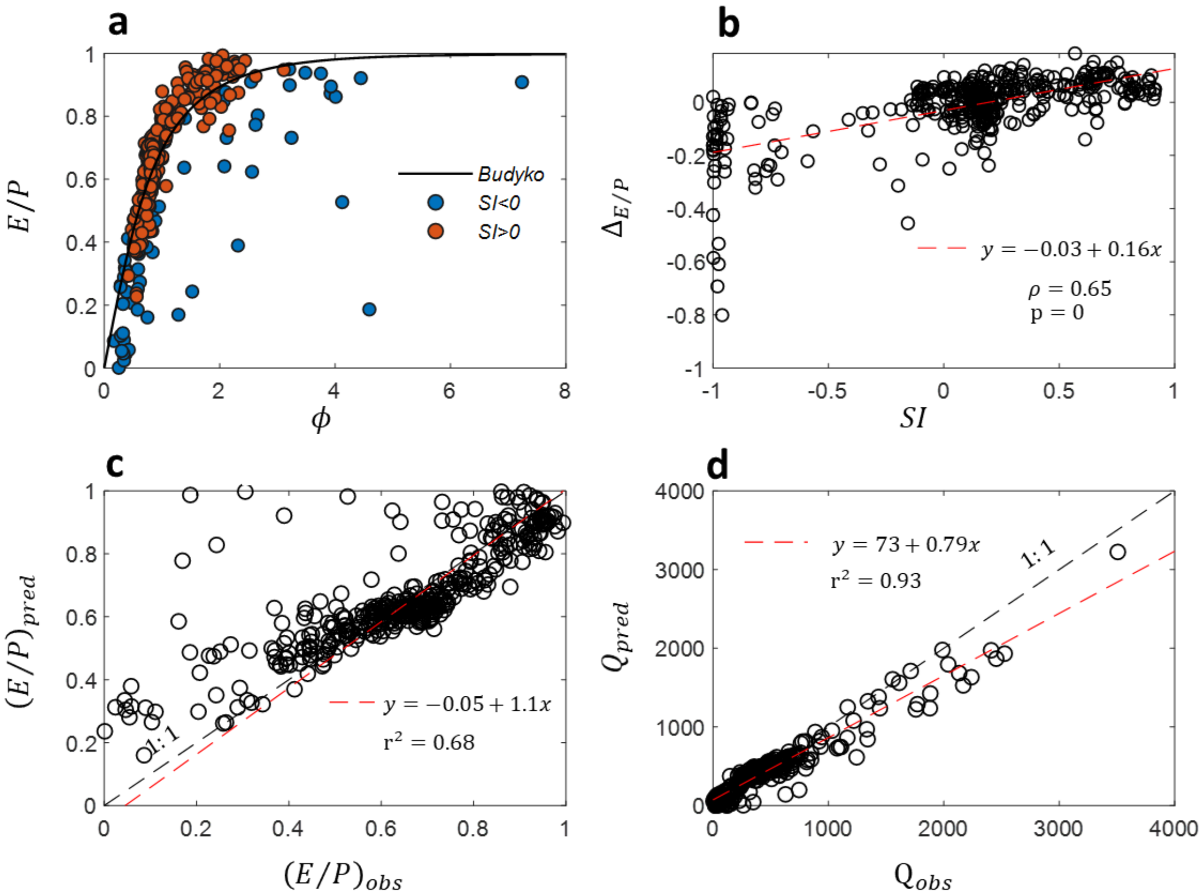

Figure 2. Effects of seasonality on water partitioning through the Budyko Framework. (a) Location of the 328 selected US catchments within the $\phi - E/P$ space labeled with SI<0 (blue dots) and SI>0 (red). (b) Systematic deviation ($\Delta_{E/P}$) from the Budyko curve associated with, SI, showing that catchments with off-phase climates (SI<0) tend to have lower E/P rates $\Delta_{E/P}$<0), whereas catchments with in-phase climates tend to have higher E/P ($\Delta_{E/P}$>0). (c) Predicted E/P ratio by the Budyko equation versus the observed. (d) Predicted mean annual streamflow by the Budyko equation versus the observed. SI = seasonality index (equation (7)).

2.3. Revisiting the Budyko framework

2.3.1. Hypothesis 1: Aridity, Seasonality, and Water Availability

The aridity index can be understood as a representation of the competition between the atmospheric water demand versus the surface water availability (or supply). By making this assumption more explicit, we can instead re-write the aridity index in terms of monthly averages as:

$$\phi' = \frac{[PET]}{[A]}, \quad (8)$$

where $[A]$ represents the mean monthly water availability, in mm, in place of $[P]$, which is commonly used as an *approximation* of $[A]$. We will attempt to better define [A] in the following paragraphs considering an evidence-derived formulation. Let us now assume the Budyko equation to be the *representation* of the relationship between and $\frac{E}{P}$ and the "actual" aridity index ϕ', i.e., equation (8).

The previous assumption allows us to hypothesize of the systematic deviations with respect to seasonality as follows: Catchments with in-phase seasonality ($SI > 0$) are located above the Budyko curve, allowing us to infer that their water availability is *lower* than the mean precipitation, i.e., that $[A] < [P]$. Thus, a proper estimate of $[A]$ would lead to $\phi' > \phi$, meaning that their position in the Budyko space would shift to the right, thus closer to the Budyko curve. On the other hand, the fact that catchments with $SI < 0$ are generally located below the curve lets us infer that their water availability is *higher* than the mean precipitation, meaning, i.e., that $[A] > [P]$ and $\phi' < \phi$, which would also bring that catchment closer to the Budyko curve. Finally, for catchments with little or no seasonality ($SI = 0$), the water availability can be taken as equivalent to mean precipitation, i.e., that $[A] = [P]$, and in this case, aridity is properly estimated.

The hypothesis outlined above makes the following relationship clear:

$$[A] = [P] + \Delta_A, (9)$$

where Δ_A (in mm) appears as a term quantifying the deficit or surplus between the actual water availability, $[A]$, and $[P]$. The previous explanation also leads to:

$$\text{when } SI > 0: \quad [A] < [P] \text{ and } \Delta_A < 0, (10a)$$

$$\text{when } SI < 0: \quad [A] > [P] \text{ and } \Delta_A > 0, \qquad (10b)$$

$$\text{when } SI = 0: \quad [A] = [P] \text{ and } \Delta_A = 0., (10c)$$

Which suggests Δ_A to be a function of seasonality:

$$\Delta_A = f(SI). (11)$$

2.3.2. Hypothesis 2: Budyko's implicit assumption.

How can we estimate Δ_A, and therefore $[A]$? The systematic deviations with respect to seasonality also allows the formulation of an additional hypothesis regarding the Budyko framework: *the Budyko equation represents catchments where precipitation is uniform throughout the year*. And this is straightforward to conclude, since catchments with uniform P fall closer to the curve, while others with seasonal climates do not. We will explore this hypothesis by further expanding on some of its implications. Since such catchments follow the Budyko curve, the following must hold:

$$If\ P \approx uniform, \quad [A] = [P], (12)$$

and

$$\phi' = \frac{[PET]}{[A]} = \frac{[PET]}{[P]} = \left[\frac{PET}{P}\right], (13)$$

Equation (12) suggests that $[A]$ can be approximated by $[P]$ only P is uniform, while equation (13) brings a consequence of equation 12 for the aridity index. Combined, *equations (12) and (13) represent the revised Budyko framework in terms of aridity*. Following equation (13), an additional relationship, obtained from applying the Reynolds decomposition of the humidity indices can be explored to derive meaningful representations of $[A]$:

$$\left[\frac{P}{PET}\right] = [P].\left[\frac{1}{PET}\right] + cov\left(P, \frac{1}{PET}\right) (14)$$

By taking $[A] = [P]$ on the r.h.s of equations 14 (see equation (12)), and eliminating the covariance term (i.e. assuming P = uniform), one arrives at a possible formulation for $[A]$:

$$[A] = \frac{\left[\frac{P}{PET}\right]}{\left[\frac{1}{PET}\right]} \qquad (15)$$

2.3.3. Exploring the Links Between Seasonality and Water Availability

A more in-depth assessment of equation (15) provided here. A simple way of computing $[A]$ arises from equation (15) as:

$$[A] = \frac{\sum \overline{P_\iota} \cdot {}^{1}/_{\overline{PET_\iota}}}{\sum {}^{1}/_{\overline{PET_\iota}}} \qquad (16)$$

where P_i and PET_i are multi-year mean monthly values of P and PET at each month (12 values each). Equation (16) means that that the average water availability is computed as the weighted average of monthly precipitation, in which the weights are represented by the inverse of the monthly PET values. On one hand, the water availability is directly proportional to $\overline{P_\iota}$, as it has been normally treated in traditional formulations of aridity, but the inverse proportionality suggests additionally that increasing values of $\overline{PET_\iota}$ lead to lower values of $[A]$. Equation (16) makes it explicit how the water availability term is computed as an interaction between P and PET, and not a single function of precipitation. Based on equation (16), a formulation for Δ_A and $[A]$ arise as:

$$\Delta_A = [A] - [P] = \frac{\sum \Delta_{\overline{P_\iota}} \cdot {}^{1}/_{\overline{PET_\iota}}}{\sum {}^{1}/_{\overline{PET_\iota}}} \qquad (17)$$

$$[A] = [P] + \frac{\sum \Delta_{\overline{P_\iota}} \cdot {}^{1}/_{\overline{PET_\iota}}}{\sum {}^{1}/_{\overline{PET_\iota}}} \qquad (18)$$

In which, $\Delta_{\overline{P_\iota}}$ is the departure of the mean precipitation at a given month, from the mean monthly precipitation value of all months, or:

$$\Delta_{P_i} = \overline{P_\iota} - [P], \qquad (19)$$

In short, equation 17 shows us that Δ_A represents the weighted average of the precipitation departures from uniformity, in which the weights are represented by the inverse monthly PET values. Most importantly, equation 17 helps us define the water availability as shown in equation

18, in which $[A]$ is shown to be a combination of $[P]$ and Δ_A: For uniform precipitation patterns, i.e. a non-seasonal march of monthly precipitation values, Δ_A will approach 0, bringing the equality $[A] = [P]$, the case in which the availability is correctly estimated as the mean precipitation, thus conforming to the revised assumption about the Budyko equation, as previously shown.

In the next sections we will test equation (15) and explore its properties with the use of empirical data from US catchments.

3. Results

3.1. Water availability and seasonality.

The results of the formulation of $[A]$ can be seen in **Figure3a,** where we compare normalized values of Δ_A with respect to $[A]$. The figure shows how equation (17) adequately follows the rationale on how $[A]$ and seasonality are linked, explained in 2.3.1. Therefore, the results shown in sequence will refer to $[A] = \left[\frac{P}{PET}\right] / \left[\frac{1}{PET}\right]$. **Figure3a** also shows an almost direct translation between the two variables, providing an additional (quantitative) interpretation for the *SI* and it's relationship with deficit of surplus in water availability. On **Figure3b**, we can see how the aridity values of the selected catchments change (as $\Delta_\phi(\%) = 100 \times \frac{(\phi' - \phi)}{\phi}$) with respect $\Delta_A / [P]$ values. The percent changes in aridity range from approximately -50% to almost 160% for the selected catchments when ϕ' is used. The geographical distribution of such changes for the selected US catchments is shown in **Figure S3**.

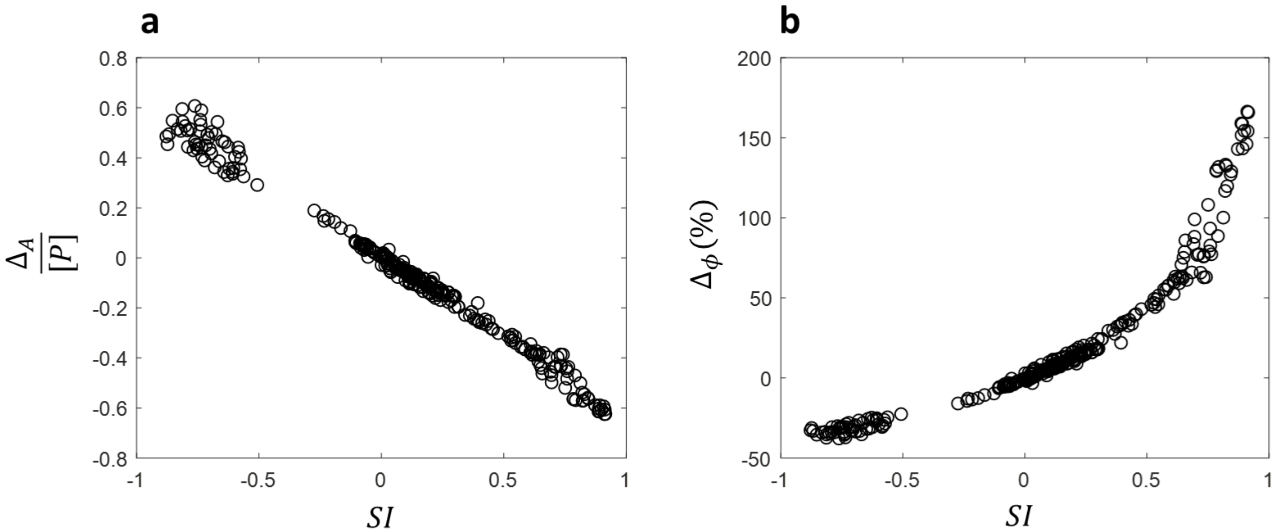

Figure 3. (a) Comparison between the normalized water availability correction $\frac{\Delta_A}{[P]}$ versus SI. The Seasonality Index (SI) indicates a linear relationship between $\frac{\Delta_A}{[P]}$ and SI, thus confirming $\frac{\Delta_A}{[P]}$ as a seasonality metric in itself. (b) Correction to aridity index ($\Delta_\phi(\%) = 100 \times \frac{(\phi' - \phi)}{\phi}$).

3.2. Performance of the Budyko equation when using ϕ'

The results of the assumptions discussed above into the calculation of the aridity index and its implications on the long-term water balance, as per the Budyko framework, are shown in **Figure 3**, which repeats the same plots as in **Figure 2**, however with the aridity index estimated as ϕ'. It is possible to see from **Figure 4a** that the adoption of the formulation of ϕ' leads to an overall better agreement of the cloud of points with respect to the Budyko curve. The once significant relationship between observed and estimated evaporative fractions shown in **Figure 2b** is not anymore detected when ϕ' is used, showing that seasonality has been included in its formulation. Finally, the performance metrics shown in **Figure 4c** and **d** indicate that the use of ϕ' leads to a higher explanatory power of the long-term water balance partitioning over the US catchments, in terms of both observed and predicted evaporative ratios (**Figure 4c**) as well as streamflow (**Figure 4d**).

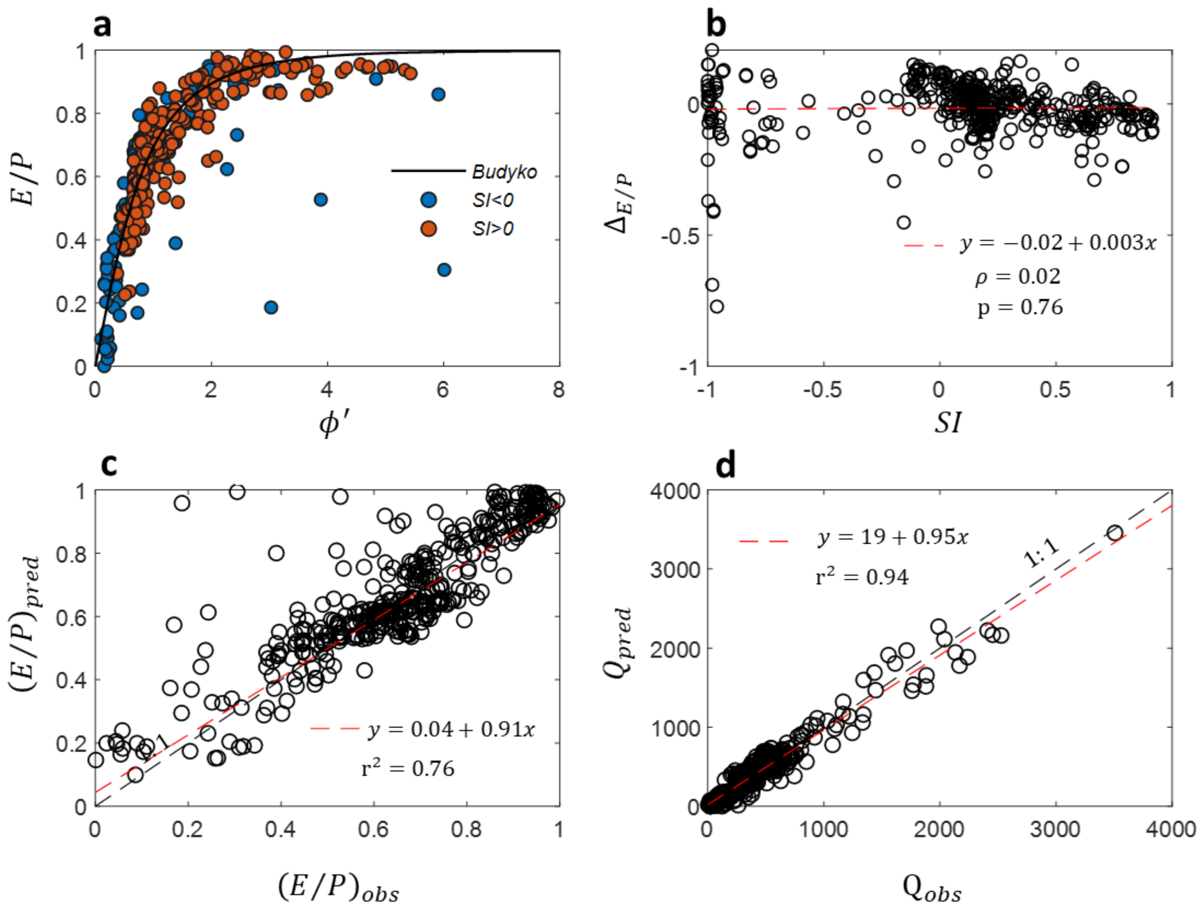

Figure 4. Revised Budyko Framework through incorporation of seasonality into the calculation of the aridity index, ϕ'. (a) Location of the selected US catchments within the Budyko space, (b) deviation from the Budyko curve associated with seasonality index, (c) the predicted (Budyko equation) versus observed E/P ratios. d – Predicted (Budyko equation) versus observed mean annual streamflow.

4. Discussion

4.1. Overall merit of this work

This study presents a straightforward approach to incorporating the effects of seasonality (based on mean monthly water marches of P and PET) on the long-term balance through the Budyko framework. By revising the assumptions behind the reason why catchments with distinct seasonality patterns fall far from the Budyko curve, we were able to arrive at a formulation for aridity that incorporates the effects of long-term seasonality.

It is important to emphasize that our approach does not lead to different conclusions with respect to the net effects of seasonality on the long-term fluxes as our results conform with most of what other authors have found so far, i.e. in phase seasonality favors E over P, while off-phase seasonality tend to yield the opposite (Milly., 1994a; Milly., 1994b; Yokoo et al., 2008; Gerrits et al., 2009; Berghuijs et al., 2014; Beck et al., 2015; Tang and Wang., 2017). However, we have provided a simple method that does not require site-specific calibration of specific Budyko-type equation (Shao et al., 2012; Abatzoglou and Ficklin, 2017) or asks for the explicit knowledge of spatial distribution of storage capacity and its spatial variability, among other catchment physical properties (Milly., 1994a; Milly., 1994b; Yokoo et al., 2008).

A clear distinction made here is the differentiation between the previously assumed denominator of the aridity index, taken as the average precipitation $[P]$, versus the newly proposed expression for water availability (equation 15). We have shown that (at the mean monthly timescale) $[A]$ can be larger or smaller than $[P]$, which points out that at timescales finer than annual, monthly precipitation is not a good approximation for water availability, since that at such timescales the interactions between P and PET cannot be ignored. This allows to conceptually define water availability (and aridity) as a *coupled land-atmosphere process*.

4.2. The role of storage on water availability.

The inclusion of seasonality in the long-term water balance has traditionally led to incorporation of storage in its formulations (Milly et al., 1994a, Milly et al., 1994b, Hickel and Zhang, 2006; Chen et al., 2013), whereas our results appear as a climate-only approach arising from empirical reasoning on the deviations from the Budyko curve. While that the main mechanism allowing for the intra-annual variability of water availability can only be explained by the existence of storage/release mechanisms and carryover of moisture between months, our climate-driven water availability term should to some extent reflect storage properties and processes. In this way, our findings can be taken as reflecting the co-evolution between ecosystems and climate at natural catchments, suggesting that storage capacity and its variability should be connected to the long-term climate. Such link between long term aridity (as $[PET]/[P]$), seasonality and storage properties in natural catchments has indeed been suggested in the literature for explaining catchment-scale root zone storage capacity (Gao et al., 2014) and rooting distance (Gentine et al., 2012).

Alongside with most studies on the role of seasonality and the long-term water balance, our results differ from Potter et al., 2005, who found higher runoff values in summer dominated rainfall regions in Australia. Such disagreement does not invalidate out findings but asks for an in-depth assessment of the processes taking place. We believe Australian catchments might be subject to two competing processes, i.e. the within year variation of atmospheric supply and demand versus the occurrence of intense rainfall events, triggering fast stormflow, while our work only suggests an approach for one of them. We believe therefore that the observed quick flow production during summer months might be surpassing the water availability dynamics suggested here. The investigation of how our framework can potentially shed light to the results of Potter et al., (2005) might be worth pursuing in the future, where a similar approach as presented here could be envisioned with a shift from monthly to daily timescales in order for finer timescale processes to be captured.

4.3. Implications for the aridity-seasonality index

A combined aridity-seasonality index has the advantage of reducing the dimensionality of how the long-term climate is described into a single variable. We have shown that the use of such variable improves our ability to describe the geographical (between-catchment) distribution of the water balance partitioning, thus conferring a higher explanatory power to the Budyko framework and also pointing out to a means towards the inclusion of factors beyond the means of $[P]$ and $[PET]$ in its formulation, as it has been recently asked for in the scientific community (Berghuijs et al., 2020).

We should also remind that in its essence, what confers a practical meaning to the definition of the aridity index is its explanatory capacity over the partitioning of land-surface water fluxes. Thus, our approach is also advantageous in that it provides a more valuable formulation of aridity, as seen by its enhanced explanatory power of both E/P as well as Q (**Figure 4**). An improved definition of aridity has implications beyond the Budyko framework, as many studies have used it to assess impacts of future climate change scenarios on the terrestrial water balance (Wang et al., 2014; Huang et al., 2016; Huang et al., 2017). While many studies also advocate for the use of different measures from aridity for climate change impact estimation (Berg and McColl, 2021), citing among other factors its uncoupled nature between land-surface and atmosphere (Greve et al., 2019), our work might provide a means toward an improved representation of terrestrial aridity through a simple climate-based index.

4.4. Linking mean and intra-annual climatic variations to the long-term water balance.

An interesting implication of our work is related to how processes at different timescales affect the long-term water balance. Our results provide a simpler counterpoint to a more modelling-intensive strategies such as the work of Yao et al., (2020) who have used a (calibrated) conceptual rainfall-runoff model to arrive at the conclusion that aside from its mean conditions, the intra-annual climatic variability is the main controlling timescale on the long-term water balance. We have shown how the aridity index encapsulates not only the average competition between PET and P but their mean intra-annual variability, as equation 18 provides a formulation in that the average water availability (and the aridity) can be decomposed into a long-term and a seasonal component.

5. Summary and Conclusions

This work proposed a strategy on how climate seasonality can be incorporated into a widely used long-term water balance formulation, the Budyko framework. Two hypotheses were investigated. The first hypothesis defines the denominator of the aridity index as the water availability term and provides a rationale for interpreting the deviations from the Budyko curve with respect to climate seasonality. The second hypothesis is that the Budyko curve represents catchments with uniform monthly marches of P, which we used to arrive at a mathematical definition of water availability. We have shown that the water availability term is a function of mean precipitation and seasonality, and that its use improves the explanatory power of the Budyko equation for the geographical distribution of the land-surface water balance partitioning.

Our results are in line with other investigations with respect to the impacts of seasonality on the long-term water balance but provide a simpler formulation, in which no knowledge of land-surface properties (storage related features of the landscape) is needed, and no site-specific calibration of parametric Budyko equations are necessary to incorporate the effects of seasonality. The absence of storage related properties in our formulation suggests an intrinsic relationship between climates and their underlying storage capacity/properties as it has been suggested by other investigations. Our investigation simply hints on such linkage, as an in-depth analysis on how this such interconnections operate should be subjected to a different kind of analysis.

While the aridity-seasonality index proposed here provides a better understanding of water balance partitioning across the continental USA, its use could be promoted for assessments of aridity and possibly as a tool to investigate climate-change impacts from global models.

Our results also represent a useful strategy for incorporation of additional controlling factors into the Budyko framework, as it has been asked for in the hydrologic community. Finally, aside from suggesting a useful catchment-scale water balance framework, this paper highlights how phenomena occurring at different timescales (intra-annual and average climate conditions) might be combined in a simple yet meaningful way.

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Water Resources Research

Supporting Information for

Impacts of Climate Seasonality on Water Availability and Long-Term Water Balance – A Aridity-Seasonality Index (ASI)

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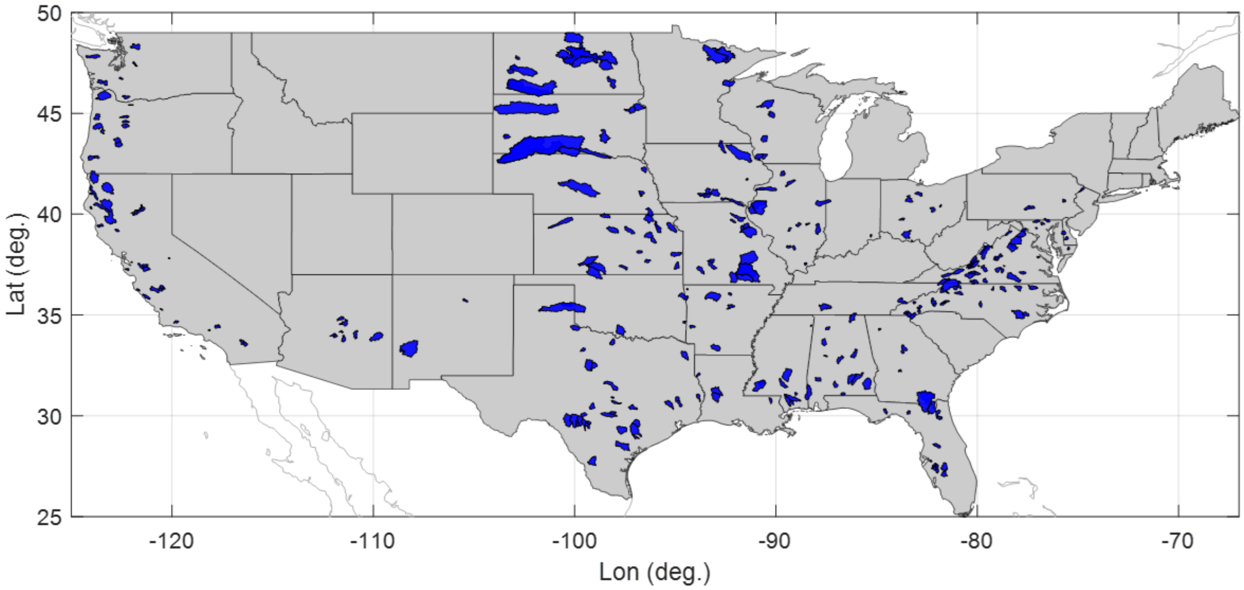

Figure S1. Location of the 328 CAMELS catchments used in this study.

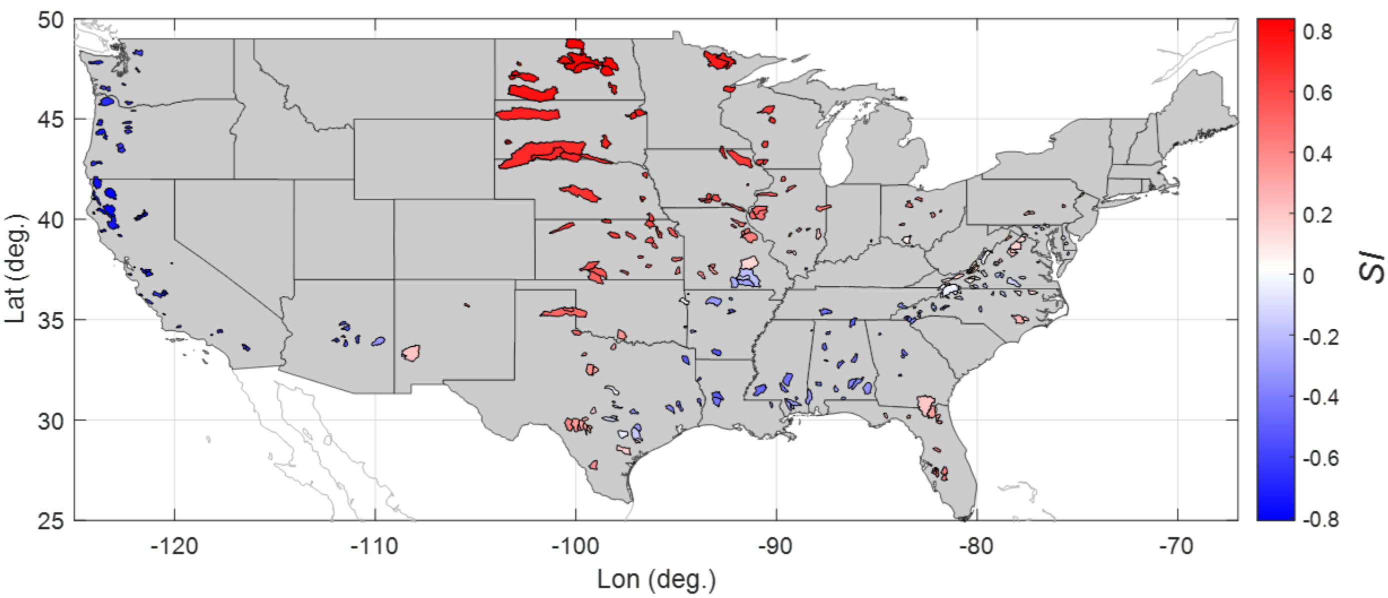

Figure S2. Selected catchments color-labeled according to the Seasonality Index (SI), from Woods et al., (2009).

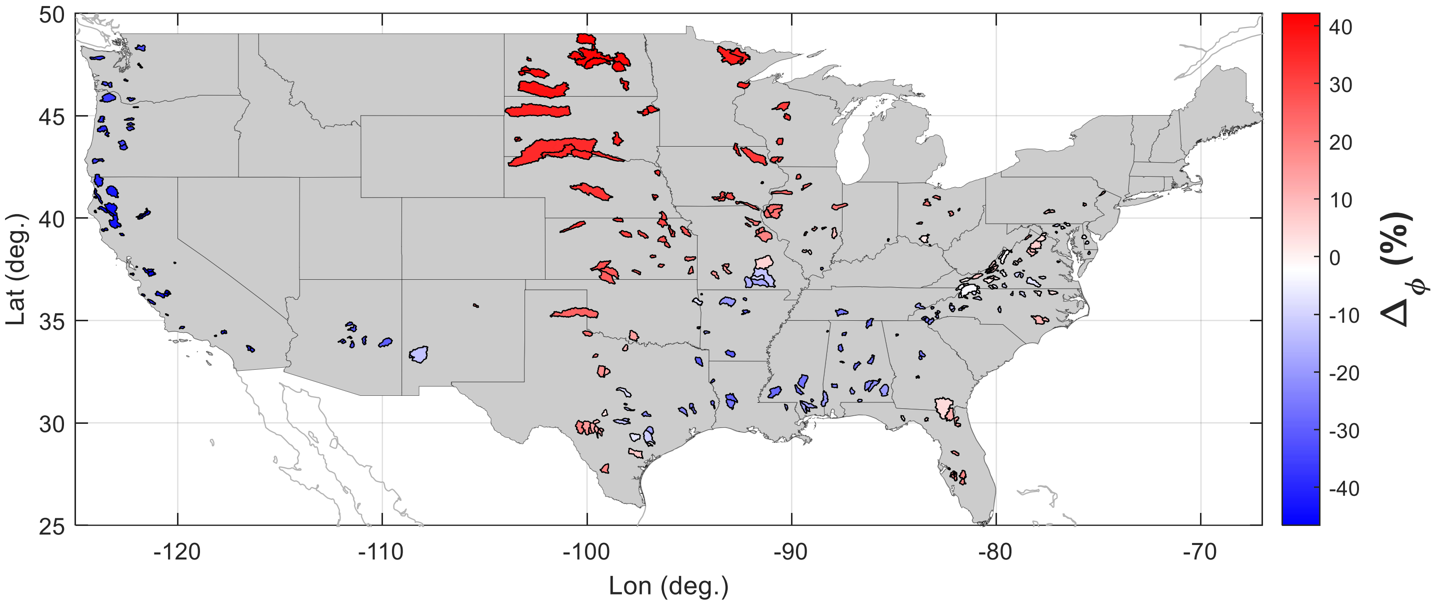

Figure S3. Selected catchments color-labeled according to the percent difference between two aridity indices, $\boldsymbol{\Delta_\phi}(\%) = \mathbf{100} \times \frac{(\boldsymbol{\phi'} - \boldsymbol{\phi})}{\boldsymbol{\phi}}$.