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

Antônio Alves Meira Neto[1]*, Guo-Yue Niu[1]

[1]University of Arizona, Department of Hydrology and Atmospheric Sciences

*Corresponding author: aamneto@email.arizona.edu

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.

19 **ABSTRACT**

20 This study investigates the impacts of climate seasonality, i.e., the seasonal cycle of precipitation

21 (P) relative to that of potential evaporation (PET), on surface water supply and the long-term water

22 partitioning and proposes an augmented aridity index considering climate seasonality in addition

23 to climatic mean. Evaporation tends to be favored over streamflow at long-term timescales when

24 both cycles occur in tandem (in-phase seasonality), while the opposite occurs (less evaporation,

25 more streamflow) when the two cycles are out-of-phase. We propose a straightforward approach

26 to incorporating the seasonality effects on the mean annual water balance into the Budyko

27 framework, by revising the water availability (A) in the formulation of the aridity index (ϕ). We

28 hypothesize the Budyko curve represents catchments with uniform monthly values of P, leading

29 to a mathematical formulation of A that better represents the coupled, land-atmosphere nature of

30 the water availability. Our results also provide a simple mathematical framework for incorporating

31 the seasonality into the aridity index, thus reducing the dimensionality of the long-term water

32 balance problem through an aridity-seasonality index (ϕ'). The formulation used here was able to

33 improve the explanatory power of the Budyko framework for 328 catchments within the

34 continental US, being proved as a useful strategy for the incorporating climate variations into its

35 formulation in addition to climatic mean.

36

1. Introduction

37

38 Climate seasonality (or simply seasonality) refers to how the seasonal cycles of precipitation and

39 potential evaporation (PET), which is controlled by radiation, temperature, humidity, and wind

40 speed, are related to each other. An "in-phase" seasonality refers to a climate when precipitation

41 falls in the boreal summer and thus in phase with PET, while an "out-of-phase" refers to when

42 precipitation falls in the boreal winter (Hickel and Zhang, 2006; Yokoo et al., 2008; Potter et al.,

43 2005; Yao et al., 2020). Seasonality influences not only the water balance at shorter, intra-annual

44 timescales but also the long-term fluxes of streamflow and evapotranspiration (Budyko 1974;

45 Milly, 1994a; Milly 1994b; Potter et al., 2005; Berghuijs et al., 2014; Padron et al., 2017; Yao et

46 al., 2020). Additionally, the interest in seasonality and its controls on the water balance go beyond

47 improving our ability to explain the spatial differences in how freshwater resources are distributed,

48 as shifts in seasonality have been reported to be both currently occurring (Feng et al., 2013) as well

49 as associated with future climate scenarios (Konapala et al., 2020; Montaldo and Oren, 2018).

50 How does seasonality affect the mean annual water balance? In a broader sense, most hydrologists

51 would regard this as a quite straightforward question. By using a terminology that will be followed

52 along this manuscript, it can be argued that the monthly march of potential evaporation (or

53 evapotranspiration) represents how the atmospheric demand to evaporate the water available at the

54 land surface progresses throughout the year. On the other hand, the monthly march of precipitation

55 would resemble that of the water available for evaporation. Thus, for climates in which both cycles

56 occur in tandem (or in-phase), evaporation would be relatively favored over infiltration (and

57 ultimately streamflow generation) while for climates where both cycles are offset (or off-phase),

58 a lower atmospheric demand would be present during the months with higher surface water

59 availability, leading, therefore, to more water being infiltrated and consequently being released

60 into the streams.

61 Many studies on the impacts of seasonality versus climate mean on the long-term water balance

62 have confirmed this simple explanation both theoretically via models (Milly, 1994a; Milly, 1994b;

63 Woods, 2003; Potter et al., 2005; Yokoo et al., 2008; Gerrits et al., 2009) and through empirical

64 evidence associated or not with modelling efforts (Hickel and Zhang, 2006; Berghuijs et al., 2014;

65 Beck et al., 2015; Tang and Wang, 2017). Most authors agree that the mechanisms mediating the

66 effects of seasonality on the long-term water balance are associated with the soil storage capacity

67 and its spatial variability, making it necessary to incorporate the knowledge of soil storage capacity

68 for a meaningful representation of the long-term water balance across catchments. There seems,

69 however, to be exceptions for the rationale above. Potter et al., (2005) suggests that for catchments

70 with significantly lower soil moisture capacity, higher (mainly infiltration-excess) runoff rates

71 would still occur for in-phase climates, as seen in Australian catchments.

72 The Budyko (1974) framework (or hypothesis) is arguably the most widely used analytical tool

73 for investigating the mean annual water balance. In it, the long-term water balance partitioning,

74 represented as the ratio of mean annual evapotranspiration over the mean annual precipitation

75 (E/P), is considered to be solely a function of climate aridity ϕ, which conceptually represents

76 the competition between atmospheric water demand and water availability, and is written as the

77 ratio of the mean annual potential evaporation to precipitation ($\phi = PET/P$). The Budyko

78 framework has received in the last decades a great deal of attention due to its empirical nature and

79 mathematical simplicity (Berghuijs et al., 2020), with applications ranging from prediction of

80 water fluxes in ungauged basins (Bloeschl et al., 2013), global-scale assessments of water

81 availability under climate change scenarios (Milly and Dunne, 2016; Yang et al., 2019), and

82 investigations on how other factors aside from aridity control the long-term water balance

83 (Donohue et al., 2012; Berghuijs et al., 2014; Abatzoglou and Ficklin, 2017; Padrón et al., 2017).

84 The effects of secondary climatic and landscape factors on the long-term water balance can be

85 seen through the existence of systematic deviation from the Budyko curve (Berghuijs et al 2020).

86 **Figure 1** illustrates the systematic deviations for the case of seasonality: a catchment with in-phase

87 seasonality is assumed to be plotted above the empirical Budyko curve, meaning its evaporative

88 fraction (E/P) is higher than expected, whereas catchments with off-phase seasonality are plotted

89 below the curve, meaning that less water is evaporated into the atmosphere.

90 The uses of the Budyko framework in exploring the role of seasonality are diverse (Milly., 1994;

91 Sankarasubramanian and Vogel, 2001; Potter et al., 2005; Hickel and Zhang., 2006; Yokoo et al.,

92 2008; Shao et al., 2012; Fu and Wang, 2019). On one hand, hydrologic model outputs can be

93 investigated in the $\phi - E/P$ space, by casting their modeling results as "Budyko-like" curves

94 (Milly, 1994; Yokoo et al., 2008; Gerrits et al., 2009; Tang and Wang., 2017). For instance, Milly

95 (1994) developed an analytical bucket-type soil-water model, showing how off-phase seasonality

96 tends to increase runoff. Yokoo et al., (2008) uses a lumped, physically based model, arriving at

97   similar conclusions as in Milly (1994). A strategy that has received much attention consists of

98   improving the explanatory power of the Budyko hypothesis by fitting parametric versions of the

99   Budyko equation to additional factors, which often include some measures of seasonality (Shao et

100 al., 2012; Abatzoglou and Ficklin, 2017). While complex models that reproduce the shape of the

101 Budyko curve might shed light on the underlying mechanisms controlling the mean annual water

102 balance, the multitude of modelling assumptions together with their parameterizations limits their

103 use and universality. Alternatively, parameterized Budyko-type equations cannot be used at

104 ungaged basins and fail in providing the necessary understanding as to why those factors play such

105 roles (Berghuijs et al., 2020).

106 This paper proposes a way forward to incorporate climatic seasonality into the Budyko framework

107 with no need of parameterization. We pose a novel hypothesis within the Budyko framework and

108 explore its implications through a revised aridity index. The aridity-seasonality index (ASI)

109 accounts for the effects of long-term means and seasonality of P and PET, thus reducing the

110 dimensionality of the long-term water balance problem through the Budyko framework and

111 providing a higher explanatory power over long-term evaporation and runoff partitioning.

112 Additionally, this revised index leads to a redefinition of the concept of water supply/availability

113 within the Budyko framework. We used observations from 328 catchments distributed within the

114 conterminous United States. This paper is organized as follows: *First*, we briefly introduce the

115 catchment dataset and some quality control criteria leading to the final catchment selection, along

116 with some basic computations. *Second*, we provide a formal introduction to the long-term water

117 balance and the Budyko framework, as well as a metric of seasonality. *Third*, we revise the

118 seasonality issue through the Budyko equation by investigating an alternative hypothesis about its

119 origin that leads to alternative formulation of the aridity index. *Fourth*, an assessment of the

120 implications of the proposed changes is shown. *Last,* we discuss the meaning of the implemented
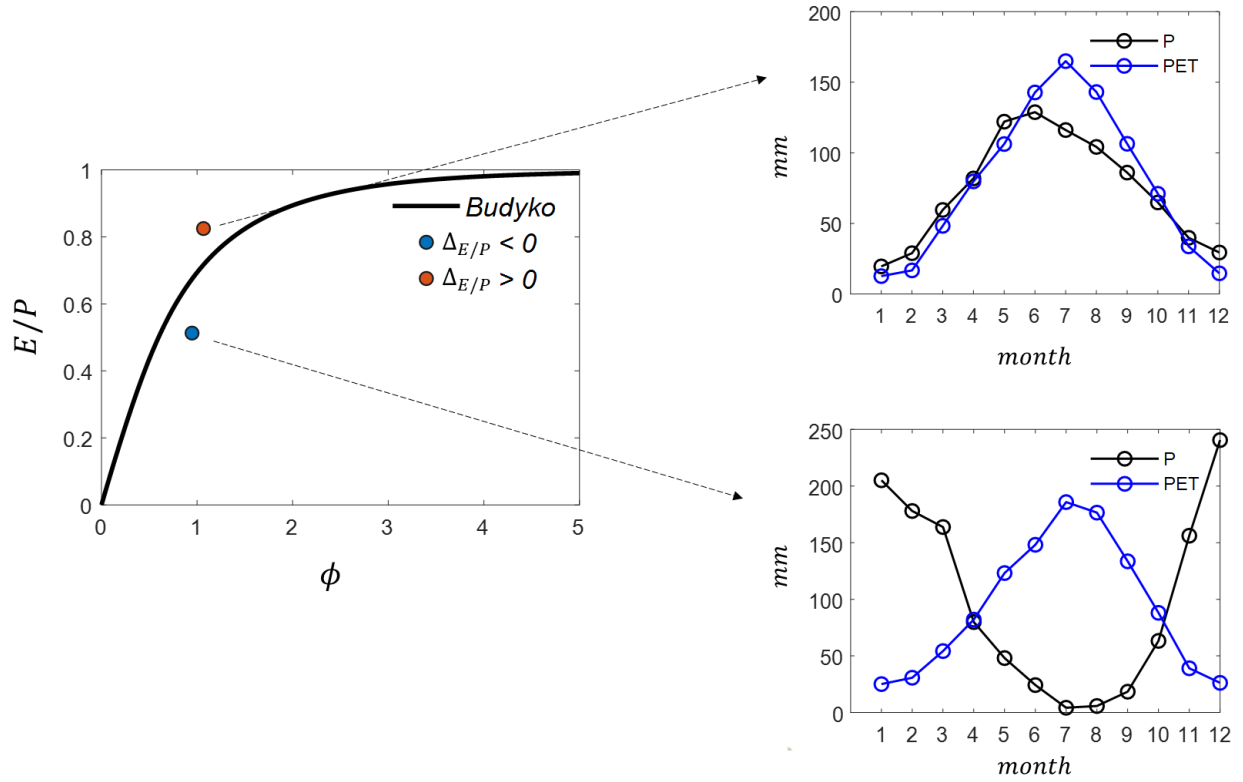
121 changes.

122

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. $\Delta_{E/P}$ represents the deviation between observed E/P versus Budyko's predicted values.

127

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

137   higher than 30%, and (iv) catchments with area smaller than 20 km². The resulting subset

138   contained 328 catchments (**Figure S1)**.

139   We used the Reference-crop Penman-Monteith formulation for calculating daily values of PET

140   (in mm) as:

141

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

143

144   where Rn is the net radiation at the surface $(MJ.m^{-2}.day^{-1})$, G is the heat flux into the

145   subsurface in $(MJ.m^{-2}.day^{-1})$, e and e_S are respectively the actual and saturated vapor pressure

146    $(kPa.K^{-1})$, u is the wind speed at 2 m $(m.s^{-1})$, T is the air temperature at 2 m (K), Δ is the slope

147   of the relationship between saturation vapor pressure and temperature $(kPa.K^{-1})$ and γ is the

148   psychrometric constant $(kPa.K^{-1})$. Rn is calculated as:

149

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

151

152   where Rs is the incoming solar radiation $(MJ.m^{-2}.day^{-1})$, α is the surface albedo of the

153   reference crop $(\alpha = 0.23)$, and Rnl is the net longwave radiation $(MJ.m^{-2}.day^{-1})$. Briefly, we

154   computed equations (1) and (2) based on the procedure described in Zotarelli et al., (2009). All

155   atmospheric inputs were obtained from the North American Land Data Assimilation System phase

156   2 (NLDAS-2), Xia et al., (2012).

157

158   **2.2. The Budyko Framework and Seasonality.**

159   At sufficiently long timescales, the interannual changes in storage can be negligible, allowing us

160   to write the long-term water balance as:

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

162   where Q is the mean annual streamflow (mm). Budyko (1974) proposed an analytical solution for

163   the above equation, based on the physical reasoning that at very humid sites $(\phi \to 0)$ the

164 evaporative fraction must tend to zero ($E/P \rightarrow 0$), while at very arid sites ($\phi \rightarrow \infty$), E/P should

165 tend to 1:

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

167 In this study, we define both E/P and ϕ in terms of mean monthly values, i.e., ϕ as the ratio of

168 mean monthly potential evapotranspiration to precipitation ($\phi = \overline{PET}/\bar{P}$) and the evaporative

169 fraction as $\bar{E}/\bar{P}$. This modification brings no mathematical change in the values of the computed

170 variables, since both numerators and denominators are simply being divided by 12.

171 Several methods for quantifying seasonality exist in the literature, with metrics considering only

172 the progression of monthly values of precipitation throughout the year (Markham, 1970; Walsh &

173 Lawler, 1981), as well as methods considering monthly marches of both P and PET (Milly, 1994;

174 Woods, 2009; Feng et al., 2013; Feng et al., 2019). A common way to represent the seasonal

175 (monthly) progression of P and PET is achieved using sinusoidal functions (Milly, 1994; Woods,

176 2009; Yokoo et al., 2008):

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

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

179 where t is the time (months), δ_P and δ_{PET} are normalized (dimensionless) seasonal amplitudes,

180 and s_P and s_{PET} are phase shifts (in months). The seasonality metric chosen for this study

181 following Woods (2009) uses the sinusoidal approximations to quantify the extent to which the

182 seasonal cycles of precipitation and PET are in-phase or out-of-phase:

$$SI = \delta_P sgn(\delta_{PET}) \cos\left(\frac{2\pi(s_P - s_{PET})}{12}\right). (7)$$
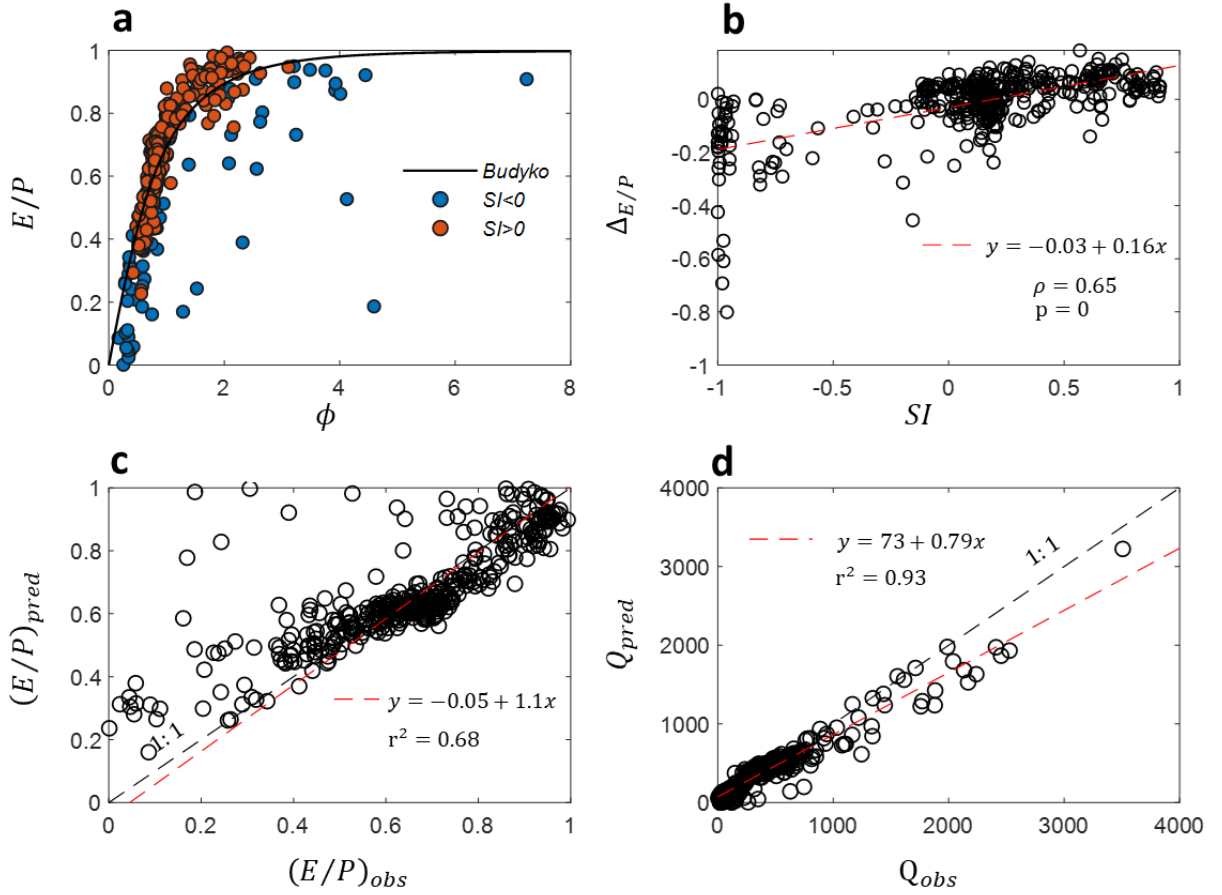
184 SI values range from -1 for a strong off-phase climate, with predominant winter precipitation, 0

185 for precipitation uniformly distributed throughout the year, and +1 for a strong in-phase

186   seasonality, or with predominant summer precipitation. **Figure S2** presents the geographical

187   distribution of SI values for the selected US catchments.

188

189   **Figure 2a** displays the selected US catchments within the Budyko space, where the catchments

190   are labelled with respect to their SI values, along with the Budyko curve (equation 4). The effects

191   of seasonality on the location of a catchment within the $\phi - E/P$ space as suggested from previous

192   studies seem to be supported by visual inspection of **Figure 2a**. A more rigorous assessment of

193   such a pattern is shown in **Figure 2b**, in which the deviations from the Budyko curve ($\Delta_{E/P}$),

194   computed as the difference between the observed evaporative fractions $\left(\frac{E}{P}\right)_{obs}$ and the evaporative

195   fractions predicted by equation (4), $\left(\frac{E}{P}\right)_{Budyko}$, are shown to be significantly correlated with SI

196   (correlation coefficient r = 0.65, p = 10^{-30}-3). This significant positive correlation supports the

197   hypothesis that catchments under in-phase climates tend to have higher evaporation rates and less

198   runoff ($\Delta_{E/P} > 0$, or a general tendency to be located above the Budyko's curve), with catchments

199   under off-phase climates suggesting the opposite lower E/P or, $\Delta_{E/P} > 0$ and a tendency to be

200   located below Budyko's curve).

201

202   We also show in **Figure 2c** and **Figure 2d**, the predictability of the Budyko equation (equation

203   (4)) with respect to the evaporative fraction and the long-term streamflow, which will be used later

204   in this manuscript for comparison. The performances shown here exemplify the ability of the

205   Budyko equation to explain the spatial variability of the long-term water balance partitioning for

206   the selected US catchments.

207

208

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

216
217 **2.3. Revisiting the Budyko framework**

218   **2.3.1.   Hypothesis 1: Aridity, Seasonality, and Water Availability**

219   The aridity index can be understood as a representation of the competition between the atmospheric

220   water demand versus the surface water availability (or supply). By making this assumption more

221   explicit, we can instead re-write the aridity index in terms of monthly averages as:

222

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

223   where $[A]$ represents the mean monthly water availability, in mm, in place of $[P]$, which is

224   commonly used as an *approximation* of $[A]$. We will attempt to better define [A] in the following

225   paragraphs considering an evidence-derived formulation. Let us now assume the Budyko equation

226   to be the *representation* of the relationship between and $\frac{E}{P}$ and the "actual" aridity index ϕ', i.e.,

227   equation (8).

228   The previous assumption allows us to hypothesize of the systematic deviations with respect to

229   seasonality as follows: Catchments with in-phase seasonality ($SI > 0$) are located above the

230   Budyko curve, allowing us to infer that their water availability is *lower* than the mean precipitation,

231   i.e., that $[A] < [P]$. Thus, a proper estimate of $[A]$ would lead to $\phi' > \phi$, meaning that their

232   position in the Budyko space would shift to the right, thus closer to the Budyko curve. On the other

233   hand, the fact that catchments with $SI < 0$ are generally located below the curve lets us infer that

234   their water availability is *higher* than the mean precipitation, meaning, i.e., that $[A] > [P]$ and

235     $\phi' < \phi$, which would also bring that catchment closer to the Budyko curve. Finally, for catchments

236   with little or no seasonality ($SI = 0$), the water availability can be taken as equivalent to mean

237   precipitation, i.e., that $[A] = [P]$, and in this case, aridity is properly estimated.

238   The hypothesis outlined above makes the following relationship clear:

239

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

240   where Δ_A (in mm) appears as a term quantifying the deficit or surplus between the actual water

241   availability, $[A]$, and $[P]$. The previous explanation also leads to:

242

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

243

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

244 $$\text{when } SI = 0: \quad [A] = [P] \text{ and } \Delta_A = 0., (10c)$$

245 Which suggests Δ_A to be a function of seasonality:

246 $$\Delta_A = f(SI). (11)$$

2.3.2. Hypothesis 2: Budyko's implicit assumption.

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

$$\text{If } P \approx uniform, \quad [A] = [P], (12)$$
$$\text{and}$$
254
$$\phi' = \frac{[PET]}{[A]} = \frac{[PET]}{[P]} = \left[\frac{PET}{P}\right], (13)$$

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

260 $$\left[\frac{P}{PET}\right] = [P].\left[\frac{1}{PET}\right] + cov\left(P, \frac{1}{PET}\right) (14)$$

263

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

264 $$[A] = \frac{\left[\frac{P}{PET}\right]}{\left[\frac{1}{PET}\right]} \tag{15}$$

265

2.3.3. Exploring the Links Between Seasonality and Water Availability

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

$$[A] = \frac{\sum \bar{P}_i \cdot 1/\overline{PET_i}}{\sum 1/\overline{PET_i}} \tag{16}$$

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

$$\Delta_A = [A] - [P] = \frac{\sum \Delta_{\bar{P}_i} \cdot 1/\overline{PET_i}}{\sum 1/\overline{PET_i}} \tag{17}$$

$$[A] = [P] + \frac{\sum \Delta_{\bar{P}_i} \cdot 1/\overline{PET_i}}{\sum 1/\overline{PET_i}} \tag{18}$$

280 In which, $\Delta_{\bar{P}_i}$ is the departure of the mean precipitation at a given month, from the mean monthly
281 precipitation value of all months, or:

$$\Delta_{P_i} = \bar{P}_i - [P], \tag{19}$$

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

286   18, in which $[A]$ is shown to be a combination of $[P]$ and Δ_A: For uniform precipitation patterns,

287   i.e. a non-seasonal march of monthly precipitation values, Δ_A will approach 0, bringing the

288   equality $[A] = [P]$, the case in which the availability is correctly estimated as the mean

289   precipitation, thus conforming to the revised assumption about the Budyko equation, as previously

290   shown.

291   In the next sections we will test equation (15) and explore its properties with the use of empirical

292   data from US catchments.

3. Results

3.1. Water availability and seasonality.

295   The results of the formulation of $[A]$ can be seen in **Figure3a,** where we compare normalized

296   values of Δ_A with respect to $[A]$. The figure shows how equation (17) adequately follows the

297   rationale on how $[A]$ and seasonality are linked, explained in 2.3.1. Therefore, the results shown

298   in sequence will refer to $[A] = \left[\frac{P}{PET}\right]/\left[\frac{1}{PET}\right]$. **Figure3a** also shows an almost direct translation

299   between the two variables, providing an additional (quantitative) interpretation for the *SI* and it's

300   relationship with deficit of surplus in water availability. On **Figure3b**, we can see how the aridity

301   values of the selected catchments change (as $\Delta_\phi(\%) = 100 \times \frac{(\phi'-\phi)}{\phi}$) with respect $\Delta_A/[P]$

302   values. The percent changes in aridity range from approximately -50% to almost 160% for the

303   selected catchments when ϕ' is used. The geographical distribution of such changes for the

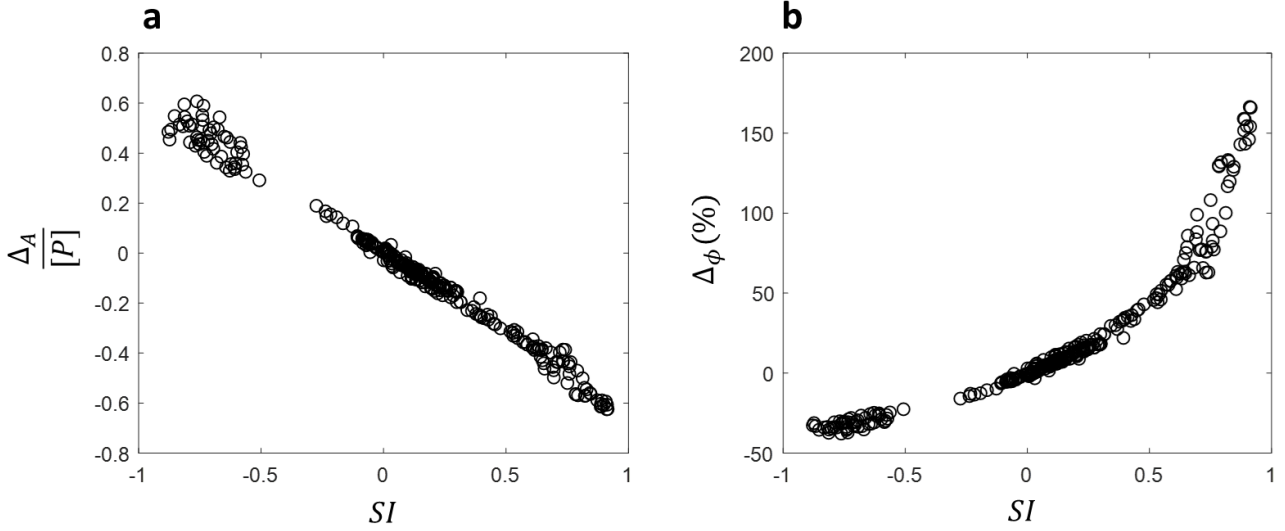304   selected US catchments is shown in **Figure S3**.
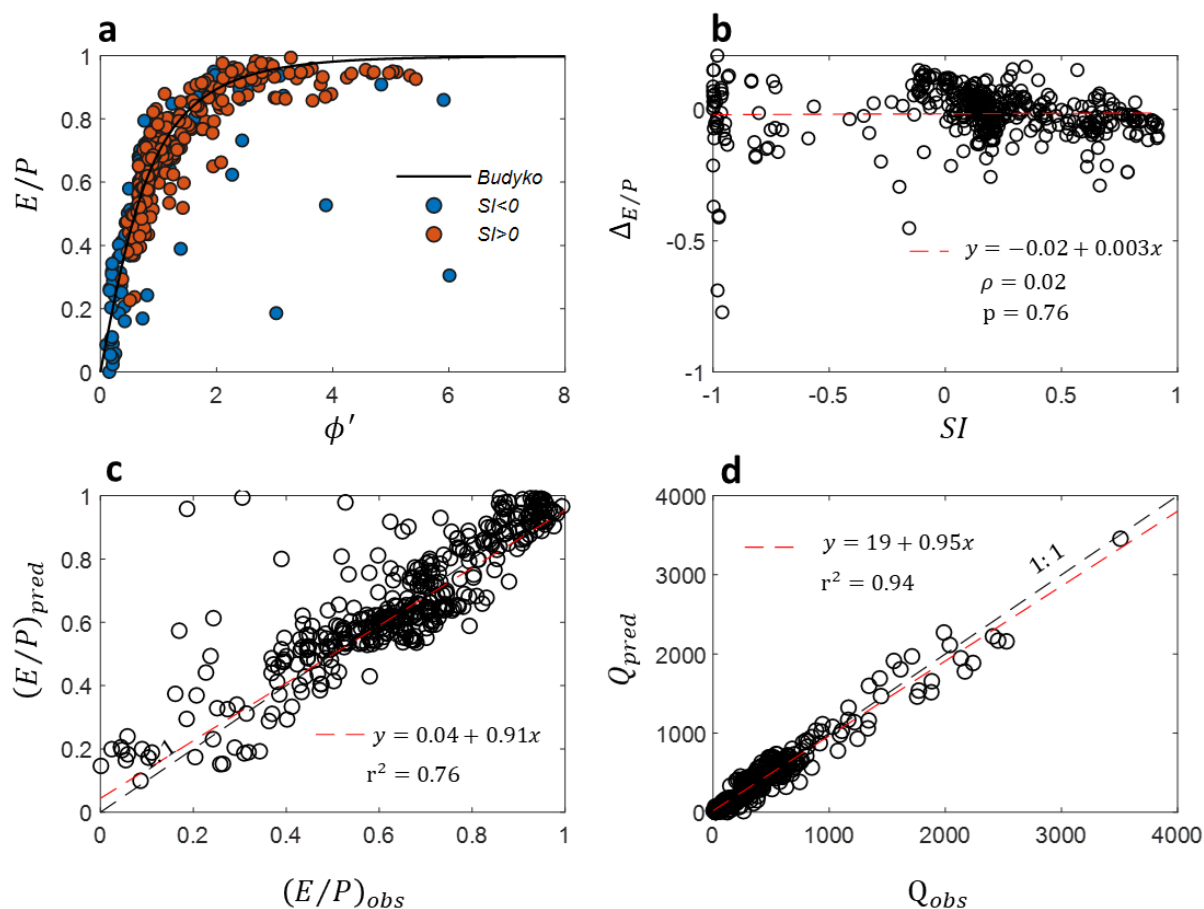
a

b

305

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 ($\Delta_\phi(\%) = 100 \times \frac{(\phi' - \phi)}{\phi}$).

309

310 **3.2. Performance of the Budyko equation when using ϕ'**

311 The results of the assumptions discussed above into the calculation of the aridity index and its

312 implications on the long-term water balance, as per the Budyko framework, are shown in **Figure**

313 **3**, which repeats the same plots as in **Figure 2**, however with the aridity index estimated as ϕ'. It

314 is possible to see from **Figure 4a** that the adoption of the formulation of ϕ' leads to an overall

315 better agreement of the cloud of points with respect to the Budyko curve. The once significant

316 relationship between observed and estimated evaporative fractions shown in **Figure 2b** is not

317 anymore detected when ϕ' is used, showing that seasonality has been included in its formulation.

318 Finally, the performance metrics shown in **Figure 4c** and **d** indicate that the use of ϕ' leads to a

319 higher explanatory power of the long-term water balance partitioning over the US catchments, in

320 terms of both observed and predicted evaporative ratios (**Figure 4c**) as well as streamflow (**Figure**

321 **4d**).

322

323

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

329

330 **4. Discussion**

331   **4.1. Overall merit of this work**

332 This study presents a straightforward approach to incorporating the effects of seasonality (based

333   on mean monthly water marches of P and PET) on the long-term balance through the Budyko

334   framework. By revising the assumptions behind the reason why catchments with distinct

335   seasonality patterns fall far from the Budyko curve, we were able to arrive at a formulation for

336   aridity that incorporates the effects of long-term seasonality.

337 It is important to emphasize that our approach does not lead to different conclusions with respect

338   to the net effects of seasonality on the long-term fluxes as our results conform with most of what

339   other authors have found so far, i.e. in phase seasonality favors E over P, while off-phase

340   seasonality tend to yield the opposite (Milly., 1994a; Milly., 1994b; Yokoo et al., 2008; Gerrits et

341   al., 2009; Berghuijs et al., 2014; Beck et al., 2015; Tang and Wang., 2017). However, we have

342   provided a simple method that does not require site-specific calibration of specific Budyko-type

343   equation (Shao et al., 2012; Abatzoglou and Ficklin, 2017) or asks for the explicit knowledge of

344   spatial distribution of storage capacity and its spatial variability, among other catchment physical

345   properties (Milly., 1994a; Milly., 1994b; Yokoo et al., 2008).

346 A clear distinction made here is the differentiation between the previously assumed denominator

347   of the aridity index, taken as the average precipitation $[P]$, versus the newly proposed expression

348   for water availability (equation 15). We have shown that (at the mean monthly timescale) $[A]$ can

349   be larger or smaller than $[P]$, which points out that at timescales finer than annual, monthly

350   precipitation is not a good approximation for water availability, since that at such timescales the

351   interactions between P and PET cannot be ignored. This allows to conceptually define water

352   availability (and aridity) as a *coupled land-atmosphere process*.

353 **4.2. The role of storage on water availability.**

354 The inclusion of seasonality in the long-term water balance has traditionally led to incorporation

355   of storage in its formulations (Milly et al., 1994a, Milly et al., 1994b, Hickel and Zhang, 2006;

356   Chen et al., 2013), whereas our results appear as a climate-only approach arising from empirical

357   reasoning on the deviations from the Budyko curve. While that the main mechanism allowing for

358   the intra-annual variability of water availability can only be explained by the existence of

359 storage/release mechanisms and carryover of moisture between months, our climate-driven water

360 availability term should to some extent reflect storage properties and processes. In this way, our

361 findings can be taken as reflecting the co-evolution between ecosystems and climate at natural

362 catchments, suggesting that storage capacity and its variability should be connected to the long-

363 term climate. Such link between long term aridity (as $[PET]/[P]$), seasonality and storage

364 properties in natural catchments has indeed been suggested in the literature for explaining

365 catchment-scale root zone storage capacity (Gao et al., 2014) and rooting distance (Gentine et al.,

366 2012).

367 Alongside with most studies on the role of seasonality and the long-term water balance, our results

368 differ from Potter et al., 2005, who found higher runoff values in summer dominated rainfall

369 regions in Australia. Such disagreement does not invalidate out findings but asks for an in-depth

370 assessment of the processes taking place. We believe Australian catchments might be subject to

371 two competing processes, i.e. the within year variation of atmospheric supply and demand versus

372 the occurrence of intense rainfall events, triggering fast stormflow, while our work only suggests

373 an approach for one of them. We believe therefore that the observed quick flow production during

374 summer months might be surpassing the water availability dynamics suggested here. The

375 investigation of how our framework can potentially shed light to the results of Potter et al., (2005)

376 might be worth pursuing in the future, where a similar approach as presented here could be

377 envisioned with a shift from monthly to daily timescales in order for finer timescale processes to

378 be captured.

379 **4.3. Implications for the aridity-seasonality index**

380 A combined aridity-seasonality index has the advantage of reducing the dimensionality of how the

381 long-term climate is described into a single variable. We have shown that the use of such variable

382 improves our ability to describe the geographical (between-catchment) distribution of the water

383 balance partitioning, thus conferring a higher explanatory power to the Budyko framework and

384 also pointing out to a means towards the inclusion of factors beyond the means of $[P]$ and $[PET]$

385 in its formulation, as it has been recently asked for in the scientific community (Berghuijs et al.,

386 2020).

387   We should also remind that in its essence, what confers a practical meaning to the definition of the

388   aridity index is its explanatory capacity over the partitioning of land-surface water fluxes. Thus,

389   our approach is also advantageous in that it provides a more valuable formulation of aridity, as

390   seen by its enhanced explanatory power of both E/P as well as Q (**Figure 4**). An improved

391   definition of aridity has implications beyond the Budyko framework, as many studies have used it

392   to assess impacts of future climate change scenarios on the terrestrial water balance (Wang et al.,

393   2014; Huang et al., 2016; Huang et al., 2017). While many studies also advocate for the use of

394   different measures from aridity for climate change impact estimation (Berg and McColl, 2021),

395   citing among other factors its uncoupled nature between land-surface and atmosphere (Greve et

396   al., 2019), our work might provide a means toward an improved representation of terrestrial aridity

397   through a simple climate-based index.

398   **4.4. Linking mean and intra-annual climatic variations to the long-term water balance.**

399   An interesting implication of our work is related to how processes at different timescales affect

400   the long-term water balance. Our results provide a simpler counterpoint to a more modelling-

401   intensive strategies such as the work of Yao et al., (2020) who have used a (calibrated) conceptual

402   rainfall-runoff model to arrive at the conclusion that aside from its mean conditions, the intra-

403   annual climatic variability is the main controlling timescale on the long-term water balance. We

404   have shown how the aridity index encapsulates not only the average competition between PET and

405   P but their mean intra-annual variability, as equation 18 provides a formulation in that the average

406   water availability (and the aridity) can be decomposed into a long-term and a seasonal component.

407

408   **5. Summary and Conclusions**

409   This work proposed a strategy on how climate seasonality can be incorporated into a widely used

410   long-term water balance formulation, the Budyko framework. Two hypotheses were investigated.

411   The first hypothesis defines the denominator of the aridity index as the water availability term and

412   provides a rationale for interpreting the deviations from the Budyko curve with respect to climate

413   seasonality. The second hypothesis is that the Budyko curve represents catchments with uniform

414   monthly marches of P, which we used to arrive at a mathematical definition of water availability.

415   We have shown that the water availability term is a function of mean precipitation and seasonality,

416 and that its use improves the explanatory power of the Budyko equation for the geographical
417 distribution of the land-surface water balance partitioning.

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

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

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

434

439

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