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A global assessment of runoff sensitivity to changes in precipitation, potential evaporation, and other factors

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Key points

- Budyko-based global assessment for the sensitivity of runoff to changes in precipitation, potential evaporation, and other factors.
- At a global scale, surface water resources are most sensitive to changes in precipitation, but regional exceptions exist.
- In drylands, sensitivities of runoff to precipitation and potential evaporation changes are lower than the sensitivity to all other factors.

Abstract

Precipitation (P) and potential evaporation (E_p) are commonly studied drivers of changing freshwater availability, as aridity (E_p/P) explains ~90% of the spatial differences in mean runoff across the globe. However, it is unclear if changes in aridity over time are also the most important cause for temporal changes in mean runoff and how this degree of importance varies regionally. We show that previous global assessments that address these questions do not properly account for changes due to precipitation, and thereby strongly underestimate the effects of precipitation on runoff. To resolve this shortcoming, we provide an improved Budyko-based global assessment of the relative and absolute sensitivity of precipitation, potential evaporation, and other factors to changes in mean annual runoff. The absolute elasticity of runoff to potential evaporation changes is always lower than the elasticity to precipitation changes. The global pattern indicates that for 83% of the land grid cells runoff is most sensitive to precipitation changes, while other factors dominate for the remaining 17%. This dominant role of precipitation contradicts previous global assessments, which considered the impacts of aridity changes as a ratio. We highlight that dryland regions generally display high absolute sensitivities of runoff to changes in precipitation,

however within dryland regions the relative sensitivity of runoff to changes in other factors (e.g. changing climatic variability, CO_2 – vegetation feedbacks and anthropogenic modifications to the landscape) is often far higher. Nonetheless, at the global scale, surface water resources are most sensitive to temporal changes in precipitation.

1. Introduction

Unraveling the main drivers of runoff change is key for the prediction and management of global freshwater resources [Milly *et al.*, 2008; Wagener *et al.*, 2010; Sivapalan *et al.*, 2012; Jiménez Cisneros *et al.*, 2014]. Potential evaporation (E_P) and precipitation (P) (often summarized together as the aridity index, E_P/P) are the dominant factors that determine how precipitation is partitioned between mean annual runoff (Q) and evaporation (E) differently between catchments [Budyko, 1974; Blöschl *et al.*, 2013]. The Budyko framework [Budyko, 1974] utilizes this prominent role of aridity and, in its parametric form [e.g. Fu, 1981], states that the mean annual balance between E and Q can be expressed as a function of aridity and other factors:

$$F(\phi, \omega) = \frac{E}{P} = 1 - \frac{Q}{P} \tag{1}$$

where F is an analytical equation describing the evaporative fraction (E/P) or runoff ratio (Q/P), ϕ is aridity (E_P/P), and ω is a parameter that accounts for all other factors that influence the mean-annual partitioning of precipitation (e.g. climate seasonality, soils, vegetation, topography).

Aridity (ϕ) is established as the dominant factor determining the spatial differences (i.e. between-catchment) in the mean partitioning of precipitation into runoff and evaporation across the globe [e.g. Budyko, 1974; Blöschl *et al.*, 2013; Greve *et al.*, 2014]. Temporal changes in precipitation and potential evaporation are often also considered to be of primary relevance for changes to mean runoff and evaporation over time [e.g. Bates *et al*., 2008; Sherwood & Fu, 2014; Greve *et al*., 2014; Greve & Seneviratne, 2015]. However, it is uncertain [Bates *et al*., 2008; Cramer *et al*., 2014] whether documented changes to mean precipitation and potential evaporation also translate to aridity being the dominant driver of changes in runoff or evaporation over time, and how this degree of dominance varies across the land surface. In addition, recent global assessments suggest that other factors (as summarized by ω) may play a more important role for changes in water availability [Jaramillo & Destouni, 2014; Gudmundsson *et al*., 2016; 2017]. These other factors that may influence temporal changes in mean annual runoff include changes in *climatic variability* (e.g. climate seasonality [Berghuijs *et al*., 2014a], snow conditions [Berghuijs *et al*., 2014b; Barnhart *et al*., 2016], storminess [Milly, 1994]), *CO_2 - vegetation feedbacks* (e.g., CO_2 fertilization [van der Sleen *et al*., 2015], water-use efficiency changes [Ukkola *et al*., 2015], tree-line movement [Goulden & Bales, 2014]), and *anthropogenic modifications* (e.g. land use change [Woodward *et al*., 2014], irrigation [Jaramillo & Destouni, 2015], reservoir construction [Jaramillo & Destouni, 2015]).

In recent years, the Budyko framework has been increasingly used to quantify the relative sensitivity of water availability to changes in aridity and other factors [e.g. Roderick & Farquhar, 2011; Wang & Hejazi, 2011; Creed *et al*., 2014; Roderick *et al*., 2014; Jaramillo & Destouni, 2014; Zhou *et al*., 2015; Kumar *et al*., 2016; Gudmundsson *et al*., 2016; 2017; Wang *et al*., 2016]. These studies assume that E and Q follow the Budyko curve (Eq. 1) when ϕ changes [Berghuijs & Woods, 2016], which allows the sensitivity of E and Q to changes in aridity (ϕ) and other factors (ω) to be evaluated analytically. There are currently three published global assessments that quantify whether water availability is more sensitive to changes in aridity or other factors [Zhou *et al.*, 2015; Gudmundsson *et al.*, 2016; 2017]. In principle, comparing the relative strength of the partial derivatives of F with respect to aridity ($\partial F/\partial \phi$) and to other factors ($\partial F/\partial \omega$) will help to identify the relative importance of changes in aridity versus other factors. However, as shown later in this article, such an approach prohibits accounting for the effects of precipitation changes on runoff, which biases findings and needs to be assessed and resolved if we want to better quantify the relative importance of aridity and other factors for changes in water availability.

In this study, we address this challenge by first providing a technical assessment of previous approaches (Section 2). We then provide methodological improvements to this theory that focus on changes to total runoff (Q) instead of partitioning ratios (E/P, Q/P) (Section 3). In order to assess the implications of this revised theory, we then apply this revised method to a global hydro-climatic dataset (Section 4) to answer: 1) How does the distribution of the sensitivity of runoff to P, E_p, and other factors scale across the globe? and 2) How does this impact our interpretation of the sensitivity of water resources to change (Section 5)?

2. Summary of current approaches

Published global assessments that quantify whether water availability is more sensitive to changes in aridity or other factors [Zhou *et al.*, 2015; Gudmundsson *et al.*, 2016; 2017] use a near-identical approach which is based on Fu's equation (a commonly used parametric Budyko curve) [Fu, 1981]:

$$F(\phi, \omega) = 1 + \phi - (1 + \phi^{\omega})^{\frac{1}{\omega}} \tag{2}$$

where $F = E/P \approx 1 - Q/P$, $\phi > 0$, and $1 \leq \omega \leq \infty$.

The partial derivative of F with respect to ϕ is given by:

$$\frac{\partial F}{\partial \phi} = 1 - \phi^{\omega-1}(\phi^{\omega} + 1)^{\frac{1}{\omega}-1} \tag{3}$$

and the partial derivative of F with respect to ω is given by:

$$\frac{\partial F}{\partial \omega} = -(\phi^{\omega} + 1)^{\frac{1}{\omega}} \cdot \left(\frac{\phi^{\omega} \ln(\phi)}{\omega(\phi^{\omega} + 1)} - \frac{\ln(\phi^{\omega} + 1)}{\omega^2} \right) \tag{4}$$

Regions where aridity is considered the dominant factor determining changes in water availability are identified by comparing the sensitivity of F to relative changes in aridity and other factors:

$$\left| \frac{\partial F}{\partial \phi} \zeta \phi \right| > \left| \frac{\partial F}{\partial \omega} \zeta \omega \right| \tag{5}$$

where ζ represents the same relative change:

$$\zeta = \frac{\Delta\phi}{\phi} = \frac{\Delta\omega}{\omega} \tag{6}$$

In practice Eq. 5 is a comparison of whether the evaporative ratio (F) responds more strongly to a relative change in aridity or an identical relative change in other factors. That is to say, if both ϕ and ω change by a similar percentage, which of the two has a bigger influence on the fraction of P that is converted into Q (or E)? Gudmundsson *et al*. [2016; 2017] apply their equations to a global gridded dataset of P, E and E_p and identify the relative importance of ϕ vs. ω across the Earth's land surface, and find that changes in water availability are only dominated by changes in aridity in very humid climates (~ $\phi<1$). The approach of Zhou *et al*. [2015] is largely similar to what is presented above, but evaluates dominance based on the effect of absolute changes in ϕ and ω (i.e. $\left|\frac{\partial F}{\partial \phi^{-1}}\right| > \left|\frac{\partial F}{\partial \omega}\right|$), which can be problematic due to the physical inconsistency of the mathematical approach [for more details see: Berghuijs and Woods, 2016; Gudmundsson *et al*., 2016; 2017]. Note that the probabilistic components of

Gudmundsson *et al*. [2016] are omitted in the above description, as they are not directly relevant for the analytical revisions discussed here.

The analyses outlined above assume that precipitation partitioning will not be influenced by changes in water storage. This assumption is unlikely to hold at sub-annual, or occasionally at annual time-scales [e.g. Condon & Maxwell, 2016], and requires averaging conditions over multiple years. In addition, it is important to again note that these analyses assume that E and Q follow the Budyko curve (Eq. 1) when ϕ changes; this assumption may be less accurate at the time-scales over which the catchment establishes a new dynamic equilibrium (i.e. as vegetation and soils are adapted to the prevailing climatic conditions and human interferences), and may also be unrepresentative for shorter time-scales [Berghuijs & Woods, 2016].

3. Revising current approaches

3.1 Exclusion of precipitation effects

The above-presented approach provides valuable steps forward for better understanding the dominant drivers of changing water availability. However, Equations 3 and 5 lump the sensitivity of Q to P and E_p into a single term. Such an approach is not sufficient to explain the full sensitivity of the system, because both the output F $(=E/P=1-Q/P)$ and input ϕ $(=E_p/P)$ are a function of P. Thus, in principle we require a total derivative to assess its sensitivity to ϕ changes:

$$\frac{\mathrm{d}F}{\mathrm{d}\phi}=\frac{\partial F}{\partial \phi}+\frac{\partial F}{\partial P}\frac{\mathrm{d}P}{\mathrm{d}\phi} \tag{7}$$

Previous approaches which only used the partial derivative of F with respect to ϕ (i.e. equation (3)) are in effect assuming that P does not change when ϕ changes (i.e. $\frac{dP}{d\phi}=$

0), which is clearly unrealistic. This limiting assumption is important since it means that derived sensitivities of runoff and evaporative ratios to aridity versus all other factors [Zhou *et al*., 2015; Kumar *et al*., 2016; Gudmundsson *et al*., 2016; 2017], or studies that attribute total water availability changes to changes in both factors [e.g. Jaramillo & Destouni, 2014], implicitly ignore changes in P (via the normalization used in F) and thereby underestimate the contribution of ϕ changes. Although we could pursue equation (7) further, we think it is more revealing to examine the sensitivities of Q and E to P, E_p and ω separately.

3.2 Including precipitation effects

We can overcome the assumption of fixed P by quantifying the sensitivity of Q (or E) to the separate changes in P, E_p and ω. We focus on Q because runoff is the primary sustainable water resource for society [Oki & Kanae, 2006]. Rewriting Fu's equation (Eq. 2) whereby aridity is expanded into E_p/P allows expressing Q as:

$$Q(P, E_P, \omega) = P \cdot \left(-\frac{E_P}{P} + \left(1 + \left(\frac{E_P}{P} \right)^{\omega} \right)^{\frac{1}{\omega}} \right) \qquad (8)$$

Consistent with the previous section, equation 8 by itself cannot be used to express the sensitivity of runoff to changes in aridity; it is necessary to derive partial differential expressions for each of the terms (P, E_p and ω) separately. We derived three elasticities of Q that compare the relative sensitivities to changes in P, E_p and ω:

$$\epsilon_{Q,P} = \frac{\partial Q/Q}{\partial P/P} = \frac{(\phi^{\omega}+1)^{\frac{1}{\omega}-1}}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}} \qquad (9)$$

$$\epsilon_{Q,E_P} = \frac{\partial Q/Q}{\partial E_p/E_p} = \frac{\phi^{\omega}(\phi^{\omega}+1)^{\frac{1}{\omega}-1} - \phi}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}} \qquad (10)$$

$$\epsilon_{Q,\omega} = \frac{\partial Q/Q}{\partial \omega/\omega} = \frac{(\phi^{\omega}+1)^{\frac{1}{\omega}} \cdot \left(\frac{\phi^{\omega}\ln(\phi)}{\phi^{\omega}+1} - \frac{\ln(\phi^{\omega}+1)}{\omega}\right)}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}} \tag{11}$$

Where $\epsilon_{Q,x}$ is the relative change in Q due to a relative change in either P, E_p or ω. This distinction is not necessarily new. For example, Roderick and Farquhar [2011] presented separate equations for the sensitivity of Q to E_P, P and n (where $n = \omega$ - 0.72 [Yang *et al.*, 2008]) using a different parametric Budyko style equation [Choudhury, 1999]. However, this distinction has been ignored in subsequent global applications.

To illustrate the elasticities for varying conditions of ϕ and ω, we display the absolute elasticity of Q to P ($\epsilon_{Q,P}$), elasticity of Q to E_P (ϵ_{Q,E_P}), elasticity of Q to other factors ($\epsilon_{Q,\omega}$), and the relative sensitivity to E_P compared to P ($\epsilon_{Q,E_P}/\epsilon_{Q,P}$) (Figure 1a-d) for a range of ϕ and ω values that cover most of the hydro-climatic conditions globally. It is important to note that the absolute sensitivity of Q to P changes is always higher than to E_P changes (Figure 1d). For high ϕ and ω values the differences between $\epsilon_{Q,P}$ and ϵ_{Q,E_P} are minor but in other situations lead to approximately 10 times higher sensitivities to P than to E_p (Figure 1d).

Previous assessments that use inequality (Equation 5) to decipher the relative dominance of ϕ versus ω [Zhou *et al.*, 2015; Gudmundsson *et al.*, 2016; 2017] implicitly assume that P remains constant when ϕ changes (see equation (7)). In practice this is equivalent to comparing the elasticities of ϵ_{Q,E_P} to $\epsilon_{Q,\omega}$ (i.e. $\left|\frac{\partial F}{\partial \phi}\zeta\phi\right| > \left|\frac{\partial F}{\partial \omega}\zeta\omega\right|$ is equal to $\left|\epsilon_{Q,E_P}\right| > \left|\epsilon_{Q,\omega}\right|$). We now know that for any combination of ϕ and ω the sensitivity of runoff to P is always higher than the sensitivity of runoff to E_P, sometimes by an order of magnitude (Figure 1, panel d). This emphasizes a key finding, that missing the impact of changes in P within the lumped sensitivity to aridity can strongly underestimate the role of these climatic changes, particularly in arid regions with high ω values.

3.3 Assessing the relative importance of changes in P, E_P and ω to runoff

Equations (7, 9 – 11) clarify that a single sensitivity of Q to aridity changes does not exist without specifying $\mathrm{d}P/\mathrm{d}\phi$, and that changes in E_p and P are better considered separately. It is now possible to evaluate the sensitivity of Q to the three factors combined in order to examine the relative importance of each of the drivers:

$$\theta_x = \frac{|\epsilon_{Q,x}|}{|\epsilon_{Q,\omega}| + |\epsilon_{Q,E_P}| + |\epsilon_{Q,P}|} \qquad (12)$$

where θ_x is the relative sensitivity of Q to each factor x (ω, E_p and P). θ_x can vary from close to zero (i.e.: almost no influence from that particular factor), to close to one (i.e.: the sensitivity to that factor is much stronger than the sensitivity to the two other factors), whereby $\theta_\omega + \theta_{Ep} + \theta_P = 1$. We can use ϕ and ω as the bivariate plotting space in which to explore the relative sensitivity of Q to these three factors (Figure 2). From this figure, it can be seen that the relative sensitivity to precipitation changes primarily depends on ϕ (Figure 2a). The relative sensitivity to changes in E_p is increases with high ω values (Figure 2b), and the relative sensitivity to changes in ω depends on both ϕ and ω (Figure 2c).

4. Application to a global dataset

4.1 Deriving grid-cell characteristics

We use the WATCH model ensemble data for the period 1901-2000 to determine the global pattern of the aridity index ϕ, and the ω parameter for the period 1901-2000 (http://www.eu-watch.org) [Weedon *et al*., 2011] (Figure 3). Data are monthly values of evaporation, precipitation, and potential evaporation with a 0.5° by 0.5° spatial resolution. Aridity is derived based on long-term mean values of precipitation and potential evaporation for the period 1901-2000. ω is calculated based on the minimum root mean square error of equation (2) for 10-year values of E/P and ϕ (for exact procedures see Supplementary Material). This is done to reduce the effects of potential "space-time asymmetry" [Berghuijs & Woods, 2016], i.e. that the characterization that Fu's equation (describing differences between places), may not fully capture changes over time at individual locations. While our estimates of ϕ and ω are to some extent dataset dependent, and may change when alternative methods for estimating potential evaporation or precipitation are used, the patterns of ϕ and ω largely agree with earlier studies that have also determined these factors globally [Zhou *et al*., 2015; Gudmundsson *et al*., 2016; 2017].

4.2 Global pattern of runoff elasticities

We can now provide a more realistic global assessment on the sensitivity of runoff to changes in the key drivers. Based on the derived global ϕ and ω characteristics (Figure 3) we provide the global distribution of Q elasticities to changes in P, E_p and ω (Figure 4). Precipitation elasticity ($\epsilon_{Q,P}$) has a minimum value of 1.0 indicating that the relative change in Q is always equal or larger than the relative change in P. The median $\epsilon_{Q,P}$ is 2.17 and for 53% of the land grid cells a relative P change is amplified into a relative Q change by over a factor of two. Generally, dryland regions (i.e. $E_p/P > 1.5$ [Feng & Fu, 2013]) have higher $\epsilon_{Q,P}$ values. Dryland regions are globally widespread (~1/3rd of the land surface), and Q in many of these areas (e.g. Central and Western Australia, Southern Africa, Sahara and surroundings, parts of the western US, Patagonian Desert, Middle East, Turkestan Desert, Great Indian Desert and the Gobi Desert) has a far higher sensitivity (median 3.9) to P changes than Q in more humid (i.e. $E_P/P \leq 1.5$) climates (median 1.9). In addition, across the globe the elasticity of Q to P ($\epsilon_{Q,P}$) always exceeds the absolute elasticity of runoff to E_P (ϵ_{Q,E_P}). The absolute ϵ_{Q,E_P} has a median value of 1.17, indicating that a percentage change in E_P results in a greater percentage change in Q for just over half of the land grid cells. The regional differences in ϵ_{Q,E_P} are largely similar to that of $\epsilon_{Q,P}$; dryland regions show higher elasticity values than the humid regions. Yet, there are strong differences in the magnitudes of these elasticities, as highlighted by the frequency distributions of the absolute Q elasticity to E_P (Figure 4) and their median value for dryland (2.8) and humid (0.9) regions. The elasticity of Q to changes in ω ($\epsilon_{Q,\omega}$) has a comparable range of values to ϵ_{Q,E_P}, whereby the median value is also 1.17, indicating again that a percentage change in ω for approximately half of the land surface leads to a greater percentage change in Q, and vice versa for the other half. Consistent with the other elasticities, $\epsilon_{Q,\omega}$ is generally higher in dryland regions. However the range of $\epsilon_{Q,\omega}$ is larger, with high elasticities in many dryland regions (median 6.5) and low elasticities in humid regions (median 0.75). Yet overall, the frequency distributions indicate $\epsilon_{Q,\omega}$ is generally much lower (and right-skewed) than $\epsilon_{Q,P}$.

4.3 The relative sensitivity of mean annual runoff to *P*, *E*

Based on the results of the previous section we can now calculate the relative sensitivity of runoff to changes in P, E_P and ω (Figure 5). For 83% of the land grid cells, P is consistently a more important contributor to changes in Q ($\Theta_P > \{\Theta_{E_P}, \Theta_\omega\}$), see Eq. 12) while changes in the parameter ω (representing all other factors) are more dominant for 17% of the land surface ($\Theta_\omega > \{\Theta_P, \Theta_{E_P}\}$). There is no land area where Θ_{E_P} was most important. Regions where changes in ω are more dominant are almost exclusively limited to dryland areas (Figure 6). Precipitation is most important for surface freshwater availability within the equatorial tropics (i.e.: Amazon, Congo, and archipelagos of the Western Pacific), large areas of the North American continent, eastern parts of continental Asia, New Zealand, Europe, and around the Pampas of South America. These results substantially differ from, and are in places almost the direct reciprocal of, the results reported in previous global assessments that determined the sensitivity of runoff to aridity [Zhou *et al*., 2015; Gudmundsson *et al*., 2016; 2017]. For example, using Gudmundsson *et al.* [2016; 2017] approach (ignoring the probabilistic component) we would identify that for 47% of the grid cells aridity is less important than all other factors, while this reduces to 17% in our approach if we compare it only to precipitation. This emphasizes the need for explicitly acknowledging precipitation effects when evaluating the sensitivity of runoff changes.

5. Discussion

5.1 Dominant drivers of changing freshwater availability

Improving the realism of regional patterns of the sensitivity of runoff to the dominant drivers of change is important, as unraveling the main drivers is key for the prediction and management of global freshwater resources [Milly *et al*., 2008; Wagener *et al*., 2010; Sivapalan *et al*., 2012; Jiménez Cisneros *et al*., 2014]. Our argument that the sensitivity to potential evaporation and precipitation needs to be considered separately is not necessarily novel. Yet, available global assessments [Zhou *et al*., 2015; Gudmundsson *et al*., 2016; 2017] have ignored this distinction.

This distinction is not just conceptually important; it strongly affects the factors to which water availability is globally most sensitive. Our findings suggest that, contrary to previous global assessments [Gudmundsson *et al*., 2016; 2017; Zhou *et al*., 2015], runoff is generally most sensitive to precipitation changes, rather than to changes in other factors (such as vegetation, human impact, etc). Equivalent comparisons with other Budyko based studies that attribute recent changes in water availability to aridity or other factors [e.g. Jaramillo & Destouni, 2014] are not possible. However, since changing precipitation effects are also implicitly excluded in that study, we expect that the percentages of factors that change water availability will strongly shift towards a more dominant role of precipitation (and thus aridity) when re-evaluated using the approach presented here.

Our revised global patterns on the relative sensitivity of water availability to changes in P, E_P, and ω reveals that runoff is most sensitive to changes in precipitation for 83% of the land grid cells. Because runoff is always more sensitive to changes in precipitation than to changes in potential evaporation it automatically follows that other factors dominate for the remaining 17%. The latter occurs almost exclusively in dryland regions, which broadly agrees with the findings of Gudmundsson *et al*. [2016]. However, our results disagree with the subsequent interpretation that "*this implies that projected intensifications of aridity in drylands may have less influence on water availability than commonly assumed"* [Gudmundsson *et al*., 2016]. This is because the dominance of other factors remains relative and the elasticity of runoff to precipitation in dryland regions is generally far higher (median 3.9) than in humid or temperate regions (median 1.9) (Figure 4). This means that dryland regions are very sensitive to precipitation changes, but should they occur, the burden of runoff changes in these regions is likely to fall on the more poorly constrained roles of changing climatic variability, CO_2 – vegetation feedbacks and anthropogenic modifications to the landscape.

This is an important point on which to be accurate, since water scarcity is suffered by almost all dryland areas of the world [Mekonnen & Hoekstra, 2016], where aquifer replenishment is also often very small relative to the scale of groundwater withdrawals [Gleeson *et al*., 2012; Richey *et al*., 2015]. Yet, data availability, model development, and predictive capacity for changes to the hydrological cycle remain biased towards more temperate and well-studied regions, which have far lower sensitivities to changes in runoff. This may result in low confidence for the causal attribution of changes to runoff in drylands [Bates *et al*., 2008; Cramer *et al*., 2014], emphasizing this is where greater hydrological information and conceptual advances are needed.

5.2 Limitations and future improvements

Our approach provides a revised global overview of runoff elasticity to changes in precipitation, potential evaporation, and other factors. Nonetheless, in order to quantify past and future drivers of changing freshwater availability, we also need to include information on the magnitude of past, or anticipated future, changes in E_p, P, and ω [Berghuijs & Woods, 2016]. Another limitation of our study is that we do not provide any uncertainty estimates of the derived elasticities. The global dataset we used may introduce uncertainty for the approximation of individual grid cells due to various causes. Alternative datasets may yield different ϕ and ω values and thus different sensitivities. Furthermore, the spatial patterns of the sensitivities to various changes have a 0.5° by 0.5° spatial resolution; and do not provide any information on sub-grid variability. Therefore, we acknowledge that improved (and more observation based) datasets may further refine results in the future. However, the larger-scale differences and gradients that are the focus of our analysis are unlikely to change significantly based on the dataset used, especially since the global pattern of ϕ and ω values obtained here is largely consistent with other studies.

Global Budyko-based assessments of the sensitivity to aridity changes analyze how the long-term means of ϕ and ω co-vary between locations, to approximate how F responds to these changes. An important constraint of this approach is that it implicitly assumes that spatial differences in runoff and evaporation translate directly into how this partitioning should change in time [Berghuijs & Woods, 2016]. This assumption is not necessarily unreasonable; it reflects a hydrological system that has coevolved, and is in balance with, its climate conditions [Perdigao & Blöschl, 2014; Sivapalan & Blöschl, 2015] and the Budyko framework often predicts temporal changes in runoff and evaporation as well or better than land-surface models [Roderick *et al.*, 2014]. However, in practice, this assumption can lead to both over- and under-estimation of the temporal sensitivity of runoff to aridity changes and potentially biases the relative importance of ϕ and ω [Berghuijs & Woods, 2016]. Although we tried to limit this uncertainty by deriving ω values based on decadal variations of F and ϕ, these may need revision as better data becomes available in future assessments. Nonetheless, the large number of data points means that, while individual grid cells may have their uncertainty, the large number of locations included counterbalances uncertainties contained within individual locations and makes our general conclusions more reliable.

Finally, it is important to note that in this paper we only highlight the sensitivities of runoff to changes in P, E_p and ω, without providing the information on the observed magnitudes of change in these factors. These magnitudes of change will depend on the timescales over which changes are evaluated [Sivapalan & Blöschl, 2015]. Such information is needed when runoff changes over a particular time-period are attributed to particular factors. The regional differences in dominant factors of such an attribution study can thereby differ from the relative sensitivities that we have exposed in this paper. Attributing runoff changes using our revised approach is thereby a logical next step in understanding the drivers of changes in global freshwater availability.

6. Conclusions

Motivated by the question of whether mean runoff is more sensitive to changes in aridity or changes in other factors (the lumped effects of e.g. changing climatic variability, CO_2 – vegetation feedbacks and anthropogenic modifications to the landscape), we resolve critical shortcomings of previous Budyko-based global assessments on the relative role of aridity for changes in water availability; efforts that examined the main drivers of changes in freshwater availability but without accounting for precipitation effects. Our revised global assessment of the elasticity and sensitivity of runoff to changes in precipitation, potential evaporation, and other factors reveals the spatial sensitivity of runoff to P, E_p, and other factors scale across the globe, which compared to previous assessments changes our interpretation of the sensitivity of water resources to change. For 83% of the land surface runoff is most sensitive to precipitation changes, while other factors dominate for the remaining 17%. Potential evaporation elasticity of runoff is always lower than precipitation elasticity of runoff, and in some arid regions this difference can be an order of magnitude. Water resources in dryland regions are highly sensitive to precipitation changes, but the sensitivity of runoff to changes in other factors (e.g. changing climatic variability, CO_2 – vegetation feedbacks and anthropogenic modifications to the landscape) is for these regions often even higher. Consistent with spatial differences of mean runoff, but contradicting recent assessments that ignored precipitation effects, it are changes in *P* that primarily determine changes in water availability.

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List of Figures

Figure 1: The (absolute) elasticity of runoff to precipitation ($\epsilon_{Q,P}$, panel a), elasticity of runoff to potential evaporation (ϵ_{Q,E_p}, panel b), elasticity of runoff to other factors ($\epsilon_{Q,\omega}$, panel c), and the relative strength of potential evaporation and runoff elasticity ($\epsilon_{Q,E_p}/\epsilon_{Q,P}$, panel d) for different aridity (ϕ) and ω parameter values. The presented ranges of ϕ and ω values cover the hydro-climatic conditions of most land grid cells globally.

Figure 2: The relative sensitivity of runoff to changes in precipitation (θ_P, panel a), potential evaporation (θ_{Ep}, panel b), and other factors (θ_ω, panel c) for different aridity (ϕ) and ω parameter values. The presented ranges of ϕ and ω values cover the hydro-climatic conditions of most land grid cells globally.

Figure 3: Global hydro-climatic characteristics of the Budyko framework. The spatial pattern of the runoff ratio *(Q/P,* panel a), the aridity index (ϕ, panel b), and the ω parameter (panel c) based on the WATCH data of the period 1901-2001. The relative occurrences of all three indices are indicated by the histograms (note the logarithmic x-axes for the histograms) (panels d-f).

Figure 4: The absolute runoff elasticity to precipitation ($\epsilon_{Q,P}$, panel a), potential evaporation (ϵ_{Q,E_P}, panel b), and other factors ($\epsilon_{Q,\omega}$, panel c) across the world. For each elasticity value we provide the spatial pattern and the associated relative occurrence indicated by the histograms (panels d-f). High elasticity values are generally found in dryland regions, whereas lower sensitivities are found in more humid regions.

Figure 5: The relative sensitivity of runoff to changes in precipitation (Θ_P panel a) potential evaporation (Θ_{E_P} panel b), and other factors (Θ_ω panel c). For all relative sensitivities, we provide the spatial pattern and the associated relative occurrence indicated by the histograms (panels d-f). For 83% of the land grid cells, runoff is most sensitive to precipitation. Exceptions where other factors are more dominant are almost exclusive to dryland regions.

Figure 6: The absolute runoff elasticities and relative sensitivities of runoff to changes in precipitation, potential evaporation, and other factors for dryland regions (i.e. aridity exceeds 1.5, panels a-b) and humid areas (i.e. aridity does not exceed 1.5, panels c-d). This stratification highlights that dryland regions generally display higher absolute sensitivities of runoff to changes in precipitation compared to humid areas (panels a, c), however within dryland regions the relative sensitivity of runoff to changes in other factors (e.g. changing climatic variability, CO_2 – vegetation feedbacks and anthropogenic modifications to the landscape) is often even higher (panel b).

Figure 1.

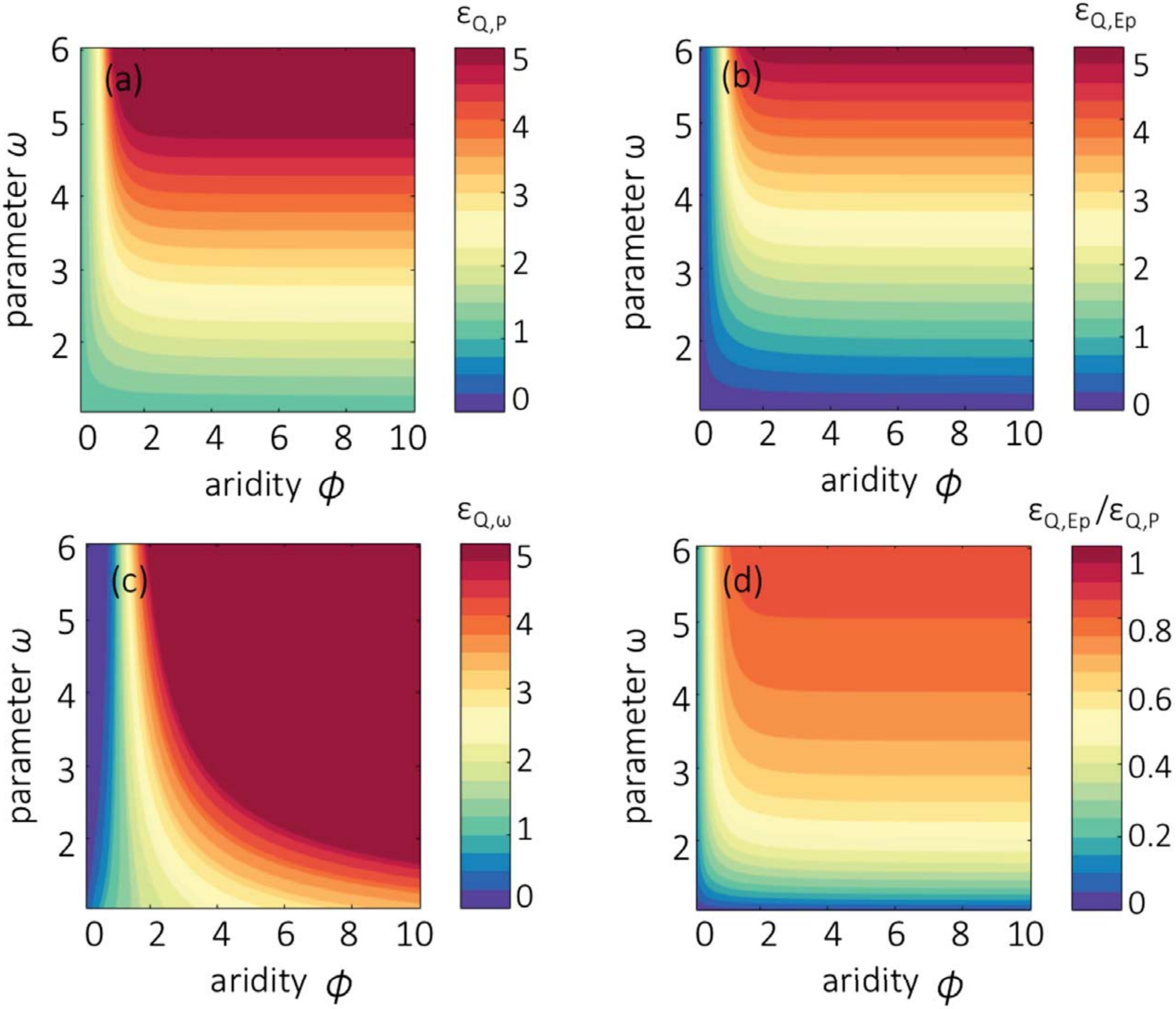
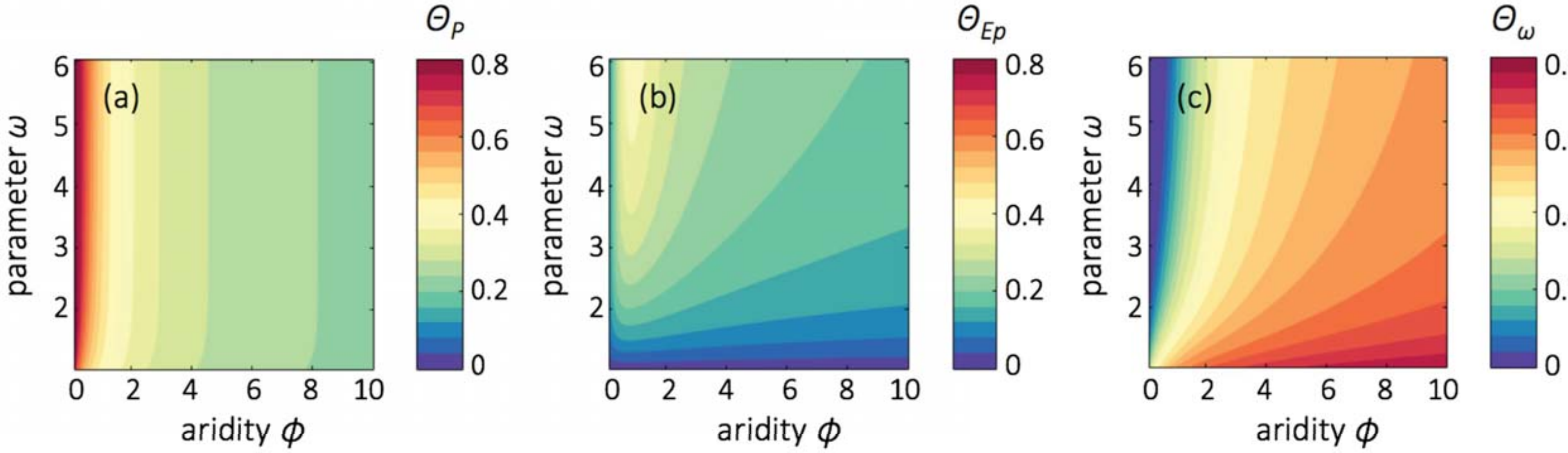

(a)
(b)
(c)
(d)
parameter ω
aridity ϕ
εQ,P
εQ,Ep
εQ,ω
εQ,Ep /εQ,P
0
1
2
3
4
5
6
8
10
0.2
0.4
0.6
0.8

Figure 2.



Θ_P
(a)
parameter ω
aridity ϕ
0
2
4
6
8
10
1
2
3
4
5
6
0.8
0.6
0.4
0.2
0
Θ_{Ep}
(b)
parameter ω
aridity ϕ
Θ_ω
(c)
parameter ω
aridity ϕ

Figure 3.

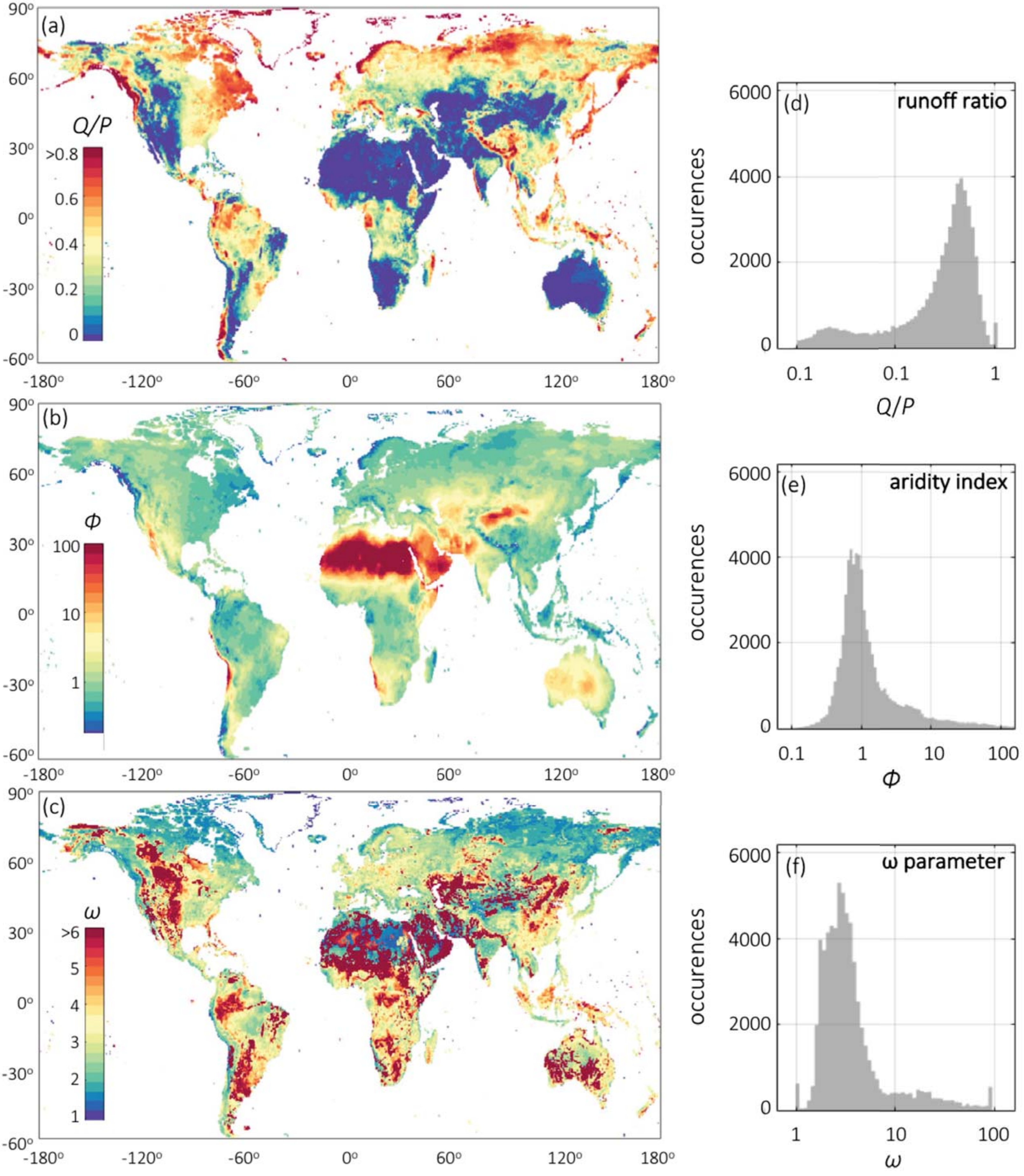

(a)
Q/P
>0.8
0.6
0.4
0.2
0
90º
60º
30º
0º
-30º
-60º
-180º
-120º
-60º
0º
60º
120º
180º
(b)
Φ
100
10
1
(c)
ω
>6
5
4
3
2
1
(d)
runoff ratio
occurences
6000
4000
2000
0
0.1
0.1
1
Q/P
(e)
aridity index
occurences
0.1
1
10
100
Φ
(f)
ω parameter
occurences
1
10
100
ω

Figure 4.

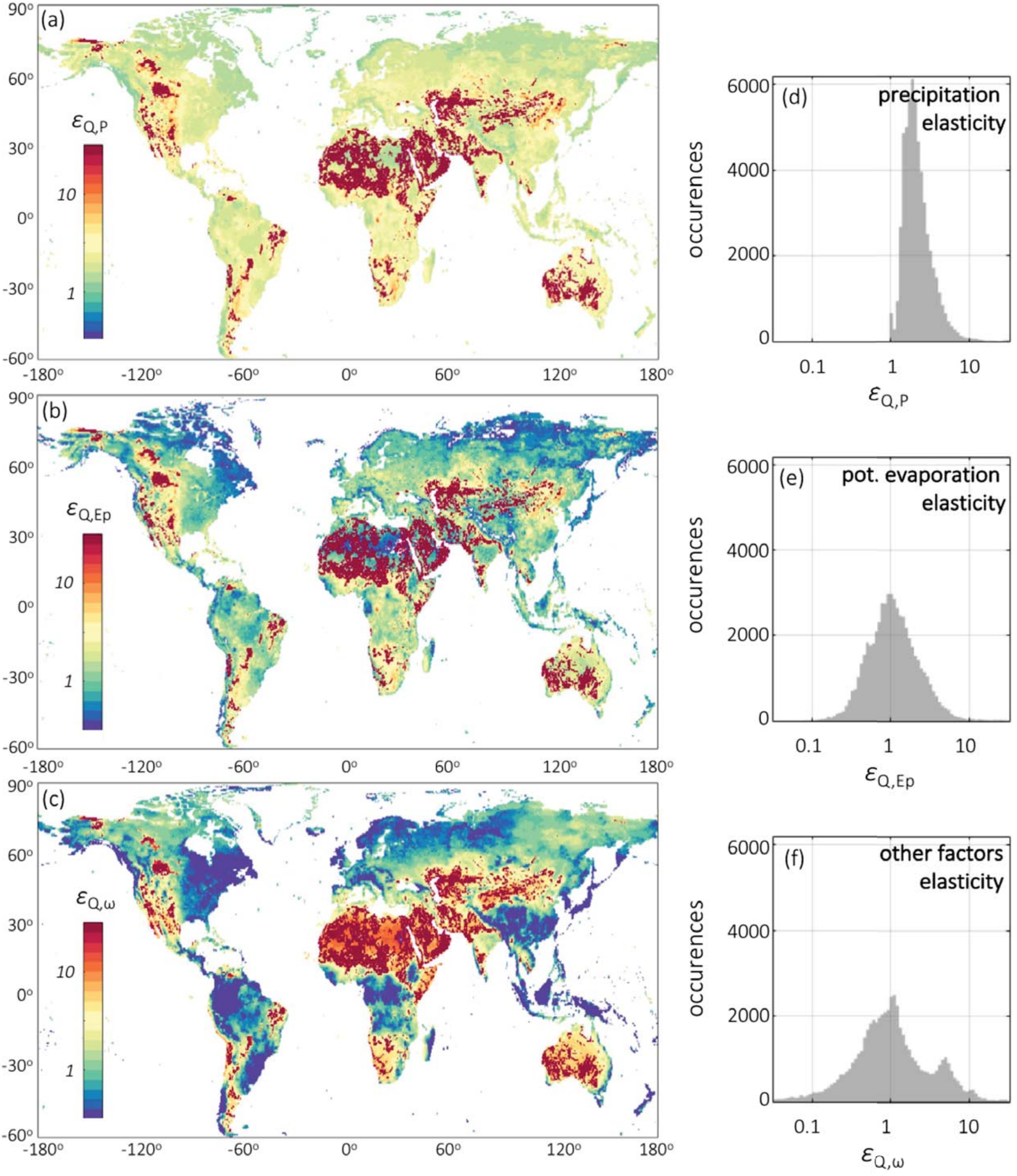

(a)
$\varepsilon_{Q,P}$
10
1
(b)
$\varepsilon_{Q,Ep}$
10
1
(c)
$\varepsilon_{Q,\omega}$
10
1
90°
60°
30°
0°
-30°
-60°
-180°
-120°
-60°
0°
60°
120°
180°
(d)
precipitation elasticity
(e)
pot. evaporation elasticity
(f)
other factors elasticity
occurences
6000
4000
2000
0
0.1
1
10
$\varepsilon_{Q,P}$
$\varepsilon_{Q,Ep}$
$\varepsilon_{Q,\omega}$

Figure 5.

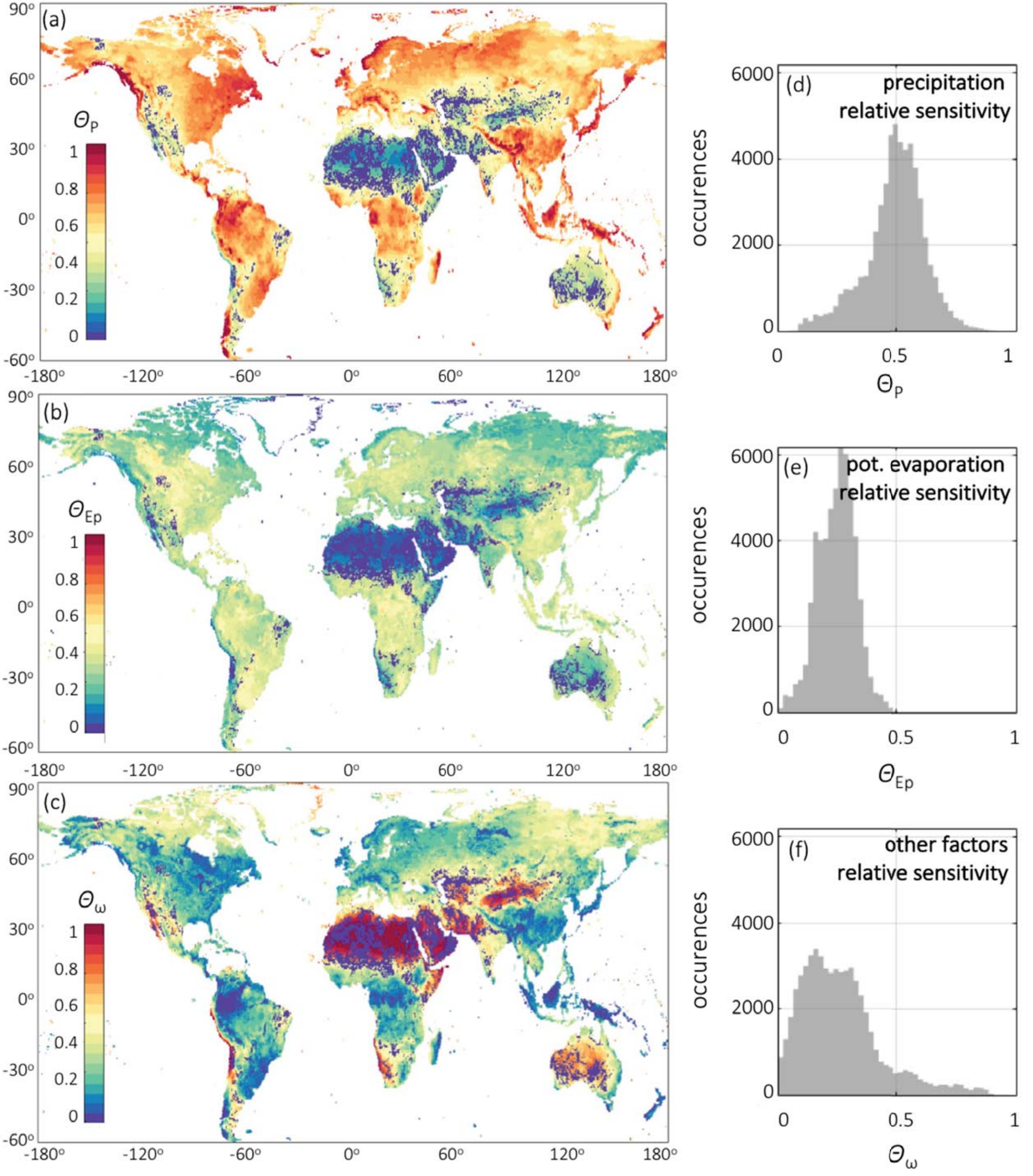
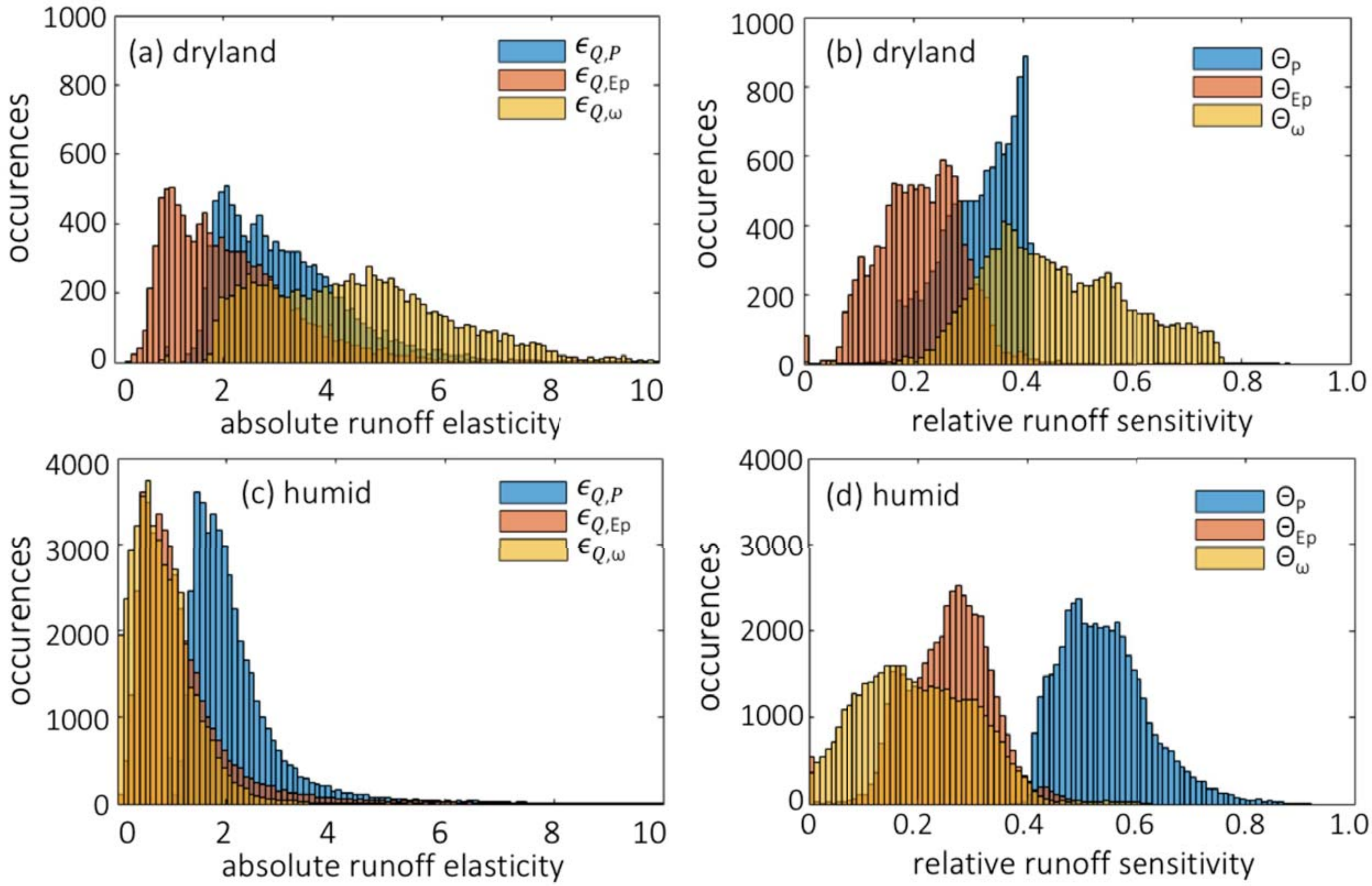

(a)
Θ_P
1
0.8
0.6
0.4
0.2
0
90°
60°
30°
0°
-30°
-60°
-180°
-120°
-60°
0°
60°
120°
180°
(b)
Θ_{Ep}
(c)
Θ_ω
(d)
precipitation relative sensitivity
occurences
6000
4000
2000
0
0
0.5
1
Θ_P
(e)
pot. evaporation relative sensitivity
Θ_{Ep}
(f)
other factors relative sensitivity
Θ_ω

Figure 6.


(a) dryland
$\epsilon_{Q,P}$
$\epsilon_{Q,\mathrm{Ep}}$
$\epsilon_{Q,\omega}$
occurences
1000
800
600
400
200
0
0
2
4
6
8
10
absolute runoff elasticity
(b) dryland
Θ_P
Θ_{Ep}
Θ_{ω}
occurences
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1.0
relative runoff sensitivity
(c) humid
$\epsilon_{Q,P}$
$\epsilon_{Q,\mathrm{Ep}}$
$\epsilon_{Q,\omega}$
occurences
4000
3000
2000
1000
0
0
2
4
6
8
10
absolute runoff elasticity
(d) humid
Θ_P
Θ_{Ep}
Θ_{ω}
occurences
4000
3000
2000
1000
0
0
0.2
0.4
0.6
0.8
1.0
relative runoff sensitivity