Reply to reviewer #2

1.This study proposes a generalization of the Budyko framework beyond the use of a single average aridity index. The key idea is to better account for seasonality and the related phase lags between precipitation and radiation and also for storage characteristics. While, I like the scope of the study and agree that the proposed generalizations are really important, I think the study suffers from several short comings.

Response:

Thank you very much for taking time to review our manuscript. All comments are greatly appreciated and considerably improve our manuscript. We have addressed all the comments carefully and will make revisions accordingly.

2. My major concern is the obvious inconsistency between the “discretization” of the hydrological year into 4 months long periods, with the conceptualization of the first partitioning stage of the Ponce-Shetty model. The idea that precipitation equals recharge/infiltration dW of/in the subsurface store and fast “flow” Q is only correct during rainfall events, because evaporation and transpiration can be neglected then.

P= Q + dW.

This equation is not correct during a 4 months period, consisting of rain and fair weather periods, it simply violates the mass balance, because parts of P are released as evaporation and transpiration during this period. This implies that a one parameter Budyko (Eq 17.) cannot be used to model this partitioning for increments of 4 months, because in this time precipitation is simply not equal to fast runoff and storage change, but parts are released as ET. This does simply violate mass conservation at the soils surface, and the problem arises from the fact that the entire model is formulated for steady state partitioning, which essentially implies that storage changes are zero. This can be easily inferred from the water balance equation for any compartment (e.g. the soil), which should be the based for any kind of model concept (which is not the case here). So I think that the entire model analysis is based on a physically inconsistent reasoning. Either you have changes in storage or have steady states, you cannot have both.

Response:

Thank you very much for your comments. In the second partitioning stage, wetting (W_j) is decomposed into evaporation (E_j) and baseflow ($Q_{b,j}$), which is consistent with mass conservation. The objective of assuming two partitioning stages is not to simulate water storage variations after a specific rainfall event, but to describe a 4-month water balance. Thus, variables in the two partitioning stages are quantities after aggregating all hydrological processes over a 4-month timescale. Equation (17) for the first partitioning stage can be viewed as an approximate quantification after summing all rainfall events. Water storage decreases after rainfall events, and the second partitioning stage describes hydrological processes that are aggregated during all periods without rainfall. Likewise, the original Ponce-Shetty model uses these two partitioning stages to formulate an annual water balance consisting of multiple rainy and fair weather periods (L′vovich, 1979; Ponce and Shetty, 1995).

The Ponce-Shetty model derives the equations for modelling two partitioning stages based on the proportionality hypothesis (Ponce and Shetty, 1995; Sivapalan et al., 2011). Here we used the mathematic forms of Budyko-type equations because Budyko hypothesis shares the same upper and

lower bounds as the proportionality hypothesis (Wang et al., 2015; Zhao et al., 2016). Empirical data also validate their upper and lower bounds (Sivapalan et al., 2011). Applying the mathematical forms of Budyko-type equations to model these two partitioning stages has been suggested by Sivapalan et al. (2011), as cited "Guided by additional physical insights and process understanding, other mathematical forms could be adopted for these relationships (of two partitioning stages); this is left for further research".
The "discretization" of the hydrological year into three 4-month periods is based on the assumption of zero carrying-over water storage between two consecutive time intervals. Validation of this assumption is provided in the reply to comment #2 of the first reviewer.

3. The manuscript would benefit from proof reading, at least I miss "definite articles" in front of many nouns.
Response:
Thank you for your comment. We will check the articles and improve this manuscript.

4. I would avoid abbreviations like "E" in headers, there are better ways to keep thinks short.
Response:
We will improve our expressions.

5. Fluxes are generally equal to storages changes in time (not to storage itseltf), would be nice to have proper equations, with proper variable definitions.
Response:
Thank you for your comment. We will revise our definition of wetting (W_j) and explain most variables from a water balance perspective. In the revision, wetting (W_j) will be redefined as the fraction of precipitation not contributing to surface runoff, the same as Ponce and Shetty (1995).

6. I miss units/dimensions for most of the variables.
Response:
Climatic variables in this study share a common unit of a millimeter (Line 93-95). We will also add units in all figures.

7. Equation 8 proposes that the entire stock is "active" and released as base flow or ET. This is not consistent with soil physics and soil water retention curve, which corroborate that water stored at tension larger than pF =4.2 (permanent wilting point) is not available for transpiration (and also not for base flow generation).
Response:
Thank you for your comment. We will revise the definitions of W_j as in the reply to comment #5. In addition, water storage capacity (S_c) will be calculated from permanent wilting to field capacity.

8. Eq. 9 is not correct, see comment above, expect that the authors refer to the active storage.
Response:
Thank you for your comment. We will revise the definitions of W_j as in reply to comment #5.

9. With boundary conditions you mean upper and lower bounds of the terms?

Response:

Yes. Boundary conditions define constrains for the solutions of two partitioning stages. They are the basis for analytically deriving the Budyko-type equations (Zhou et al., 2015).

10. P going to infinity doesn't make sense to me, at least not physically.

Response:

The objective of assuming P to be infinite is to explore the upper bound of W_j in a very wet condition (i.e., P/Sc to be infinite). Although catchments with infinite P/Sc rarely exist in reality, this assumption provides the upper bound for analytical derivation. Similarly, the Budyko-type equations are derived by assuming P/PE to be infinite (Yang et al., 2008; Zhang et al., 2004; Zhou et al., 2015).

11. Soil water storage is also limited by infiltration capacity, not only by storage volume. Both factors are not necessarily correlated, think about clay soils.

Response:

We agree that multiple factors may limit soil water storage. Incorporating infiltration capacity is necessary for hydrological models at a daily or hourly timescale. However, infiltration capacity may not largely impact evaporation at the monthly timescale, given that some monthly hydrological models do not incorporate infiltration capacity (Martinez and Gupta, 2010; Thomas, 1981; Zhang et al., 2008; Zhang et al., 2020). Thus, our equations for mean annual evaporation do not include this parameter in order to maintain a parsimonious framework.

Reference:

L′vovich, M.I. (1979) World water resources and their future, American Geophysical Union.

Martinez, G.F. and Gupta, H.V. 2010. Toward improved identification of hydrological models: A diagnostic evaluation of the "abcd" monthly water balance model for the conterminous United States. Water Resources Research 46(8), W08507.

Ponce, V.M. and Shetty, A.V. 1995. A conceptual model of catchment water balance: 1. Formulation and calibration. Journal of Hydrology 173(1), 27-40.

Sivapalan, M., Yaeger, M.A., Harman, C.J., Xu, X. and Troch, P.A. 2011. Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. Water Resources Research 47(2).

Thomas, H.A. 1981 Improved methods for national water assessment, water resources contract: WR15249270, p. 59.

Wang, D., Zhao, J., Tang, Y. and Sivapalan, M. 2015. A thermodynamic interpretation of Budyko and L'vovich formulations of annual water balance: Proportionality Hypothesis and maximum entropy production. Water Resources Research 51(4), 3007-3016.

Yang, H., Yang, D., Lei, Z. and Sun, F. 2008. New analytical derivation of the mean annual water-energy balance equation. Water Resources Research 44(3), W034103.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W. and Briggs, P.R. 2004. A rational function approach for estimating mean annual evapotranspiration. Water Resources Research 40(2), 1-14.

Zhang, L., Potter, N., Hickel, K., Zhang, Y. and Shao, Q. 2008. Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. Journal of Hydrology

360(1), 117-131.

Zhang, S., Yang, Y., McVicar, T.R., Zhang, L., Yang, D. and Li, X. 2020. A proportionality-based multi-scale catchment water balance model and its global verification. Journal of Hydrology 582, 124446.

Zhao, J., Wang, D., Yang, H. and Sivapalan, M. 2016. Unifying catchment water balance models for different time scales through the maximum entropy production principle. Water Resources Research 52(9), 7503-7512.

Zhou, S., Yu, B., Huang, Y. and Wang, G. 2015. The complementary relationship and generation of the Budyko functions. Geophysical Research Letters 42(6), 1781-1790.