The Budyko framework beyond stationarity

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Referee comment

Referee #2:

We thank the reviewer for her/his comments. It is our assessment that the criticism can be pinned down to three major issues. These will be addressed at first, followed by a point-to-point response to the specific comments. Unfortunately, it was sometimes hard to fully grasp the reviewers intent, due to incomplete sentences, typos and inconsistent punctuation. However, we attempt to respond to the concerns raised by the reviewer in the best possible way.

General comments

1. The reviewer argues that the modified boundary condition provided in equation 7 is not correct. However, a key assumption underlying the original Budyko framework is stationarity, i.e. water storage does not change over time. This assumption is further also expressed in the boundary conditions underlying Fu's equation. The aim of our study is to relax the stationarity assumption and to explicitly account for storage changes. This could be e.g. the case due to seasonal changes in water storage components such as soil moisture or groundwater, e.g. due to carry-over effects from wet to dry seasons. Hence, even under conditions of low water supply through P, high rates of E can be sustained and consequently E>=P. This is also evident in Figure 10a, where springtime values of E/P usually exceed the steady-state supply limit.
This results in the modified (and criticized) boundary condition. Since E>=P is possible, y = (P-E)/Ep is not necessarily positive, but necessarily larger than -1 (since we assume that E<=Ep). At y0, E is then limited by P and water storage changes and a further increase in Ep has no effect on E. This (and only this) is expressed in equation 7, after redefining the sign convention of the minimum value ymin (y0 = -ymin) for convenience. We regret that we did not manage to communicate this clearly in the submitted manuscript and we will revise this accordingly. It is further not evident to us, why the Bouchet-Morton (or complementary) relationship does invalidate our very basic assumption dE/dEp =0 at -y0 if we assume E<=Ep. This would also imply that the well-established and widely-used assumptions of Fu (1981) and Zhang et al. (2004) are invalid. A more thorough explanation on the strong statement of the reviewer that our assumption is invalid would have been beneficial.

2. The reviewer criticized that many different y0-parameters (for each individual month) are needed to compute E. However, this is only the case in monsoon regions with complex seasonal hydroclimatology. Figure 9a shows that for the vast majority of land regions a single y0-value is sufficient to obtain high correlations between the modeled and observed time series. Also figure 10 shows that for a region in central Europe the model performs equally well with a single y0-value compared to multiple y0-values for each month. We will revise the text to really make clear that there is in fact no need for monthly values of y0 in most land regions and a single value is sufficient. However, we also make clear that a single y0-value does not permit an adequate assessment of the more complex seasonal pattern in monsoon climates and hence, more elaborate parameter sets are needed.

3. We further would like to stress that the manuscript is a manipulation of (or a development based on) Fu's equation, which will also be clearly communicated in the revised version.

Specific points

The specific points displayed below do represent our attempt to reformat the formless structure of the text provided by the reviewer.

Comment: p6800 lines 8-9: the water balance is always closed what you meant I think is negligible storage
Response: Thanks! We will revise the text accordingly.

Comment: p6801 before equation 1 define the time scale of applicability and the fact that Budyko only applies on large-scale to remove groundwater contribution improve the clarity of paragraph
Response: Thanks! We will add this information to the revised text.

Comment: after equation 1: why would it be only a problem with supply it is steady for both
Response: We will revise the text accordingly.

Comment: line 4: You should cite Zhou et al. 2015 GRL, which is close to your derivation Change "complex hybrid of various"...
Response: We cited Zhou et al. (2015) already in line 1, but we will cite it here as well. Zhou et al. (2015) is now cited several times throughout the manuscript. We will also change the text accordingly.

Comment: Equation 2 is missing groundwater and you should state that it is valid at the watershed level otherwise you need to include lateral flow
Response: Groundwater is included in S, which integrates all relevant terrestrial water storage components such as soil moisture, snow, water stored in vegetation, groundwater, etc. For the purpose of our study it is not necessary to distinguish these (although it might be important for detailed investigations). We will also clarify that we consider catchment scales.

Comment: p6802: in fact multi-year varilability has to be avoided for the budyko framwework to be valid, this should be discussed clearly line 6: even on interannual time scales Budyko is not valid (see carry over effect of water storage so that the budyko curve can be higher than 1 for instance)
Response: We will add this information to the revised text. It is further important to note that even though the physical processes leading to E>=P are different at monthly, seasonal and multi-annual time scales, the response itself is similar (i.e. the exceedance of the supply limit). Hence, our modification of Fu's equation is in fact capable to also represent carry-over effects on multi-annual time scales.

Comment: Equations 3 and 4: have a look at Zhou et al. 2015 GRL
Response: As mentioned above we are aware of Zhou et al. (2015), which was also cited in the submitted version of the manuscript. However, we modify here the derivation of Fu's equation. Equation 3,4,5 and 6 do exactly represent the set of differential equations and boundary conditions as introduced by Fu (1981) and Zhang et al. (2004).

Comment: p6805: y0 is really a function of time, you should comment on this
Response: Not necessarily. In fact, y0 is clearly defined as the minimum value of equation 4a under given conditions. It thus represents the maximum amount of additional water besides P that is available to E. However, y0 is (similar to k) also a function of several other (yet unknown) variables and quantities See also general comment 2.

Comment: line 7: y0=1 you could mention that this is when E=Emax=Ep. Also you should clearly define Ep because E can be larger than Ep in many cases (because of roughness or large LAI)
Response: We will add this information to the text. We further refer to the very general, standard definition of Ep that ideally accounts for all potential controls (including roughness and LAI). We do not

refer to any specific estimate of Ep (as e.g. Penman, Thornthwaite, etc.). Hence, Ep is always larger or equal to E.

Comment: p6806 can you give more physical explanation after equation 11
Response: We will add an additional sentence to the revised manuscript, clarifying that y0 represents an estimate of the maximum amount of water that originates from storage changes and contributes to E. See also our response to a previous comment.

Comment: section 5: please carefully discuss the time scale effect Also Penman Monteith should be Penman for potential evaporation. What is done for the reference roughness? What do you consider as a reference, this is important.
Response: We use here a monthly, global dataset which can be downloaded here: http://hydrology.princeton.edu/data.pdsi.php and which is based on a Penman-Montieth Ep algorithm. Details are provided in the Methods section of Sheffield et al., 2012. The Penman-Monteith equation is originally defined to compute actual E. However, if the stomatal resistance is set to zero, the Penman-Monteith equation provides an estimate of Ep. The aerodynamic resistance is further defined after: Shuttleworth, W. J. in *Handbook of Hydrology* (ed. Maidment, D. R.) 4.1–4.53 (see also Sheffield et al., 2012)

Comment: p6809: define your frequency of y0 computation end of section 5: you should have a discussion on the fact that you have added many parameters to really retrieve E (see Fig 9) so it is not really a predictive model but more a model for physical interpretation. Also the main trouble is that we do not have access to E at the watershed scale so how can this be used on water shed data where P and Q only are measured?
Response: Please see general comment 2. The new formulation is further not intended to solely work for watershed data, but also for other spatial units (e.g. gridboxes). Also, the new formulation does not provide estimates of Q, but represents a simple method to model E. It is our assessment that the estimation of E (also at other than watershed units) is of great importance for numerous assessments and applications in climate science.

Comment: p6811 line21: physically well defined: in fact it is more mathematically defined some physical explanation would be nice.
Response: Thanks. We will change the wording accordingly.

Comment: Equation A1: can you give further steps for this equation? Derivation A2 to A8 is very elegant.
Response: Thanks! Equation A1 simply represents a necessary condition that needs to be fullfilled to solve the set of differential equations presented in the main text. This approach is, however, similar to the derivation presented in Fu (1981) and Zhang et al. (2004).

Comment: Figure 9: we really need at least monthly estimates of y0 to get ET right so why not run a simple water balance model?
Response: See general comment 2.