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A general framework for understanding the response of the water cycle to global warming over land and ocean

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Response to Comments by Referee (Prof. Savenije)

Referee comments in Italics

This is a very interesting and well prepared paper, which clearly shows that interpretation of climate change effects only make sense if we distinguish between land and ocean, where the land is moisture constrained whereas the ocean is not. The Budyko framework is a very useful way to analyse the sensitivity of the hydrological fluxes to changes in energy and precipitation input. This paper is brilliant in its simplicity, and I very much welcome a resubmission.

We thank the reviewer for the positive comments.

There are two sets of comments that I would like to make. The first set refers to the correct use of units, the second to an additional feature that becomes clear if a different functional form of the Budyko curve is chosen.

1a. In the paper the evaporation is sometimes expressed as a volumetric flux per unit area (mm year) and sometimes as an energy flux per unit area (W m-2). In the latter case the evaporative flux is symbolized by LE. Although the paper doesn't say so, the convention for L (Specific latent heat) is the energy (heat) required to evaporate 1 kg of water (=2.45 kJ/g). It then still requires multiplication with the density to become a volumetric flux per unit area. So the equation should use ρLE for LE (if E is expressed in a volume flux per unit area, as the paper does). Unless of course L has the unit J m-3. So preferably include the density, or explain that L includes the density. This also applies to all the places where LE or LE are used (eqs. 5, 6, 7, 8, 11, 12; p15275, L10, L19; p15276, L1, L5; p15277, L8 and caption of Table 2).

Good point. We use common hydrologic units (volume per area per time) but we agree that it is dimensionally inconsistent. The equations themselves are dimensionally correct – it is in the tables and in the Budyko analysis where we make this dimensional error. We could spell this out in section 2 (Methods).

1b. Another mistake often made is that G in eq.(5) is not the storage of heat, but the storage increase over time. It is the temporal derivative of the heat storage and not the storage itself, as is suggested on p15274, L7 and in the caption of Table 2. This may seem like nitpicking, but in HESS we want to be precise in the correct use of units and dimensions. Of course one might say that the term storage means the process of storing, but this is not what in hydrology is the convention. The storage of water is the water stored. The term dS/dt in the *water balance means the temporal change of storage and not the storage; similarly G is the temporal change of heat stored in the earth and not the amount stored. The temporal derivative of the storage is the process of storing or depleting. Maybe a way out is to replace the term 'heat storage' into 'the process of heat storage', or to replace it with 'heating up'.*

Good point. We agree. We can use the suggested terms or we could say the change in enthalpy which is actually what that term represents.

2. The authors prefer to use a Budyko curve of the type presented in (1). A simpler form of the Budyko curve is

$$\frac{E}{P} = \left(1 - \exp\left(-\frac{E_0}{P}\right)\right)$$

This exponential equation may have the disadvantage that it does not have the additional parameter n, which allows additional tuning, but the authors don't make use of n anyway. An advantage of this equation is that it links to the probability distribution of rainfall (see: De Groen and Savenije, 2006, and Gerrits et al., 2009), and hence has some physical reasoning behind it. A further advantage of this equation is that ε_o *and* ε_p *have physical meaning. It can be shown that* ε_o *equals the runoff coefficient:*

$$\varepsilon_o = \frac{P-E}{P} = \frac{Q}{P} = C_R$$

This follows simply from partial differentiation of the exponential Budyko curve. In fact, Figure 3b shows the global distribution of the runoff coefficient. If the colour scale is changed to a maximum of 1.0 (now it is scaled at a maximum of $16*10^{-1}$*=1.6, which is a physically impossible number), then we recognise immediately the distribution of the runoff coefficient over the world. I think using the exponential definition of the Budyko curve makes the paper even more transparent. In addition it can be shown that:*

$$\varepsilon_p = 1 - \frac{E}{P}\left(1 - \frac{E_0}{E}C_R\right) = 1 - \frac{E}{P} + \frac{E_0}{P}C_R = \left(1 + \frac{E_0}{P}\right)C_R$$

So ε_p *is proportional to the runoff coefficient and is strengthened by the aridity index. These expressions can also be obtained directly by derivation of the exponential Budyko curve:*

$$\mathrm{d}Q = \frac{\partial Q}{\partial P}\mathrm{d}P + \frac{\partial Q}{\partial E_0}\mathrm{d}E_0$$

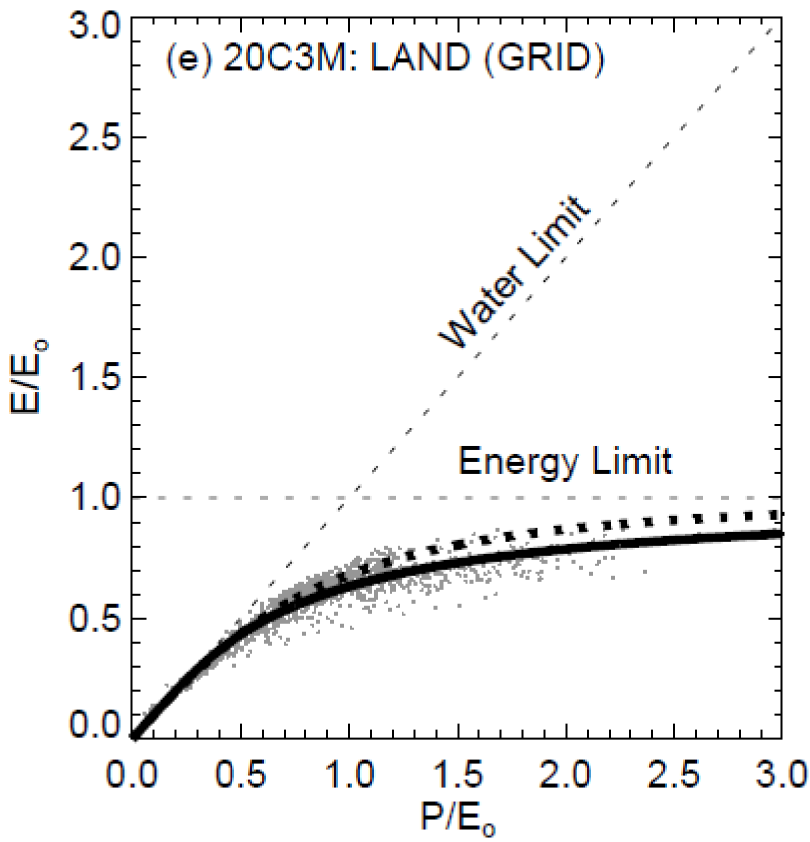
$$\mathrm{d}Q = \frac{Q}{P}\left(1 + \frac{E_0}{P}\right)\mathrm{d}P - \frac{Q}{P}\mathrm{d}E_0 = C_R\left(\left(1 + \frac{E_0}{P}\right)\mathrm{d}P - \mathrm{d}E_0\right)$$

or:

$$\frac{\mathrm{d}Q}{Q} = \left(1 + \frac{E_0}{P}\right)\frac{\mathrm{d}P}{P} - \frac{\mathrm{d}E_0}{P}$$

We see that the main control on runoff change is the runoff coefficient itself. The larger the runoff coefficient, the larger the runoff increases with increasing precipitation. Further, since the change in the potential evaporation is not so large, the runoff change is affected by the aridity index E_0=P. The aridity index strengthens the sensitivity of runoff to rainfall.

Very good point/s and a very clear commentary. We first note that this sensitivity framework is not actually in the cited references – as far as we are aware it is presented in this particular review for the first time! We agree that the resulting partial differentials are easier to interpret. We have also plotted the suggested form for the Budyko curve. In the modified Fig. 2e we show the new form suggested by Prof Savenije:



Modified Fig. 2e New form of the Budyko curve is shown as a full heavy line and falls slightly below the original dashed line.

We conclude that the Savenije equation actually follows the data more closely than our original default equation. If we modified our default equation to use n=1.5 (as noted in the original figure caption) then it would be more or less the same as the Savenije equation.

Thus the new framework offered by Prof Savenije has some clear advantages. Given that we chose not to use the tunable parameter (n) it was suggested we could use this new and simpler form. Alternatively, in real catchments the additional parameter is actually needed to adequately account for the observed variation (Donohue et al 2011 J Hydrology) and a theoretical basis is currently being developed (Roderick & Farquhar 2011 WRR, Donohue et al 2012 J Hydrology) to express that parameter in terms of standard hydrologic quantities; mean storm depth, soil water holding capacity and effective rooting depth of the vegetation.

That form also has a strong theoretical basis in terms of satisfying mathematical boundary conditions (Yang et al 2008 WRR).

We conclude that the presentation by Prof Savenije is highly novel and worthy of publication in its own right.

Further, we were aware that the maximum physical value is 1 in Fig. 3b. We simply could not draw the figure appropriately using our software. We agree that a better scale would make it clearer and will attempt to remedy that in the revision.

Michael L. Roderick, Fubao Sun, Wee Ho Lim, Graham D. Farquhar, 13/3/2014