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# *Interactive comment on* "A general framework for understanding the response of the water cycle to global warming over land and ocean" *by* M. L. Roderick et al.

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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.

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$^{-1}$) 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 ($L$=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 $\rho LE$ 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 $\rho$, or explain that $L$ includes the density. This also applies to all the places where $LE$ or $\Delta LE$ are used (eqs. 5, 6, 7, 8, 11, 12; p15275, L10, L19; p15276, L1, L5; p15277, L8 and caption of Table 2)

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 d$S$/d$t$ 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'.

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 $\varepsilon_o$ and $\varepsilon_p$ have physical meaning. It can be shown that $\varepsilon_o$ 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 $\varepsilon_p$ 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.

References: De Groen, M.M., and H.H.G. Savenije, 2006. A monthly interception equation based on the statistical characteristics of daily rainfall. Water Resources Research, 42, W12417, p. 1-10.

Gerrits, A.M.J., H.H.G. Savenije, E.J.M. Veling, and L.Pfister, 2009. Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model, Water Resources Research, 45, No. 4, W04403, p.1-15.

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