Review of hess-2020-310 "Comment on: A review of the complementary principle of evaporation: From the original linear relationship to generalized nonlinear functions by S. Han and F. Tian"

This is a review for this manuscript on behalf of S. Han and F. Tian.
This manuscript is a comment on the sigmoid generalized complementary (hereafter SGC) principle, which was developed by us in Han et al. (2012) and Han and Tian (2018) (hereafter HT18), and was reviewed in Han and Tian (2020) (hereafter HT20). Thus, this review can also be regarded as our reply to the authors' comment.

We are happy to have the conversations regarding the complementary principle, and would like to thank R. Crago, J. Szilagyi and R. Qualls for their comment. We think this manuscript is worth for publication after considering comments below.

To the best of our understanding, the authors have four claims in the comment: (1) mathematical local calibration, (2) physical assumption of the CR, (3) observational support and (4) theoretical derivation for the boundary conditions. Each of the claim will be listed and commented separately below.

1) The SGC equation models evaporation with two calibrated parameters (*a* and *b* in HT18), which violates the aim of former CR: "without requiring local calibration".

Comments: To some extent, we agree with the argument that "any CR formulation must ultimately work well without requiring local calibration of parameters". In fact, calibration-free is the dream of any model development. However, there are two routes in the studies of CR leading to this ultimate objective. One adopts an existing complementary relationship with default parameter(s), and concentrates on properly formulating the potential evaporation Epo and/or apparent potential evaporation Epa, or carefully rescaling the independent variable of an existing CR model. The authors' work with the "rescaled" CR (Crago & Qualls, 2018; Crago et al., 2016; Szilagyi et al., 2017) follows this route. We believe that, if proper formulations of Epa and/or Epo, and/or appropriate rescaling approaches are carefully conducted on a physical basis, a calibration-free CR evaporation estimation model could be ultimately achieved.

The other route, calibrating parameters for the fitting of observed points and proposing a method to determine the parameters *in priori*, is widely used in evaporation modeling (Monteith, 1965; Shuttleworth, 1993; Yang et al., 2007). Local calibration is just the first step. After the first step of local calibration, we have been working on the priori determinate of the parameters. In our recent published paper (Wang et al., 2020), we found that the parameter *b* changes with the ecosystem type, and used the ecosystem mean b values of 217 sites around the world in the B2017 with little weakening of the evaporation estimation accuracy. We are also working at the characteristics and determination methods of the other parameter *a* (Han et al., 2020).

In our opinion, both methodologies are deserved to be explored.

2) The SGC equation adopts a wet boundary condition (denoted as BC4 in the manuscript) only occurring when advections from outside (Brutsaert & Stricker, 1979) or large-scale synoptic changes (Liu et al., 2011; Shuttleworth et al., 2009) play important roles in determining the near-surface atmospheric variables, which violates the central assumption of the CR: the land surface wetness can be effectively detected from the overlying drying power of air with a constant radiation energy input (e.g., Brutsaert, 1982, 2005).

Comment: We totally agree that our wet boundary condition violates the central assumption of the CR. However, this can be regarded as an extension of original CR principle.

The complementary principle was originally proposed for the evaporation taking place from “a sufficiently large and homogeneous surface” (Brutsaert, 2015), over which the advection effects of heat and water vapor from outside are negligible or changeless (Brutsaert & Stricker, 1979; Han & Tian, 2018b; Morton, 1983). The complementary principle employs an assumption that the land surface wetness can be effectively detected from the drying power of air with a constant radiation energy input (Brutsaert, 1982; Han & Tian, 2018a, 2020). Following this assumption, we expressed $\frac{E}{E_{Pen}}$ as a function of the atmospheric wetness index $\frac{E_{rad}}{E_{Pen}}$, claimed that "the spirit of the complementary principle is still retained" (Han & Tian, 2018a), and proposed a SGC function.

The boundary condition BC4 and the upper flatness feature of the SGC function require that both E and E_{aero} increase with constant E_{rad} when E/E_{Pen} decreases from the unit (Han & Tian, 2018a, 2019). If E_{rad} is constant, an increase in E_{aero} means an increase in the vapor pressure deficit if the wind speed is changeless. But according to the assumption of the complementary principle, the vapor pressure deficit could only increase if less water was evaporated into the air, which means a decrease in E. Thus, BC4 and the upper flatness feature of the growth of $\frac{E}{E_{Pen}}$ upon $\frac{E_{rad}}{E_{Pen}}$ was questioned by considering that it is impossible for E and E_{aero} change in the same direction over a nearly wet surface (Szilagyi & Crago, 2019).

However, over a natural landscape, there are situations that advections from outside (Brutsaert & Stricker, 1979) or large-scale synoptic changes (Lintner et al., 2015; Shuttleworth et al., 2009) play important roles in determining the near-surface atmospheric variables. Then, the land surface and the atmosphere are not necessarily fully coupled. If considering the second type processes, the same direction changes in E and E_{aero} could be understood. For example, the horizontal advection of hot dry air to the wet surface would enhance both E and E_{aero} with constant E_{rad}. Thus the growth of $\frac{E}{E_{Pen}}$ upon $\frac{E_{rad}}{E_{Pen}}$ is slower with larger values of $\frac{E_{rad}}{E_{Pen}}$, which is an upper flatness feature.

In our preparing paper (Han et al., 2020), we investigated the relationship between $\frac{E}{E_{Pen}}$ and $\frac{E_{rad}}{E_{Pen}}$ over wet surfaces as the extremes. Although the assumption of the complementary principle does not hold over the land surface with ample and changeless water availability, $\frac{E_{rad}}{E_{Pen}}$ varies significantly due to the advections or the large-scale synoptic changes, and $\frac{E}{E_{Pen}}$ is still highly related with $\frac{E_{rad}}{E_{Pen}}$, and their relationship still can be described be the SGC equation. Especially, the growth of $\frac{E}{E_{Pen}}$ upon $\frac{E_{rad}}{E_{Pen}}$ (as well as E upon E_{rad}) exhibits nonlinear characteristics with slowing down growth rate for large values of $\frac{E_{rad}}{E_{Pen}}$. The results imply that $\frac{E}{E_{Pen}}$ can be expressed as a function of $\frac{E_{rad}}{E_{Pen}}$ no matter its changes come from the land surface (changes in water availability) or the atmospheric aspects (the advections or the large-scale synoptic changes). From this point, we think the complementary principle could be further generalized to cover the later processes.

Although BC4 violates the assumptions of the CR, we don't agree that it makes the exception. When above processes are negligible, the coupled land-atmosphere system can be simplified as a one-dimension vertical column, in which the land surface and overlying atmosphere are fully connected. This condition can be satisfied more easily at monthly timescale than the daily timescale. For a natural landscape, advections from outside or large-scale synoptic changes would always exist, especially at a short timescale (daily for example). Besides, the relative importance of the two processes would vary with the wetness of the surface. Under water-limited conditions, the actual evaporation and potential evaporation are tightly linked via the surface, whereas the regional or large-scale advection plays a greater role than the landscape-scale processes under energy-limited conditions (Lintner et al., 2015). For a natural landscape, the simultaneous presence of above two processes may explain why the points of $\frac{E}{E_{Pen}}$ upon $\frac{E_{rad}}{E_{Pen}}$ are scatter. The further generalization of the complementary principle could help understand the variations of parameters of the complementary functions and aid in the parameter acquisition, thus enhancing the capability of the complementary principle to estimate evaporation.

3) BC4 and the third-stage of the relationship between $\frac{E}{E_{Pen}}$ and $\frac{E_{rad}}{E_{Pen}}$, which lead to a sigmoid function, are not well supported by empirical data.

Comment: We acknowledge that it is not easy to verify BC4, either to supply a visible example of the three-stage pattern (mainly the third stage) with observed data. According to BC4, $\frac{dy_H}{dx_H}$ should be zero at the maximum x_H, which implies that the slope should be near zero around the point with maximum x_H. By contrast, the corresponding boundary condition under the strict assumption of CR is $\frac{dy_H}{dx_H} = \alpha$ at the maximum x_H. Considering it is difficult to verify the derivative at a specific point, we evaluated the slopes of y_H on a range of x_H as a compromise. As the slope is not calculated at the specific point (maximum x_H), it will not be near zero. But the smaller value of the slope for large values of x_H compared to α can serve as an evidence. With a wide range of x_H (larger than a critical value between 0.45~0.70) (HT18, Table 3), the calculated slopes ranged from 0.39- 1.30, and most of the sites (except for AU-How and NL-Loo) were characterized with the slopes smaller than α. At two sites, the slopes are much less than 1. The calculated slopes would be much closer to zero if the evaluating was conducted much near to the maximum x_H.

We think that above empirical data would support that the growth of y_H on x_H has an upper flatness part. Based on the work of HT18, we have been working on the visible supports for the third-stage. In our preparing manuscript (Han et al., 2020), we found that the relationship between daily $\frac{E}{E_{Pen}}$ and $\frac{E_{rad}}{E_{Pen}}$ is characterized with an obvious upper flatness part (the third stage) over open water surface of lakes and ocean. The observed data at five lake sites from the Lake Taihu Eddy Flux Network (Lee et al., 2014) and the global ocean surface evaporation product (Version 3) from the OAFlux project (Yu & Weller, 2007) could serve as visible surports. The deviation of the Priestley-Taylor (PT) coefficient from a fixed value around 1.26 also indicates this upper flatness third stage.

Please refer to our preparing paper (Han et al., 2020) for details.

4) The derivations of BC4 and the sigmoid function were doubtful.

Comment: To the best of our knowledge, x_m is a prognostic variable, which is calculated from the observed meteorological variables, and may be related to the aridity (Ma & Szilagyi, 2019). By contrast, in the SGC equation, $y_H = f(x_H, m, n, x_{min}, x_{max})$, we treated x_H as the only independent variable, but the others as parameters. x_{min} and x_{max} are parameters, and would affect y_H as parameters. From this point, x_{min} is different from the variable x_m in the "rescaled" CR.

We understand that the authors' concern comes from the considerations and treatments on the two parameters x_{min} and x_{max} during the derivation of BC4 and the SGC equation. Following the method of the derivation of the complementary relationship by supposing a constant energy input (Bouchet, 1963; Brutsaert & Stricker, 1979), our derivation began with an assumption of certain magnitude of E_{rad}. The values of x_{min} and x_{max} depends on the relative magnitude of the maximum and minimum values of the aerodynamic term to E_{rad}. Thus, x_{min} and x_{max} would be roughly affected by the magnitude of E_{rad}. We clearly pointed out in HT18 that "x_{max} is not independent of E_{rad}". Similar to the Priestley-Taylor coefficient, x_{max} is thought to vary with the environment, but is used as a calibrated constant parameter in the SGC equation for convenience. x_{max} is widely with a value of one.

Our derivation of the wet boundary conditions begins with an assumption of $E = E_{Pen} = E_{rad} + E_{aero}$, $\frac{E_{rad}}{E_{Pen}} = x_{max}$. Equation (17) in HT18 follows this assumption. There are two solutions for Equation (17) to hold. We adopts $\left.\frac{dy}{dx}\right|_{y=1} = 0$ in our SGC equation. However, $\left.\frac{dy}{dx}\right|_{y=1} = \frac{1}{x_{max}}$ is other solution, which is adopted in B2015.

To the best of our understanding, above two solutions represent two conditions, and can hold under each condition. $\left.\frac{dy}{dx}\right|_{y=1} = 0$ represents the condition when only advections or large-scale synoptic changes work, whereas the other represents only the land surface-atmosphere interactions work. The experimental studies in our preparing manuscript (Han et al., 2020) showed both the two conditions.

However, we have that the BCs under wet environments are complicated and are not well understood till now. This is why we stated at the end of HT20 that "it should be carefully examined for its physical base of the boundary conditions in a completely wet environment."

Other comments：

Line 30-39: The Priestley-Taylor line $E = \alpha E_{rad}$, which is equal to $\frac{E}{E_{Pen}} = \alpha \frac{E_{rad}}{E_{Pen}}$, is set as a limit on wet surface evaporation. Under the constraints on the parameters, the curve will not across the PT line. It is widely accepted that the Priestley-Taylor coefficient varies with the environment. For a wet surface, we found that evaporation would be less than E_{Pen}, but roughly equal to $E_{PT} = \alpha E_{rad}$. The SGC equation can used to represent the wet surface evaporation with varying PT coefficient. The reference point, $(x_H = x_{max},\ y_H = 1)$, represents the wet surface evaporation with the minimum Priestley-Taylor coefficient. This will be detailed in the manuscript in prepare (Han et al., 2020).

Line 54-56: We think that the wet surfaces with large-scale processes should not be considered as exceptional cases. Please refer to our preparing manuscript (Han et al., 2020).

Line 86: Because of the PT coefficient, $\frac{dy_H}{dx_B} = 1$ $(x_B = \frac{\alpha E_{rad}}{E_{Pen}})$ is equivalent to $\frac{dy_H}{dx_H} = \alpha$.

References:

Bouchet, R. (1963). Evapotranspiration réelle et potentielle, signification climatique. *International Association of Hydrological Sciences Publication, 62*, 134-142. Retrieved from http://12 - 12

Brutsaert, W. (1982). *Evaporation into the Atmosphere: Theory, History, and Applications*: D. Reidel-Kluwer, Hingham.

Brutsaert, W. (2015). A generalized complementary principle with physical constraints for land-surface evaporation. *Water Resources Research, 51*(10), 8087–8093, doi:8010.1002/2015WR017720. doi:10.1002/2015wr017720

Brutsaert, W., & Stricker, H. (1979). An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resources Research, 15*(2), 443-450. Retrieved from http://16 - 16

Crago, R., & Qualls, R. (2018). Evaluation of the Generalized and Rescaled Complementary Evaporation Relationships. *Water Resources Research, 54*, 8086-8102. doi:10.1029/2018WR023401

Crago, R., Szilagyi, J., Qualls, R., & Huntington, J. (2016). Rescaling the complementary relationship for land surface evaporation. *Water Resources Research, 52*(11), 8461-8471. doi:doi:10.1002/2016WR019753

Han, S., Hu, H., & Tian, F. (2012). A nonlinear function approach for the normalized complementary relationship evaporation model. *Hydrological Processes, 26*(26), 3973-3981.

Han, S., & Tian, F. (2018a). Derivation of a sigmoid generalized complementary function for evaporation with physical constraints. *Water Resources Research, 54*(7), 5050-5068. doi:doi: 10.1029/2017WR021755

Han, S., & Tian, F. (2018b). Integration of Penman approach with complementary principle for evaporation research. *Hydrological Processes, 32*(19), 3051-3058.

Han, S., & Tian, F. (2019). Reply to Comment by J. Szilagyi and R. Crago on “Derivation of a sigmoid generalized complementary function for evaporation with physical constraints". *Water Resources Research, 55*(2), 1734-1736. doi:10.1029/2018WR023844

Han, S., & Tian, F. (2020). A review of the complementary principle of evaporation: from the original linear relationship to generalized nonlinear functions. *Hydrology And Earth System Sciences, 24*(5), 2269-2285. doi:10.5194/hess-24-2269-2020

Han, S., Tian, F., Wang, W., & Wang, L. (2020). Sigmoid generalized complementary equation for evaporation over wet surfaces: as a nonlinear modification of the Priestley-Taylor equation.

Lee, X., Liu, S., Xiao, W., Wang, W., Gao, Z., Cao, C., . . . Wang, Y. (2014). The Taihu Eddy Flux Network: an observational program on energy, water and greenhouse gas fluxes of a large freshwater lake. *Bulletin Of The American Meteorological Society, 95*, 140530112919008.

Lintner, B., Gentine, P., Findell, K., & Salvucci, G. (2015). The Budyko and complementary relationships in an idealized model of large-scale land–atmosphere coupling. *Hydrology And Earth System Sciences, 19*(5), 2119-2131.

Liu, H., Blanken, P. D., Weidinger, T., Nordbo, A., & Vesala, T. (2011). Variability in cold front activities modulating cool-season evaporation from a southern inland water in the USA. *Environmental Research Letters, 6*(2), 024022. doi:10.1088/1748-9326/6/2/024022

Ma, N., & Szilagyi, J. (2019). The CR of Evaporation: A Calibration-Free Diagnostic and Benchmarking Tool for Large-Scale Terrestrial Evapotranspiration Modeling. *Water Resources Research, 55*(8), 7246-7274. doi:doi: 10.1029/2019wr024867

Monteith, J. L. (1965). *Evaporation and environment.* Paper presented at the Symposium of the Society of Experimental Biology, Cambridge.

Morton, F. I. (1983). Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal Of Hydrology, 66*, 1-76. Retrieved from http://98 - 98

Shuttleworth, W. J. (1993). Evaporation. In *Handbook of Hydrology*. New York: McGraw-Hill.

Shuttleworth, W. J., Serrat-Capdevila, A., Roderickc, M. L., & Scottd, R. L. (2009). On the theory relating changes in area-average and pan evaporation. *Quarterly Journal Of The Royal Meteorological Society, 135*, 1230-1247.

Szilagyi, J., & Crago, R. (2019). Comment on "Derivation of a sigmoid generalized complementary function for evaporation with physical constraints" by S. Han and F. Tian. *Water Resources Research, 55*, 868–869.

Szilagyi, J., Crago, R., & Qualls, R. (2017). A calibration-free formulation of the complementary relationship of evaporation for continental-scale hydrology. *Journal of Geophysical Research: Atmospheres, 122*(1), 264–278.

Wang, L., Tian, F., Han, S., & Wei, Z. (2020). Determinants of the asymmetric parameter in the complementary principle of evaporation. *submitted to Water Resources Research*, 2019WR026570.

Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., & Lei, Z. (2007). Analyzing spatial and temporal variability of annual water-energy balance in non-humid regions of China using the Budyko hypothesis. *Water Resources Research, 43*, W04426, doi:04410.01029/02006WR005224. Retrieved from http://161 - 161

Yu, L., & Weller, R. A. (2007). Objectively Analyzed Air–Sea Heat Fluxes for the Global Ice-Free Oceans (1981–2005). *Bulletin Of The American Meteorological Society, 88*(4), 527-540. doi:10.1175/bams-88-4-527