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New findings about the complementary relationship-based evaporation estimation methods

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Summary A novel approach has been found to estimate the equilibrium surface temperature (T_e) of wet environment evaporation (E_w) on a daily basis. Employing this temperature in the Priestley–Taylor equation as well as in the calculation of the slope of the saturation vapor pressure curve with pan measurements improved the accuracy of long-term mean evaporation (E) estimation of the Advection–Aridity (AA) model when validated by Morton's approach. Complementarity of the potential evaporation (E_p) and E terms was considered both on a daily and a monthly basis with the involved terms always calculated daily from 30 yr of hourly meteorological measurements of the 1961–1990 period at 210 SAMSON stations across the contiguous US. The followings were found: (a) only the original Rome wind function of Penman yields a truly symmetric Complementary Relationship between E and E_p which makes the so-obtained E_p estimates true potential evaporation values; (b) the symmetric version of the modified AA model requires no additional parameters to be optimized; (c) for a long-term mean value of evaporation the modified AA model becomes on a par with Morton's approach not only in practical applicability but also in its improved accuracy, especially in arid environments with possible strong convection; (d) the latter two models yielded long-term mean annual evaporation estimates with an R^2 of 0.95 for the 210 stations, which is all the more remarkable since they employ very different approaches for their E_p calculations; (e) with identical apparent E_p values the two models yielded practically identical long-term mean annual evaporation rates; (f) with the proper choice of the wind function to estimate apparent E_p the long-term mean annual E estimates of the modified AA model are still very close ($R^2 = 0.93$) to those of the Morton approach.

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Introduction

Recently there has been a renewed interest in Bouchet's (1963) complementary relationship (CR) of evaporation among hydrologists (Hobbins et al., 2001a,b; Crago and Crowley, 2005; Ramirez et al., 2005; Kahler and Brutsaert, 2006; Pettijohn and Salvucci, 2006; Szilagyi, 2001a,b, 2007; Szilagyi et al., 2001). It is understandable, since this is probably the only tool currently available to define areal evaporation based solely on widely available standard meteorological measurements, while other traditional methods, like the 'bucket model' approach, rely on water balance calculations, or need information about the water stress of the canopy, such as the Penman–Monteith (Monteith, 1973) equation. Note that here the word evaporation is used in a broad sense, including transpiration of the vegetation, since, as Brutsaert (1982) points out, the underlying physical process is the same, i.e., vaporization of water, independent of the source, be it soil, open water or the stomata of the vegetation.

The CR of Bouchet, as it is written recently, postulates an inverse relationship between actual (E) and potential evaporation (E_p) as $E + E_p$ = constant. The underlying argument is that as an originally completely wet area of regional extent with an evaporation rate of E_w dries out under constant available energy (Q_n) for evaporation and sensible heat (H) transfer between land and the air, the increase in H (since a decreasing rate of evaporation will cool the surface less efficiently), ΔH, will be fully available to raise the corresponding level of E_p, thus their sum remains constant, i.e., $2E_w$. Note that with the drying of the area, the air flowing above it will dry out as well, therefore E_p will be affected not only by ΔH but simultaneously by an increase in the vapor pressure deficit (VPD) of the air. It is important to point out that both, a change in H and an accompanying change in VPD, are needed for the CR to operate.

Let us consider an open water surface, such as a shallow lake of a certain size surrounded by drying land under a constant Q_n term consumed by sensible and latent heat fluxes. Let us further assume that the flux transfer coefficients, f_E and f_H, respectively, for latent and sensible heat in a Dalton-type formulation of $E = -f_E\ \partial e/\partial z$ and $H = -f_H\ \partial T/\partial z$, where $\partial e/\partial z$ and $\partial T/\partial z$ denote the vertical gradients in vapor pressure and air temperature above the surface, would not change in time either. From a constant Q_n assumption, $\Delta H = -\Delta E$ must be true over the land as it dries, but not necessarily over the open water surface, since an additional heat transfer must be considered in its energy balance as wind blows from the drier and thus warmer land toward the water surface, unless this transported heat is fully consumed by a corresponding increase in open water evaporation, E_p, triggered by an increase in VPD of the drier air. When such a full conversion of ΔH into ΔE_p happens, one obtains a symmetrical CR, i.e., $\Delta H = -\Delta E = \Delta E_p$.

The interesting thing is that under a constant Q_n term, it probably is unlikely that only a certain portion of ΔH would raise the latent heat flux rate over the open water surface by letting the water surface become warmer instead in the expense of a reduced E_p increase. It is so because when this latter happened then an increased water surface temperature could further boost evaporation (since over a free water surface vapor pressure and temperature are related through the Clausius–Clapeyron equation), which then would modify the sensible heat flux, eventually leading to a situation that ΔH is more or less fully consumed by a corresponding increase in open water evaporation. Therefore it is unlikely for the open water surface temperature to change significantly due to sensible heat exchange across its freely evaporating surface as long as the warmer air is sufficiently drier. This conclusion has been drawn earlier by Morton (1983) and Szilagyi (2001a, 2007).

Note that this way a near constant water temperature is fundamentally linked with a symmetric CR, meaning that one holds as long as the other, but only when the open water surface is of a certain extent. While in the open environment it may almost be impossible to verify this theoretical claim through direct measurements, simply because of the diurnal change in all the processes involved, it could, however, be performed in a fully controlled laboratory setting. The authors are anxious yet to see such an experiment.

As was mentioned, the open water body must have a certain size for the CR to become symmetric. Areal extent is important, because sensible heat transfer, due to differences of surface and air temperatures between the wet and drying surfaces, will take place not only across the free surface of the water body, but across its fixed boundary, let it be the bottom of a shallow lake or the side and bottom of an evaporation pan. When the size of the open water area is small, this additional heat transfer may be important enough to significantly alter the otherwise largely constant temperature (under a constant Q_n) of the E_p source. When this happens, the enhanced E_p rate from such an open water surface will no longer represent true potential evaporation, that is why Brutsaert (2005) named it apparent potential evaporation. Employing such values in the form of e.g., pan evaporation measurements in the CR will lead to a clear violation of its symmetric nature as was demonstrated by Kahler and Brutsaert (2006) and Szilagyi (2007). Another violation of the symmetric CR may occur when the E_p source is too large in size, since then the increased E_p-triggering effect of an enhanced VPD in the form of drier air being transported over the open water area weakens with distance along the wet surface, as the air becomes ever closer to saturation, leading to an overall diminished E_p response. For a summary of the different terms involved with the CR, see Fig. 1.

In this study Brutsaert and Stricker's (1979) Advection–Aridity (AA) model is investigated and subsequently modified based on a validation of long-term mean annual evaporation estimates by Morton's (1983) WREVAP (also called CRAE) model. At a selected station, the evaporation estimates of the two versions (one with true potential evaporation from the Penman equation, and one with apparent potential evaporation values) of the modified AA model are compared with the WREVAP model's estimates on a monthly and also on an annual basis. Finally, all the different annual evaporation estimates are compared to water balance estimates of evaporation of a nearby watershed.

Overview of the CR-based models for evaporation estimation

The original AA model (Brutsaert and Stricker, 1979) employs the Penman-equation (1948) for estimating E_p