Evaluating the advection-aridity model of evaporation using data from field-sized surfaces of HEIFE

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Abstract The advection-aridity model for estimating daily evaporation is evaluated using the data of the HEIFE experiment. In the dimensionless form of the model, the evaporation ratio (the ratio of the actual evaporation (E) to Penman potential evaporation (E_0)) is expressed as a linear function of the proportion of the radiation term (E_{rad}) in E_0. Because the value of the evaporation ratio is between 0 and 1, the advection-aridity model is only applicable under a certain range of E_{rad}/E_0, and the applicability of the model is influenced by the water availability of the surfaces implied by E_{rad}/E_0 from atmospheric conditions. The calculated evaporation ratio is negative for small values of E_{rad}/E_0, and is larger than 1 for large values of E_{rad}/E_0. Significant systemic bias would be presented if the advection-aridity model underestimated the actual evaporation under dry conditions and overestimated under wet conditions. A comparison between the reference values of the mean daily evaporation of the Gobi desert and oasis surfaces obtained by the eddy correlation method and evaporation estimates from the advection-aridity model validated the analysis.

Key words complementary relationship; advection-aridity model; HEIFE

INTRODUCTION

Evaporation is the major component of the hydrological cycle. The accurate estimation of evaporation is necessary for a better understanding of hydrological processes, especially in arid regions that occupy one-third of the entire global land area. The term "evaporation" in this study is used to include both evaporation and transpiration, and thus it is equivalent to the term "evapotranspiration". The actual evaporation is often estimated from the two primary controls: potential evaporation and water availability denoted by soil moisture or precipitation at different time scales (Penman, 1948; Budyko, 1974). On a daily timescale, variables such as soil moisture content or stomatal resistance needed to estimate the actual evaporation, are difficult to obtain. Therefore it is necessary to establish a reliable method to estimate actual evaporation from a few meteorological parameters.

The complementary relationship proposed by Bouchet (1963), in which only the standard meteorological data is needed, is frequently applied in calculating regional evaporation. Different models derived from the concept of complementary relationships exist in the literature, and the advection-aridity model proposed by Brutsaert & Stricker (1979) has been applied to different land surfaces at different timescales. But significant bias in the advection-aridity model, underestimated evaporation under dry conditions and overestimated evaporation for large values under wet conditions was presented, and the bias are more obvious on a daily timescale (Qualls & Gultekin, 1997).

In order to investigate the practicality and reliability of the advection-aridity model, the dimensionless form is used in this study, as the water availability of the surfaces can be detected easily in the dimensionless form (Yang *et al.*, 2006). However, data from surfaces under a wide range of water availability on a daily time scale should be gathered in the analysis to present the significant bias of the advection-aridity model. The requirement can be satisfied with the data from the Gobi desert and oasis surfaces of the HEIFE (Heihe River Basin Field Experiment on Land Surface Processes, 1990–1993, China) experiment used in this study. The data from the Gobi and desert surfaces is mostly under dry conditions, and the data from the oasis surface has a wide range of water availability.

METHODS AND DATA

Method used in the study

When water availability is not limited, evaporation proceeds at the potential evaporation rate, and it is defined as wet environment evaporation. As the surface dries without changing the available energy, the actual and potential evaporation rate depart from the wet environment evaporation with equal but opposite changes in fluxes. Bouchet's complementary relationship is expressed as:

$$E_p + E = 2E_w \tag{1}$$

where E is the actual evaporation, E_p is the potential evaporation, and E_w is the wet environment evaporation. However, many experimental as well as theoretical results suggest that no real complementary relationship between E and E_p exists (McNaughton & Spriggs, 1989; Qualls & Gultekin, 1997; Szilagyi, 2007). And the original formulation (1) was replaced with:

$$(E_p - E_w) = b(E_w - E) \tag{2}$$

where the proportionality b is the constant coefficient which represents the asymmetry.

However, in Bouchet's original formulation, it was not clear how the potential and wet environment evaporation should or could be estimated or measured (Kahler & Brutsaert, 2006). In the advection-aridity model, the potential evaporation is estimated by the Penman equation and E_w is estimated by the Priestley-Taylor equation (Priestley & Taylor, 1972). The Penman potential evaporation contains the radiation term and the drying power term:

$$E_0 = E_{rad} + E_{aero} \tag{3}$$

$$E_{rad} = \frac{\Delta(R_n - G)}{\Delta + \gamma} \tag{4}$$

$$E_{aero} = \frac{\gamma}{\Delta + \gamma} f(u)\left(e_a^* - e_a\right) \tag{5}$$

where E_0 is the Penman potential evaporation, E_{rad} and E_{aero} are the radiation term and the drying power terms, respectively, Δ is the slope of the saturation vapour curve at air temperature, γ is the psychrometric constant, R_n is the net radiation, G is the ground heat flux, e_a^* and e_a are the saturated and actual vapour pressure of the air, respectively, and $f(u)$ is the function of the wind speed at a reference level. In principle, the wind function can be determined by the Monin-Obukhov similarity theory (Crago & Crowley, 2005; Pettijohn & Salvucci, 2006). This function requires further knowledge on displacement and roughness lengths for momentum and water vapour:

$$f(u) = \frac{\rho_a c_p}{\gamma} \frac{\kappa^2 u}{[\ln(\frac{z-d}{z_{0m}}) - \psi_m][\ln(\frac{z-d}{z_{0v}}) - \psi_v]} \tag{6}$$

where ρ_a is the air density, c_p is the specific heat, $\kappa = 0.40$ is the von Karman constant, z is the measurement height, d_0 is the displacement height, z_{0m} and z_{0v} are the roughness lengths for momentum and water vapour, respectively, and ψ_m and ψ_v denote the stability corrections for momentum and water vapour, respectively. At daily or longer time steps, it is often assumed that the atmospheric stability is neutral so that $\psi_m = 0$ and $\psi_v = 0$. The Priestley-Taylor equation is a proportion of the radiation term in the Penman equation:

$$E_{pt} = \alpha E_{rad} \tag{7}$$

where E_{pt} is the Priestley-Taylor evaporation and α is the Priestley-Taylor coefficient.

The advection-aridity model can be expressed in dimensionless form by the substitution of the Penman potential evaporation and Priestley-Taylor evaporation into equation (2) and rearrangement:

$$\frac{E}{E_0} = \alpha(1+\frac{1}{b})\frac{E_{rad}}{E_0} - \frac{1}{b} \tag{8}$$

In this dimensionless form, the complementary relationship was consistent with the Penman and Budyko hypotheses (Yang *et al.*, 2006), and E_{rad}/E_0 reflects the humidity of the evaporating surface from atmospheric conditions. The former form and the dimensionless form of the complementary relationship are both shown in Fig. 1. It then follows that the evaporation ratio (E/E_0) increases linearly with E_{rad}/E_0. The evaporation calculated with (8) is negative when $E_{rad}/E_0 < 1/\alpha$ and is larger than the potential evaporation when $E_{rad}/E_0 > 1/\alpha(b+1)$. Since the value of the evaporation ratio is between 0 and 1, the advection-aridity model holds only when $E_{rad}/E_0 \in [1/\alpha(b+1), 1/\alpha]$. However, the value of E_{rad}/E_0 is not limited between $1/\alpha(b+1)$ and $1/\alpha$. Transitions of the slope of E/E_0 with respect to E_{rad}/E_0 should exist under arid and wet environments.

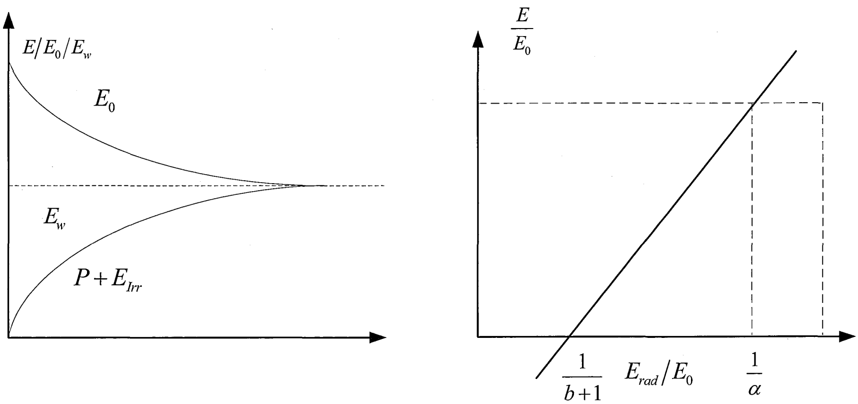

Fig. 1 Schematic representation of the former and the dimensionless form of complementary relationship.

Data used in the study

The HEIFE experiment was carried out in the middle part of the Hexi Corridor area between the Qilian Mountains and the Longshou Mountains, northwest China. A typical annual rainfall is as small as 100 mm, and the land surfaces are covered primarily with sandy and Gobi desert, with some dotted oases and irrigated farm lands (Sugita *et al.*, 2001). The desert station was located at latitude 100°10′E, longitude 39°23′N with an altitude of 1391 m above a surface of fine sand; the Gobi station was located at latitude 100°06′E, longitude 39°09′N with an altitude of about 1400 m above a surface of grit and gravel; and the oasis station was located at latitude 100°26′E, longitude 38°56′N with an altitude of 1483 m above a surface of cropland covered with wheat and maize in summer and bare land in winter.

Formal observations at the three different surfaces consisted of profile measurements on a 20 m tower of air temperature, relative humidity and wind speed, with some other basic meteorological and hydrological variables. Special intensive observations periods (IOPs) of turbulent flux carried out by means of an eddy correlation technique (Tamagawa, 1996) were also conducted for a few weeks in each of the four seasons. Because most of the net radiation and the soil heat flux (G) were not available, it was assumed that $(R_n - G) = LE + H$. Daytime was defined in this study when $(R_n - G) > 0$. The only data that were excluded were those days that recorded missing data for extended periods and whose daytime average values of Q_n or LE were negative. Moreover, air temperature, relative humidity and wind speed measured at $z = 2m$ were used in the analysis. The flux data were archived at 2-hour time steps, while the meteorological data from the tower were attained at 30-min time steps for the desert station and the oasis station. For the Gobi station, all the data were recorded at 1-hour time steps.

In this study, the relationships between the evaporation ratio and the atmospheric wetness index were evaluated at a daily time scale. All the data were first processed into daily means, and then the fluxes were calculated by the wind function derived through the Monin-Obukhov similarity theory, assuming neutral conditions (Crago & Crowley, 2005) with the daily mean variables. As bluff rough surfaces, the surface roughness in the desert and Gobi station is of the order of 10^{-3} m. However, a larger value $z_{0m} = 0.0216$ m together with $z_{0v} = 0.000174$ m were used because of the sand dune presented in the study conducted at the same desert station (Tamagawa, 1996; Sugita *et al.*, 2001). A value of $z_0 = 0.004$ m (Wang *et al.*, 1998) and an assumed value of $z_{0v} \approx 0.1 z_{0m}$ were used for the Gobi station. The displacement height $d_0 = 0$ was used by Tamagawa (1996) and Sugita *et al.* (2001) for the desert station, and this was also used for the Gobi station in this study. For the oasis station, the zero plane displacement height and the roughness length for momentum transfer can be estimated from the crop height, $d = 0.67 z_{veg}$, $z_{0n} = 0.123 z_{veg}$, and the roughness length governing transfer of heat and vapour can be approximated by $z_{0v} = 0.1 z_{0m}$. It was covered with legumes with a height of around 0.40 m in August 1991, and it was covered with wheat with a height of about 0.90 m in May and June 1992.

RESULTS AND DISCUSSIONS

The evaporation ratio of the three different land surfaces plotted with respect to E_{rad}/E_0 are shown in Fig. 2. As the evaporation ratio of the Gobi and desert surfaces are both very small, they are plotted together. For the Gobi and desert sites, there is a critical value of E_{rad}/E_0 around 0.35, before which the evaporation ratio is tiny and increases slowly with E_{rad}/E_0, and after which, evaporation ratio increases rapidly and approximately linearly with respect to E_{rad}/E_0. For the oasis sites, the evaporation ratio increases approximately linearly with E_{rad}/E_0 when the value is between 0.4 and 0.7, which implies that the evaporating surface is neither too dry nor too wet.

The advection-aridity model was only fitted for the observed data during the middle stage. The parameters α and b were optimized by minimizing the mean square error of the estimated evaporation. The optimized value of α is just around the original value 1.26. For the Gobi and desert surfaces, the model yields obvious underestimation, and the actual evaporation calculated with the model is negative even under extremely dry conditions. For the oasis surface, the model performs well as the value of E_{rad}/E_0 is well situated, but the actual evaporation is underestimated under dry conditions and overestimated under wet conditions. However, high correlations and relatively small systematic errors (Table 1) imply that there is a good agreement between the relationships predicted by the advection-aridity model and the observed relationships when the evaporating surface is neither too dry nor too wet.

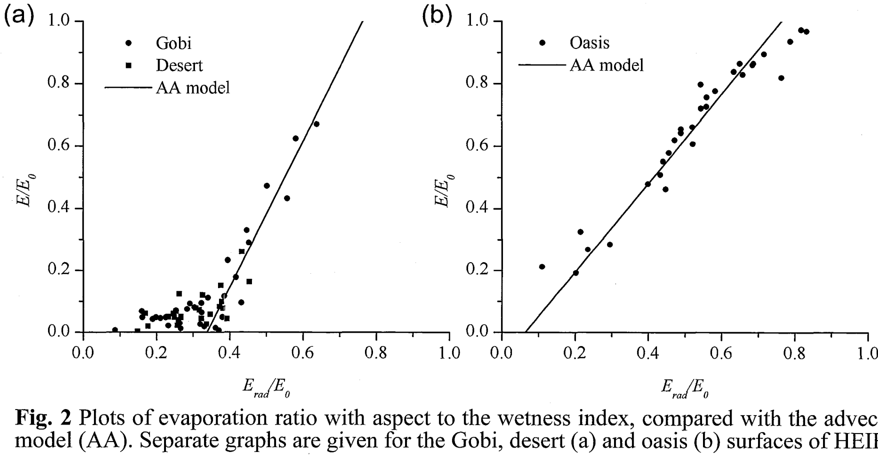

Fig. 2 Plots of evaporation ratio with aspect to the wetness index, compared with the advection-aridity model (AA). Separate graphs are given for the Gobi, desert (a) and oasis (b) surfaces of HEIFE.

Table 1 Performances of the advection-aridity model under conditions neither too dry nor too wet.

Surfaces	α	b	$^*R^2$	$^*MAE$ (W/m^2)	$^*RSME$ (W/m^2)
Gobi and desert	1.31	1.31	0.96	8.29	10.28
Oasis	11.0	1.26	0.98	4.08	5.27

* R^2 is the correlation coefficient; * *MAE* is the Mean Square Error; * *RSME* is the square-root of the Mean Square Error.

Because of the significant systemic bias of the advection-aridity model, it should be re-evaluated with different water availability. It can be supposed that the evaporation ratio is negligible under arid conditions when $x < 1/\alpha(b + 1)$, and evaporation is equal to potential evaporation under wet conditions when $x < 1/\alpha$. The evaporation ratio (E/E_0) only increases linearly with the atmospheric wetness index when $x \in [1/\alpha(b + 1), 1/\alpha]$. This statement leads to the following equation:

$$\frac{E}{E_0} = \begin{cases} 0, & 0 < x \le 1/[\alpha(1+b)] \\ \alpha(1+\frac{1}{b})x - \frac{1}{b}, & \frac{1}{\alpha(1+b)} < x < \frac{1}{\alpha} \\ 1, & 1/\alpha \le x < 1 \end{cases} \tag{9}$$

Equation (9) is similar to equations for the evaporation ratio against soil moisture.

CONCLUSIONS

In the dimensionless form of the advection-aridity model, the evaporation ratio is expressed as a linear function of E_{rad}/E_0, and is negative when $E_{rad}/E_0 > 1/\alpha$ and is larger than the potential evaporation when $E_{rad}/E_0 > 1/\alpha(b + 1)$. Since the value of the evaporation ratio is between 0 and 1, the advection-aridity model holds only when $E_{rad}/E_0 \in [1/\alpha(b + 1), 1/\alpha]$. In the advection-aridity model, the water availability of the surfaces are implied by E_{rad}/E_0 from atmospheric conditions. Therefore, the applicability of the model is influenced by water availability.

Using the mean daily evaporation of the Gobi desert and oasis surfaces obtained by the eddy correlation method, it is found that the evaporation is negligible when the evaporating surface is dry, and the evaporation approximates potential evaporation when it is wet, while the evaporation ratio increases with E_{rad}/E_0 approximately linearly. A three-stage pattern similar to the relationship between the evaporation ratio with respect to the soil moisture is found.

The linear relationship suggested by the advection-aridity model is only applicable when the evaporating surface is neither too dry nor too wet. Significant systemic bias would be presented in that the advection-aridity model underestimated the actual evaporation under dry conditions and overestimated under wet conditions. Considering the pattern of the relationship between E/E_0 and E_{rad}/E_0, the advection-aridity model should be re-evaluated or some other new functions should be derived to get a better estimation of the actual evaporation, especially under a wide range of water availability.

Acknowledgements This work was supported by Project 50579031 and 50721140161 sponsored by the National Natural Science Foundation of China. In this study, the data for HEIFE were provided by the "Digital Heihe River Basin" Project (http://heihe.westgis.ac.cn), which was granted by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences.

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