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Seasonal variability of the complementary relationship in the Asian monsoon region

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Abstract:

The complementary relationship (CR) between potential evaporation (LE_p) and actual evaporation (LE) is widely used to explain the evaporation paradox and to estimate LE, in which wet environment evaporation (LE_w) is usually calculated using the Priestley–Taylor equation. However, in many studies on the CR, it has been found that the Priestley–Taylor parameter α is not a constant. Through seasonal variation of α for estimating LE_w in the CR, this paper analyses its seasonal variability. Based on flux observation data at two flux experiment sites (Kogma in Thailand and Weishan in China) in the Asian monsoon region, seasonal variability of the CR is detected, i.e. the α value is larger in winter than in summer. This seasonal variability might be caused by seasonal variability in the transport of water vapor and sensible heat between oceans and continent. The monsoon increases air humidity and lowers air temperature in summer, which leads to a decrease in α; it increases atmospheric air temperature and vapor content in winter, increasing α. Nevertheless, during May–September, α has a range of 1.06–1.16 at the Kogma site and 1.00–1.36 at the Weishan site, which is approximate to the typical range 1.1–1.4. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS complementary relationship; seasonal variability; wet environment evaporation; Priestley–Taylor equation; flux measurement

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INTRODUCTION

An increase in actual evaporation (LE) estimated by water balance methods over large areas and a decrease in pan evaporation from measurements in many regions have been recently reported (Milly and Dunne, 2001; Walter *et al*., 2004). This has been referred to as the evaporation paradox, interpreted based on the complementary relationship (CR) between LE and potential evaporation (LE_p) (Brutsaert and Parlange, 1998). Using the CR, Brutsaert (2006) estimated LE increase at about 0.44 mm/a^2, according to typical values of global trends of net radiation, temperature and pan evaporation. Direct measurement of LE over large areas is still difficult (Kahler and Brutsaert, 2006). However, the CR in which the feedback of LE_p with LE is considered suggests an attractive method for estimating LE over a large region, without knowing underlying surface conditions such as soil moisture. This has been widely applied for LE estimation over different time scales, such as monthly (Morton, 1976; 1983; Hobbins *et al*., 2001; Szilagyi and Jozsa, 2008; Szilagyi *et al*., 2009), daily (Brutsaert and Stricker, 1979; Han *et al*., 2011), and hourly (Parlange and Katul, 1992).

The CR was first proposed by Bouchet (1963) based on energy balance in a land-atmosphere system (including a superficial soil layer, vegetation, and lower atmosphere layer). Without considering variation in exchange of water vapor and energy between the system and its surroundings, the CR can be expressed as

$$LE + LE_p = 2LE_w \tag{1}$$

Theoretically, the CR has been heuristically proven based on a series of restrictive assumptions (Morton, 1971; Szilagyi, 2001).

Nevertheless, it was found that the Bouchet hypothesis (Equation 1) was only partially fulfilled (Kim and Entekhabi, 1998; Sugita *et al*., 2001). In fact, Bouchet (1963) documented that Equation (1) was generally modified with consideration of changes to water vapor and energy exchanges of the system with its surroundings, so that $LE + LE_p \leq 2LE_w$. Whereupon the expression was modified (Ramirez *et al*., 2005; Szilagyi, 2007) as $LE + LE_p = mLE_w$, where m is a constant of proportionality. Based on 192 data pairs from 25 basins over the United States, Ramirez *et al*. (2005) determined a mean m of 1.97, but with high observed variability.

In the CR, wet environment evaporation (LE_w) was suggested by Brutsaert and Stricker (1979) to be given by the Priestley–Taylor equation (Priestley and Taylor, 1972):

$$LE_w = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G), \tag{2}$$

where α is a parameter, Δ (kPa/°C) is the slope of saturated vapor pressure at the air temperature, γ (kPa/°C) is a psychometric constant, R_n (mm/day) is net radiation and G

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(mm/day) is soil heat flux. Central to LE_w is the concept of equilibrium evaporation. According to a theory for surface energy exchange in partly open systems, embracing a fully open system and fully closed system as limits, Raupach (2000) asserted that a steady state with a steady-state LE_w could be attained; the time to reach steady state (a steady proportion of available energy transforming into latent heat $\alpha\frac{\Delta}{\Delta+\gamma}$) was 1–10 h for a shallow convective boundary layer. Because of water vapor and energy exchanges between the system and surroundings, the proportion of available energy transforming into latent heat is usually modified. Raupach (2001) parameterized the effect of air exchange between system and surroundings on equilibrium evaporation and suggested conservation equations for entropy and water vapor in an open system. This revealed that advection was likely to modify air temperature and entropy at the system reference height, causing change in the proportion $\alpha\frac{\Delta}{\Delta+\gamma}$.

On calculating LE_w in the CR, Brutsaert and Stricker (1979) suggested an average α on the order of 1.26–1.28. The value $\alpha = 1.32$ was predicted by Morton (1983). Hobbins *et al*. (2001) obtained a value of $\alpha = 1.3177$ using data from 92 basins across the conterminous United States. Xu and Singh (2005) determined α values in the advection-aridity model of Brutsaert and Stricker (1979) for three study regions at 1.18, 1.04 and 1.00. Yang *et al*. (2008) furnished an average $\alpha = 1.17$ with range 0.87–1.48 from 108 catchments in the Yellow River and Hai River basins of China, whereas Gao *et al*. (2011) suggested an α of 1–1.23 for nine sub-basins of the Hai River basin. Using data from flux measurement stations #40 and #944 from the First International Land Surface Climatology Field Experiment but not in the same period, Pettijohn and Salvucci (2006) and Szilagyi (2007) obtained different values of α, 1.10 and 1.18 (or 1.15), respectively. According to data from Weishan flux measurement station, Yang *et al*. (2009) indicated an α range of 1–1.5 for a daytime hourly average. These variable values of the Priestley–Taylor parameter α may imply the variability of the CR.

Under the condition without water limitation, LE equals LE_p, and thus Equation (1) transforms into

$$LE = LE_w \tag{3}$$

This provides a simplified condition to study CR variability. According to analysis of saturated surface evaporation, Priestley and Taylor (1972) gave an α range from 1.08 to 1.34 and took 1.26 as the average. Numerous papers report an average α of 1.26 (Davies and Allen, 1973; Stewart and Rouse, 1976; 1977; Eichinger *et al*., 1996). Nevertheless, some details about α in these studies are noteworthy. Means in June, July and September were 1.27, 1.20 and 1.31, respectively (Davies and Allen, 1973), and α was less than 1.26 when LE was large, maybe in June or July (Stewart and Rouse, 1977). Additionally, data in these studies were obtained only in particular months of the year, such as September and October (Eichinger *et al*., 1996), June to September (Davies and Allen, 1973), July (Stewart and Rouse, 1976), and June, July and September (Stewart and Rouse, 1977). Using observations from April to October over a large, shallow lake in the Netherlands, DeBruin and Keijman (1979) found α had a seasonal variation from 1.20 in August to 1.50 in April,. Seasonal variation of α in the Priestley–Taylor equation for calculating LE_w can be considered an indicator of CR variability.

In this study, seasonal variability of the CR is examined quantitatively on the basis of flux observation data from two sites in the Asia monsoon region, and then discussed theoretically. The main objectives are: (1) To quantitatively evaluate seasonal variability in the CR, and (2) to find a theoretical explanation for CR seasonal variability.

ANALYSIS OF THE CR SEASONAL VARIABILITY BASED ON FLUX OBSERVATIONS

Data and method

Flux observation data were collected from two experimental sites, Kogma and Weishan in the Northern Hemisphere (Table I and Figure 1). The Kogma site, part of the GEWEX (Global Energy and Water Cycle Experiment) Asian Monsoon Experiment (GAME), is located in the Kogma watershed of northern Thailand, with a 50 m observation tower. The Kogma watershed is covered by a hilly evergreen forest in which only a few species lose their leaves, and canopy top is about 30 m (Komatsu *et al*., 2003; Kume *et al*., 2007). The data set includes meteorological elements (air temperature, relative humidity, wind direction and speed, air pressure), radiation (longwave and shortwave radiation, net radiation), soil temperature, precipitation, soil moisture, skin temperature, sensible heat flux, latent heat flux and soil heat flux. Data were recorded as hourly averages. The energy balance closure problem was solved before data release. More details are provided at the GAME website (http://aan.suiri.tsukuba.ac.jp/).

The Weishan experiment site is located in a downstream reach of the Yellow River in China and was set up

Table I. Description of flux experiment sites

Site	Location	Altitude (m)	Vegetation type	Data period
Kogma	18°48.8’N, 98°54.0’E	1268	Evergreen forest	Feb. – Dec., 1998
Weishan	36°38.9’N, 116°03.3’E	30	Wheat, corn	May 18, 2005 – Dec. 31, 2006

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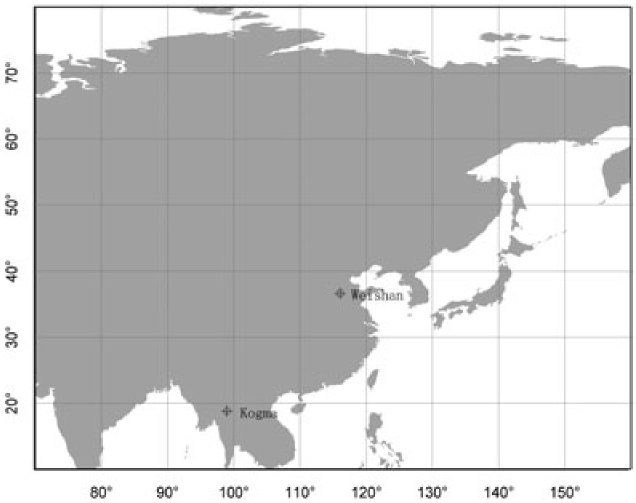

Figure 1. Location of the two flux experiment sites used in study

by Tsinghua University in 2005. Most of this region is farmland, with flat topography. Winter wheat and maize are the two major crops, rotationally cultivated. Winter wheat planting season is in early October, and the growing period is from March to mid June. The experimental field is near the centre of the irrigation district, and is a 400 m by 500 m rectangular field. Typical meteorological instruments are installed atop a 10 m tall tower, along with a radiometer and an eddy correlation system for sensible and latent heat fluxes. Observations include typical meteorological parameters, shortwave and longwave radiation (both downward and upward), sensible and latent heat fluxes, soil heat flux and others. Net radiation is estimated by the radiation balance equation. Observations were recorded as 30-min averages. Closure of the energy balance of approximately 0.8 was found, according to data from 2005 to 2006.

In this study, *LE* was calculated from observation of latent heat flux, and the LE_{w} was estimated by the Priestley–Taylor equation. It has been suggested (Morton, 1975; 1976; Brutsaert and Stricker, 1979) that LE_{p} be calculated with the Penman equation (Penman, 1948):

$$LE_{\mathrm{p}} = \frac{\Delta}{\Delta + \gamma}(R_{\mathrm{n}} - G) + \frac{\gamma}{\Delta + \gamma}E_{\mathrm{A}}, \tag{4}$$

where E_A is the drying power of the air. This can be estimated by

$$E_A = f(u)(e^* - e), \tag{5}$$

where e^* (kPa) and e (kPa) are the saturated and actual vapor pressures at the same air temperature, respectively. The wind function $f(u)$ can be estimated as

$$f(u) = 0.26(1 + 0.54u), \tag{6}$$

where u (m/s) is mean wind speed at 2 m height.

Equation (1) linking the three terms (LE, LE_{p} and LE_{w}) can be modified by horizontal advection with a seasonal variation. To reveal the CR seasonal variability caused by advection, we focus on the Priestley–Taylor parameter α. According to Equations (1) and (2), α can be calculated as

$$\alpha = \frac{\gamma + \Delta}{2\Delta} \cdot \frac{LE + LE_{\mathrm{p}}}{R_{\mathrm{n}} - G} \tag{7}$$

We can also evaluate the effect of horizontal advection on the CR as $A_{\mathrm{y}} = LE + LE_{\mathrm{p}} - 2 \times 1.26\frac{\Delta}{\Delta+\gamma}(R_{\mathrm{n}} - G)$. According to mathematical analysis, A_{y} has a similar seasonal variation as α.

The procedure for analyzing seasonal variation of α is as follows: (1) Weekly (or monthly) mean of climatic variables and latent heat flux were estimated according to the recorded 30-min average; (2) LE_p was estimated using the Penman equation; and (3) the parameter α was then calculated according to Equation (7) on the weekly (or monthly) scale.

Seasonal variation of the Priestley–Taylor parameter

Figure 2 plots weekly mean αvariation at the Kogma site, and Figure 3 shows monthly means. Both figures show identical seasonal variation, i.e. a decreasing trend from winter to summer and an increasing trend from summer to winter. In particular, monthly mean α has a maximum of 1.6 approximately in February, then falls to

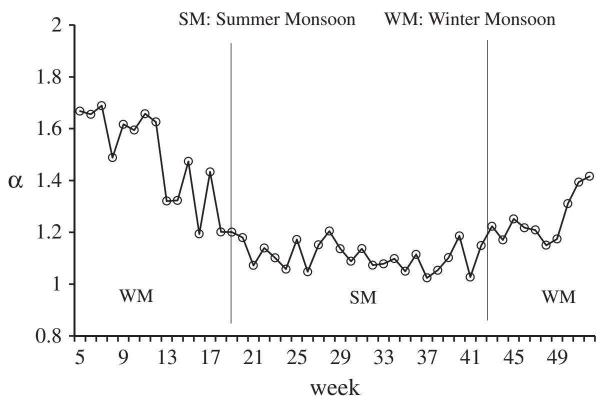

Figure 2. Seasonal variation of Priestley–Taylor parameter α on weekly scale at Kogma site

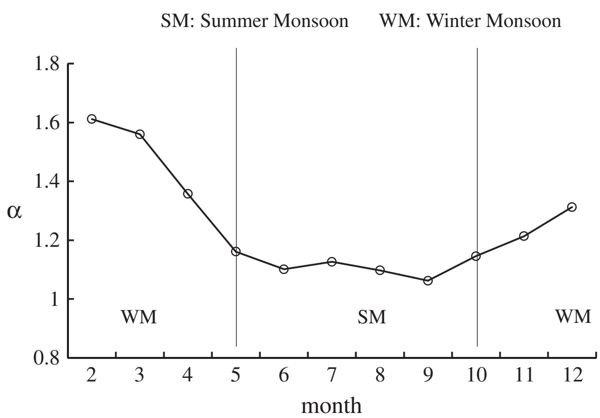

Figure 3. Seasonal variation of Priestley–Taylor parameter α on monthly scale at Kogma site

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a minimum of 1.1 approximately in summer; it increases thereafter, until winter. The monthly α ranges from 1.06 to 1.36 between April and October.

Weekly and monthly means of α were also analysed at the Weishan site. As shown in Figures 4 and 5, α has a mean of 1.18 during the summer monsoon period, and about 1.88 during the winter monsoon. In other words, the parameter α is larger in winter than in summer. In general, we discern seasonal variation of α, although the points are scattered in winter. Monthly α varies from 1.00 to 1.36 between May and October.

DISCUSSION OF SEASONAL VARIABILITY

As shown in Figures 2–5, the Priestley–Taylor parameter α changes seasonally. In 1979, DeBruin and Keijman reported that α differed slightly from 1.26 in May–September, but was about 1.50 in April and October. Similarly, Figure 3 shows that α at Kogma was between1.06 and 1.16 in May–September and was 1.36 in April. At the Weishan site (Figure 5), α had a similar seasonal variation but larger values, up to 1.60 in April and 1.38 in October.

The Asian winter monsoon originating from Siberia can reach southern Thailand, Malaysia and neighboring areas (Wangwongchai *et al*., 2005). The southwest monsoon beginning in May and ending around October transports warm, moist air from the Indian Ocean toward

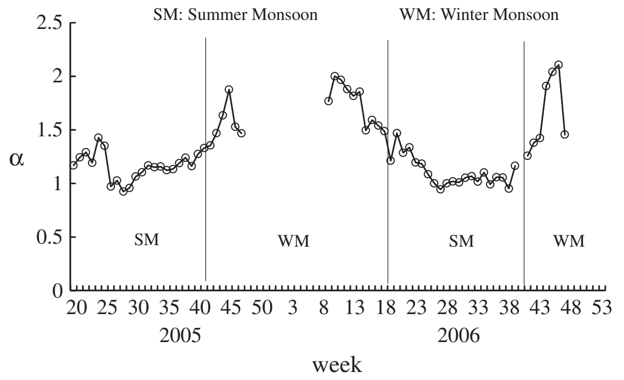

Figure 4. Seasonal variation of Priestley–Taylor parameter α on weekly scale at Weishan site

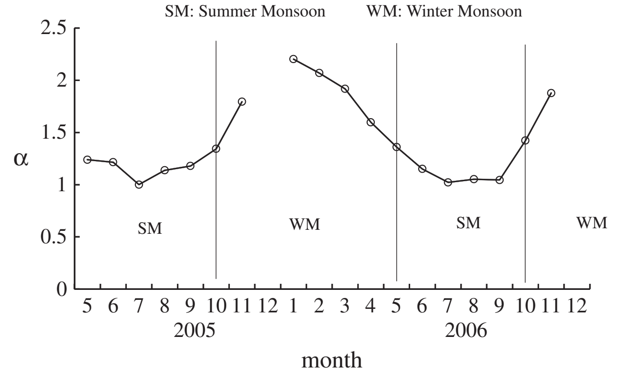

Figure 5. Seasonal variation of Priestley–Taylor parameter α on monthly scale at Weishan site

Thailand (Singhrattna *et al*., 2005). At the Weishan site in China, the Asian monsoon circulation is from ocean to continent during June–October, and from continent to ocean during October–June (Ye *et al*., 1958). We therefore speculate that the seasonal variation has some relationship with energy and vapor advection caused by the monsoon in the Asian monsoon region.

Morton (1975) noticed the effect of horizontal advection on the CR and suggested a corrected equation

$$LE + LE_p = 2 \times 1.26 \frac{\Delta}{\Delta + \gamma}(R_n - G + A), \qquad (8)$$

where A was an empirical correction factor for advection. Similarly, Mo (1995) corrected the equation for advection effect as

$$LE + LE_p = 2 \times 1.26 \frac{\Delta}{\Delta + \gamma}(R_n - G) + A_m, \qquad (9)$$

where A_m was another empirical term for advection. Nevertheless, these cannot be considered a form of energy input, but only as factors representing the effect of advection energy and water vapor on LE_w. Therefore, most studies did not introduce an advection item, but instead adjusted the Priestley–Taylor parameter for advection. The energy balance near the ground surface can be expressed as

$$R_n - G = LE + H \qquad (10)$$

Advection impacts the CR by modifying air temperature, water vapor pressure and others. As a result, the partition of available energy into latent and sensible heats will change, and the presence of advection causes $LE > R_n - G$ (Rijks, 1971; Wright and Jensen, 1972; Rosenberg and Verma, 1976) when the direction of sensible heat H is downward.

Differences in thermodynamic properties between land and ocean produce generally higher temperatures and less water vapor over continents than over oceans in summer, and lower temperatures and less water vapor over continents than oceans in winter. Consequently over continents, atmospheric circulation between land and ocean decreases temperature and increases vapor during summer, and increases both temperature and vapor in winter. It seems paradoxical that the winter monsoon increases temperature over continents. In fact, we find that the distribution of isotherms is not completely latitudinal; temperature has an inverse relationship with distance from the ocean in identical latitude continental regions. This indicates heat transport from ocean to continent by advection. We speculate that the circulation increases temperature over land, and the increase weakens with distance from the ocean, as a result of sensible heat transport.

Advection possibly affects the major assumption of the CR, that energy release from a decrease in LE compensates the increase in LE_p (Lhomme and Guilioni, 2006). The monsoon transports water vapor and sensible heat between

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ocean and continent, which causes additional seasonal changes to air humidity and temperature. The effects of these changes on the two sides of Equation (1) are asymmetric. On the left side, the terms LE_p and LE can be determined by climate variables (such as air temperature and vapor pressure), which include the effect of horizontal advection. On the right side, the effect of horizontal advection on LE_w is parameterized as only the change of air temperature (if the effect of radiation is neglected), not including changes of wind speed and humidity.

We assume a system without horizontal advection, where Equation (1) is satisfied. Since the summer monsoon imports a large amount of water vapor and reduces latent heat, the drying power of the air E_A decreases and increases the ratio $H/(R_n - G)$ (i.e. LE decreases). This reduces $(LE+LE_p)$ but causes less change in LE_w. This translates into a smaller α in Equation (1). The winter monsoon increases E_A and $LE/(R_n - G)$, which produces an increase in $(LE+LE_p)$ but less change in LE_w, resulting in a larger α in Equation (1). Following the same reasoning, we can explain the seasonal variation in α revealed by DeBruin and Keijman (1979). According to the CR, with an unlimited water supply above a lake, the evaporation LE equals the LE_p. In summer, horizontal advection reduces $(LE+LE_p)$, resulting in a small α value, but a large α in winter.

In addition, the effect of horizontal advection possibly has a regional variation. Energy is transported by atmospheric and oceanic circulations from low to high latitudes, and water vapor transported from the lower atmospheric layer over the ocean to that over land. This may induce regional variation of α (Yang *et al*., 2008).

CONCLUSION

The CR between LE and LE_p has been widely used to explain the evaporation paradox, as well as to estimate regional evaporation. The theoretical foundation of the CR is the Bouchet hypothesis, including the constraint that exchanges of water vapor and energy between the considered system and its exterior are constant. In reality, the atmosphere does not always satisfy the constraint. In the Asian monsoon region, atmospheric motions have a significant seasonal variation, accompanied by transport of water vapor and energy. Through analyzing seasonal variation in parameter α of the Priestley–Taylor equation for calculating LE_w, this paper analysed effects of horizontal advection on the CR. Based on observational data from Kogma and Weishan experimental sites in the Asian monsoon region, analyses show that α has a significant seasonal variation, which is larger in winter than in summer. The possible cause is that the summer monsoon increases water vapor content and decreases air temperature, whereas the winter monsoon increases both water vapor and air temperature. Nevertheless, from May to September, α was between 1.06 and 1.16 at Kogma and 1.00 and 1.36 at Weishan. These values are approximate to the typical range between 1.1 and 1.4.

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