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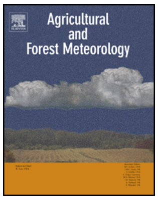

Observational study on complementary relationship between pan evaporation and actual evapotranspiration and its variation with pan type

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ABSTRACT

The pan evaporation process is essential to understanding the climate change of pan evaporation. To study the physical process of pan evaporation and its interactions with the surrounding environment, an elaborate pan evaporation experiment was carried out by means of micrometeorological method in the arid region of northwest China, in which hourly pan evaporation was measured by E601B, Class A and D20 pans, the local actual evapotranspiration was measured using eddy correlation system. Our results show that the pan water surface and the surrounding land surface constitute a significant non-uniformity of heat and moisture, and the non-uniformity energy exchange between them has an important influence on pan evaporation rate. As the environmental humidity changes, daily actual evapotranspiration and pan evaporation rates have a contradictory tendency, with the relationship between these two evaporations presenting a clear asymmetrical complementary behavior. In addition, a simple pan non-uniformity intensity index (I_E) is defined as the ratio of pan evaporation to the Penman potential evaporation (LE_{ppman}) ($I_E = LE_{pan}/LE_{ppman}$). This index reflects the non-uniformity intensity between pan water and the surrounding land. Meanwhile, the comparison of complementary relationship corresponding to three types of pans shows that the degree of complementary relationship asymmetry linearly rises as the intensity of non-uniformity between pan and surrounding environment increases.

1. Introduction

The pan, as a routine evaporimeter at hydrological and meteorological stations, is the simplest, cheapest and most practical meteorological method to measure local atmospheric evaporation demand (Stanhill, 2002). Additionally, measurement of the pan evaporation is an important reference for water resource assessment, hydrological research, climatic zoning and monitoring evaporative climate change (Thom et al., 1981; Stanhill, 2002; Bruton et al., 2000; Sabziparvar et al., 2010). Studies on the pan evaporation in the past few decades showed that pan evaporation has had an obvious downward trend in many regions of the world (Peterson et al., 1995; Roderick and Farquar, 2002; Liu et al., 2004; Zuo et al., 2005; Rayner, 2007; Fu et al., 2009; Cong et al., 2009; McVicar et al., 2012, their Table 5). However, the explanations to this phenomenon vary. For example, some studies suggested that the reduction in solar irradiance that results from increasing cloud cover and/or aerosol quantity causes the decrease of pan evaporation (Peterson et al., 1995; Roderick and Farquar, 2002). Meanwhile, some studies considered that the decreased pan evaporation is attributed to the decreased near-surface wind speed (Rayner, 2007; Roderick et al., 2007; Limjirakan and Limsakul, 2012; Yang and Yang, 2012; McVicar et al., 2012). Although the above two explanations for the decline of pan evaporation are from different perspectives, they both imply the weakening land-air hydrological cycle (Peterson et al., 1995; Fu et al., 2009; Han et al., 2012). In contrast, some researchers believed that the declining trend of pan evaporation resulted from the reduction of vapor pressure deficit caused by the increase of air relative humidity in some regions (Brutsaert and Parlange, 1998; Lawrimore and Peterson, 2000; Ji and Zhou, 2011), although global observations of the near-surface air relative humidity are average, roughly constant (Dai,

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2006; Willett et al., 2008). However, this conclusion implies the land-air hydrological cycle is accelerating (Shen et al., 2010), which has been supported by the fact that the actual soil evaporation is enhanced in some regions of the world after the increased precipitation in the same period (Dai et al., 1997; Karl and Knight, 1998; Liu et al., 2005; Brutsaert, 2006). There are two even contradictory conclusions on the climatic signals revealed by the declining trend in pan evaporation. Such situation drives researchers to explore the new answers from the physical process mechanism of pan evaporation and the relations among evaporation variables that are defined according to various observation and study approaches, such as actual evapotranspiration, reference evapotranspiration, pan evaporation and potential evaporation, and so on (Allen et al., 1998).

The complementary relationship initially proposed by Bouchet (1963) is considered as a key to solve this problem, and has been greatly developed and promoted over the past few decades (Morton, 1969, 1983; Brutsaert and Stricker, 1979; Brutsaert, 1982; Granger, 1989; Granger and Gray, 1990). The complementary relationship theory has also been widely tested and applied in different climatic zones and land surfaces (Brutsaert and Parlange, 1998; Szilagyi, 2001; Golubev et al., 2001; Haque, 2003; Ozdogan and Salvucci, 2004; Hobbins et al., 2004; Ramírez et al., 2005; Crago and Crowley, 2005; Yang et al., 2006; Huntington et al., 2011). However, most of these studies were based on the complementary relationship between empirical potential evaporation and actual evapotranspiration. Hence, some scholars pointed out that the complementary relationship is not reliable due to the lack of theoretical basis and the assumptions of strict evaporation conditions (Morton, 1983; Szilagyi, 2001). Some reports even said that the complementary relationship between potential evaporation and actual evapotranspiration is conditionally symmetrical (Kim and Entekhabi, 1998; McNaughton and Spriggs, 1989; Sugita et al., 2001).

Kahler and Brutsaert (2006) confirmed that the complementary relationship between daily actual evapotranspiration and Class A pan evaporation shows a significant asymmetry. Szilagyi (2007) pointed out that the degree of complementary relationship asymmetry between actual evapotranspiration and apparent potential evaporation is a function of surface temperature, not a constant. Meanwhile, Pettijohn and Salvucci (2006) found that the conductivity of canopy can affect the symmetry of complementary relationship. Furthermore, by building a two-dimensional physical model for Class A pan, they found that the atmospheric boundary depth and vegetation height can also affect the symmetry between pan evaporation and actual evaporation (Pettijohn and Salvucci, 2009). In addition, the evaporation area imposes significant impacts on the symmetry of complementary relationship (such as lakes, reservoirs, rivers, small ponds and pans). The open water body must have a certain size for the complementary relationship to become symmetric (Szilagyi and Jozsa, 2008).

Pans employed in measuring evaporation were not identical in different countries or regions across the world, such as Class A pan (in North American and Australia), GGI3000 (a sunken pan in Russia), BMO tank (in Britain), E601B pan and D20 pan (in China) (Fu et al., 2004; McVicar et al., 2012). Because the geometry size, installation method and structure of the pan have a significant influence on the measured results, the values measured by different types of pans were not equal on the same environmental background (Linacre, 1994; Fu et al., 2004; Martinez et al., 2006; Rotstayn et al., 2006; Yang and Yang, 2012). In the past decade, the evaporation process of Class A pan was studied in detail (Jacobs et al., 1998; Roderick et al., 2007, 2008a,b; Chu et al., 2010; Lim et al., 2012, 2013), however the careful study on other types of pans is rare. To understand the relationship between different types of pans evaporation and actual evapotranspiration, a field experiment was performed in the arid region of northwest China, where pan evaporation was simultaneously measured by D20, E601B and Class A pans. Actual evapotranspiration was observed with eddy correlation system. Simultaneously, micrometeorological method was adopted to observe the whole pans' evaporating process carefully. Our study has two objectives: (i) to analyze whether there is a complementary relationship between pan evaporation and actual evapotranspiration; (ii) to investigate the effect of different types of pans on the symmetry of complementary relationship.

2. Complementary relationship theory

The concept of complementary can be briefly summarized as follows: for a relatively large uniform surface (1–10 km) with minimal advection of heat and moisture, actual evapotranspiration (LE) and potential evaporation (LE_p) interact through land-atmosphere feedbacks, and are linked with each other by equilibrium evaporation, or wet environment evapotranspiration (LE_w). Here LE_w is the actual evapotranspiration in wet environment (with limited energy and adequate moisture). When moisture at the land surface is adequate, $LE = LE_p = LE_w$, and LE_w is only determined by the available energy which received by land surface. When the available energy maintains constant and the land surface gradually becomes dry, LE falls below LE_w and the sensible heat flux increases. This will gradually warm and dry the near-surface air, and saturation vapor pressure deficit will increase due to the lack of moisture, thus elevating LE_p. The complementary relationship between LE and LE_p can be expressed as:

$$b(LE_w - LE) = LE_p - LE_w \tag{1}$$

where b is a proportional coefficient to measure the impact of the change in actual evapotranspiration on potential evaporation. In other words, one-fold change in LE can cause b-fold changes in LE_p in opposite direction. When $b = 1$, Eq. (1) is symmetric complementary relationship, which implies that one unit decrease in LE results in one unit increase in LE_p; when $b \neq 1$, the relationship between LE and LE_p is asymmetric. Commonly, LE_w is estimated using the Priestley-Taylor equation (Priestley and Taylor, 1972; Brustaert and Stricker, 1979):

$$LE_w = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G_0) \tag{2}$$

where $\Delta(=de_0/dT)$ is the slope of the saturated vapor pressure curve corresponding to air temperature (kPa °C $^{-1}$), γ is psychrometric constant (kPa °C $^{-1}$), R_n is net radiation (W m^{-2}), G_0 is heat flux on the surface (W m^{-2}). α is the Priestley-Taylor coefficient. Commonly, α is used as a calibration coefficient; however, here α is fixed to the Priestley-Taylor original value of 1.26 to reduce the degrees of freedom (Brustaert and Stricker, 1979; Huntington et al., 2011). Potential evaporation as an index is commonly used to estimate the air evaporative demand. However, it only represents the evaporation under some special assumed conditions and is difficult to be measured directly, so some empirical formulas are generally employed to determine local potential evaporation (Donohue et al., 2010; McMahon et al., 2013).

The complementary relationship between pan evaporation and actual evapotranspiration is researched by replacing LE_p with pan evaporation, and can be expressed as:

$$b(LE_w - LE) = LE_{pan} - LE_w \tag{3}$$

Here b is proportional coefficient; $b \neq 1$ means complementary relationship is asymmetrical. The relationship between some physical variables can become more straightforward in normalized form. In order to clarify the relationship, the Formula (3) is normalized following the methods from Kahler and Brutsaert (2006) and Huntington et al. (2011) who scaled LE and LE_{pan} with LE_w