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Regional complexity in trends of potential evapotranspiration and its driving factors in the Upper Mekong River Basin

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ABSTRACT

The evaporative demand, a central process of the climate system, is expected to be altered along with the global change. The increase of surface temperature and decrease of pan evaporation is known as the "pan evaporation paradox", requiring comprehensive and detailed attribution and sensitivity analysis to understand the changes in evaporative demand dynamics. In this paper, long-term records of meteorological and hydrological datasets from 1960 to 2005 in the Upper Mekong River Basin were used to calculate and analyze the trends of Penman–Monteith potential evapotranspiration (ET_0). The results indicated no significant monotonic trend for the whole basin and the increasing and decreasing pattern of ET_0 were blended spatially. To attribute ET_0 changes to radiation, temperature, humidity and wind speed, differentiation equation methods were employed. The results demonstrated the sunshine duration hours (N) was the dominant factor contributing to ET_0 changes in the Upper Mekong River Basin. Sensitivity analysis indicated ET_0 varied greatly both temporally and spatially in relation to different climatic variables. A test of Bouchet's complementary relationship demonstrated that there were complementary relationships between actual evapotranspiration (ET_a) and ET_0 or pan evaporation (ET_{pan}) though they did not strictly obey the classical hypothesis.

1. Introduction

The potential evapotranspiration (ET_p) is an important indicator of global climate and environmental change because of its close links with key physical factors, such as temperature, radiation, wind speed, and humidity (Roderick et al., 2007). The increase of surface temperature is expected to increase potential evapotranspiration and accelerate the hydrological cycle as studies around the world indicate (Jiang et al., 2011; Fu et al., 2013), which is contradictory to the declining trend of ET_p and leads to the "pan evaporation Paradox" (Brutsaert and Parlange, 1998; Hobbins et al., 2004).

The change of ET_p is closely related with the radiation condition based on the concept of energy balance. Radiation is the driver of evapotranspiration in energy-limited environments. As noted by Roderick and Farquhar (2002), the decrease in ET_p is consistent with decreases in surface solar radiation (SSR) over the same period in various studies around the world. Cases of the energy-limited regions used in similar studies include Changjiang (Yangtze River) basin, China (Xu et al., 2006) and most regions in India (Chattopadhyay and Hulme, 1997). Wild (2009) demonstrated that there is a widespread decrease in surface solar radiation between the 1950s and 1980s ("global dimming") and a partial recovery in many regions more recently ("brightening"). Consistent changes in the fully independent data sets of SSR and pan evaporation had been identified in his study.

The contribution of wind speed to the trends of potential evapotranspiration is another important aspect that has not been fully emphasized until recently. Based on 148 studies, McVicar et al. (2012) concluded that declining rates of observed near-surface wind speed (termed "stilling") is a global phenomenon. Van Heerwaarden et al. (2010) studied how trends in different atmospheric variables (including wind) impact trends of pan and actual evapotranspiration in a fully coupled system. In general, to deepen our understanding of the changes of ET_p, the changes of wind speed should be taken into fully consideration in future studies.

In addition, humidity which is greatly constricted by precipitation also plays a key role in the evaporation process. As indicated by

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Allen and Ingram (2002), global mean precipitation would increase 3.4% per degree Kelvin, and increased precipitation would eventually lead to an increase in evaporation (Huntington, 2006). Jung et al. (2010) showed that the global increase in evapotranspiration over land is now being slowed down because of increasing moisture limitation.

As potential evapotranspiration (ET_p) is so widely related with global climate and environmental change, it is important to develop proper methods to estimate it. The reference evapotranspiration (ET_0) is considered a very good representation of ET_p under certain given conditions. It is defined as 'the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground' (Allen et al., 1998). The Penman–Monteith method is recommended by the Food and Agricultural Organization (FAO) as the best method to determine ET_0 (Allen et al., 1998), especially when sufficient meteorological data are available.

Recently, decline of potential evapotranspiration during the past 30–50 years has been reported in many different regions in the world, such as USA (Peterson et al., 1995), Canada (Burn and Hesch, 2007), China (Xu et al., 2006; Zhang et al., 2007; Liu and Yang, 2010), and India (Chattopadhyay and Hulme, 1997; Bandyopadhayay et al., 2009). Meanwhile, researchers also pointed out there were increasing trends in potential evapotranspiration across different regions, such as Nigeria (Hess, 1998), Israel (Cohen et al., 2002), Northeast Brazil (Silva, 2004), and Iran (Yagob et al., 2011). Explaining the trends in ET_p has challenged researchers all around the world.

The attribution and sensitivity analysis provide powerful ways for studying the changes of potential evapotranspiration dynamics. The attribution analysis aims at unraveling the individual contribution of each climatic variable to the long-term trends of ET_p. The sensitivity analysis concerns on evaluation of the sensitivity of ET_p in relation to different climate variables. The methods are especially important in regions with complex underlying and climate conditions. Numerous studies conducted using the two methods indicated the sunshine duration, solar radiation or wind speed played dominant roles in controlling changes of ET_0 or ET_{pan} in most regions (Roderick and Farquhar, 2002; McVicar et al., 2008; Jhajharia et al., 2009). However, no general conclusions have been drawn.

The Upper Mekong River Basin has great diversity in terrain types, vegetation, and climate zones. Detailed investigation of the variation of ET_0 and the related meteorological factors in this area is very important. In the present study, we focus on the changes in ET_0 of the basin and conduct attribution and sensitivity analysis of ET_0 in relation to different climatic variables (i.e., air temperature, relative humidity, wind speed at 2 m above ground, and sunshine duration hours). We also test whether potential and actual evapotranspiration follow Bouchet's complementary relationship hypothesis in the basin.

2. Study area

Located in Southeast Asia, the Mekong River is widely considered as one of the most important international rivers. The upper reach of the river located in China is also called the Lancang River, originating from the Qinghai–Tibetan plateau and crossing the national boundary in southwestern Yunan Province. The river is 2161 km long with a total drainage area of 167,400 km^2 (21°–34°N, 94°–102°E). The elevation varies from 486 m to 6173 m, while the annual precipitation and potential evapotranspiration vary from less than 500 to more than 1600 mm and from 858 mm to 1205 mm respectively. The large variation of elevation and water-energy conditions leads to complex terrain types (glacier, plateau, canyons, and alluvial plains et al.) and many different climate zones (the Frigid Zone, the Frigid-Temperate Zone, the Temperate Zone, the Sub-Tropical Zone, and the Tropical Zone) and therefore, very complex ecosystems and great bio-diversity (Bart et al., 2001; Kite, 2001; Shimizu et al., 2004; Zhou et al., 2006; Zuo et al., 2011; Li et al., 2012).

The basin belongs to the southwest monsoon region, which divides a year into two parts explicitly, the dry season (November–April) and the wet season (May–October). The long-term averaged precipitation for the dry season is only one tenth of that for the wet season (Kingston et al., 2011; Li et al., 2012).

3. Data and methods

3.1. Data

In this study, mean air temperature (T_{mean}), wind speed, relative humidity, precipitation, and sunshine duration datasets of 35 weather stations for the period from 1960 to 2005 were provided by the National Climate Centre (NCC) of the China Meteorological Administration (CMA) (Table 1, Fig. 1). The mean air temperature was measured at 2 m height. Wind speed was measured at 10 m and recalculated to 2 m height based on a wind profile relationship (Allen et al., 1998). The pan data were derived from the stations located in or around the three small test sub-basins. Annual precipitation was used to define the water-limited and energy limited areas.

3.2. Methods

3.2.1. Potential evapotranspiration estimation

The Penman–Monteith method, which is recommended by the Food and Agricultural Organization (FAO), is strongly physically based with both the radiative and aerodynamic terms taken into consideration (Allen et al., 1998). In this study, daily reference evapotranspiration was calculated using the Penman–Monteith method, and the monthly, seasonally and yearly reference evapotranspiration for each station were aggregated from daily data. The Penman–Monteith method can be expressed as follows (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 – reference evapotranspiration (mm day^{-1}),

R_n – net all-wave radiation at the canopy surface (MJ m^{-2} day^{-1}),
G – soil heat flux density (MJ m^{-2} day^{-1}),
T – mean daily air temperature at 2-m above ground level (°C),
u_2 – wind speed at 2-m above ground level (m s^{-1}),
e_s – saturation vapour pressure (kPa),
e_a – actual vapour pressure (kPa),
e_s–e_a – saturation vapour pressure deficit (kPa),
Δ – slope of the saturated vapour pressure curve versus air temperature (kPa C^{-1}),
γ – psychrometric constant (kPa C^{-1}).

3.2.2. Attribution analysis

In the study, the attribution analysis of ET_0 to climatic variables was examined using the differentiation equation methods, which

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