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Assessing the temporal variance of evapotranspiration considering climate and catchment storage factors

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ABSTRACT

Understanding the temporal variance of evapotranspiration (ET) at the catchment scale remains a challenging task, because ET variance results from the complex interactions among climate, soil, vegetation, groundwater and human activities. This study extends the framework for ET variance analysis of Koster and Suarez (1999) by incorporating the water balance and the Budyko hypothesis. ET variance is decomposed into the variance/covariance of precipitation, potential ET, and catchment storage change. The contributions to ET variance from those components are quantified by long-term climate conditions (i.e., precipitation and potential ET) and catchment properties through the Budyko equation. It is found that climate determines ET variance under cool-wet, hot-dry and hot-wet conditions; while both catchment storage change and climate together control ET variance under cool-dry conditions. Thus the major factors of ET variance can be categorized based on the conditions of climate and catchment storage change. To demonstrate the analysis, both the inter- and intra-annul ET variances are assessed in the Murray-Darling Basin, and it is found that the framework corrects the over-estimation of ET variance in the arid basin. This study provides an extended theoretical framework to assess ET temporal variance under the impacts from both climate and storage change at the catchment scale.

1. Introduction

Evapotranspiration (ET) is an important hydrologic process which accounts for two thirds of precipitation and consumes a significant amount of surface energy [2]. Understanding ET trend and variance is key to improving weather and climate forecasting [3] and providing better guidelines for climate change adaptation [4]. Although much work has been carried out to measure and simulate ET, our understanding of ET trend and variance is still limited. In addition to climate change, interferences introduced by human activities, such as conversion from natural vegetation to bio-fuel crops [5] and the expansion of irrigated crop land [6], also significantly affect ET pattern. If a catchment is conceptualized as a system, the system output, ET, is driven by climatic forcings and filtered by catchment processes (e.g., vegetation, soil, groundwater and human activities). The variance of ET captures the fluctuation of a hydro-climatic system and catchments' responses to climate. Thus, ET may be analyzed as the interactions between catchment and climate.

Budyko [7] pioneered in estimating long-term ET by coupling hydrologic cycle and terrestrial energy budget. He asserted that a region's ET is largely controlled by two climatic factors: precipitation (P) and incident energy (usually represented by potential evaporation, PET). In arid regions (i.e., $PET/P \gg 1$), ET is mainly constrained by P; in humid regions (i.e., $PET/P \ll 1$), ET is mainly controlled by energy supply (associated with PET); in between, ET is affected by both P and PET. The Budyko hypothesis has been validated by observations all over the world [8,9]. Based on the Budyko hypothesis, Fu [10] and Yang et al. [11] derived analytical expressions, which provide a framework to quantify long-term ET. Other empirical Budyko equations can be found in Choudhury [8] and Zhang [9]; some Budyko equations obtained by a stochastic soil moisture model can be found in [12].

The Budyko equation has been used for ET sensitivity and variability analysis due to its explicit function form. For example, Roderick and Farquhar [13] evaluated the derivatives of ET with respect to P, PET and a catchment property parameter to predict the effect of climate change on catchment water balance. Niemann and Eltahir [14] studied the sensitivity of regional hydrology to climate change using Budyko equation and a physical model in the Illinois River Basin and found that ET tends to dampen the signals in P and PET. Han et al. [15] assessed long-term and

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annual water balance in Tarim Basin in China and found that influences from irrigation on ET variability become increasingly apparent with the increase of irrigation amount in the arid basin. Especially, besides those assessments using models or data, Koster and Suarez [1] proposed an analytical framework based on Budyko equation to quantify ET variance as below:

$$\sigma^2_{\mathrm{ET}} = \left[F(\bar{\phi}) - F'(\bar{\phi})\bar{\phi}\right]^2 \sigma^2_{\mathrm{P}} \tag{1}$$

where $\bar{\phi}$ is the long-term average aridity index defined as PET/P; $F(\bar{\phi})$ is the Budyko equation. According to the results from this equation and a general circulation model, they found that water availability appears to be the critical factor on the inter-annual ET variance. Later, they validated Eq. (1) by a global observation dataset for its predictability of ET variance [16]. Following that, Eq. (1) has been applied to assessing ET variance by many studies [16–18]. However, Eq. (1) does not account for many other factors that are also important for ET variance. For example, based on the assessment of 1337 catchments in the United States, Sankarasubramanian and Vogel [18] found that the buffer effect of soil storage capacity could be an important factor on ET variability. Potter and Zhang [19] derived analytical expression for ET variance at the inter-storm scale from a stochastic soil moisture balance model and assessed the impacts of storm property and soil moisture on inter-storm ET variance. Koster [16] pointed out that Eq. (1) performs well under dry climates, but the temporal coincidence of P and surface energy can affect ET variance under wet climates, which is not considered in Eq. (1).

This study addresses the limitation of Eq. (1) by re-examining its assumptions. First, Eq. (1) is based on the long-term average water balance by assuming negligible storage change (i.e., P is the only water source for ET). At the annual or monthly time scale, however, P is not the sole source of water availability, since catchment storage change plays an important role to balance the water budget. The estimation of annual ET was found biased without considering subsurface water storage change [20,21]. Even at the long-time scale, accumulated groundwater over-exploitation provides an additional source for ET [22–24]. Thus, incorporating catchment storage change caused by both natural factors and human activities will improve the understanding of ET temporal variance. Second, Eq. (1) assumes that ET variance is only driven by the fluctuation of P and captures neither the effects from PET variance nor the temporal coincidence between P and PET. For example, Potter et al. [25] demonstrated that the in-phase P and PET seasonality leads to higher ET ratio (ET/P) than the out-of-phase P and PET seasonality does. As a result, Eq. (1) is limited to arid regions where P dominates the hydrologic processes; however under moderate and wet climates, the effect of P on ET variance diminishes. For example, an analysis of world-wide ET during the period of 1961–1999 [26] showed that P accounts for 95% of the ET variance in dry basins, but only 55% in wet basins. Particularly in cold areas, the accumulation and melting of snowpack are controlled by radiative energy, which further affect vegetation growth and ET flux [27]. As a result, PET becomes an essential factor in understanding ET variance in basins with limited energy supply. Furthermore in arid regions with intensive irrigation, P would not dominate ET as a result of irrigation application to maintain crop yield [15]. In such case, ET variance is closely related to farmers' response to climate fluctuation.

The goal of this study is to identify climate and catchment storage factors governing ET temporal variance by extending the relationship analytical framework of Koster and Suarez [1] to a more comprehensive one by incorporating the water balance and the Budyko hypothesis. The questions to address include: (1) how the fluctuations of climatic variables shape ET variance under a wide spectrum of climate conditions; (2) how climate and catchment storage change affect ET variance at various time scales (e.g., inter- and intra- annual scale). In part 2, we develop the framework for ET variance analysis based on the Budyko hypothesis and water balance and discuss the dominant factors affecting ET under various conditions. In part 3, we apply the framework in Murray-Darling River Basin to assess inter- and intra-annual ET variance. In part 4, we discuss some implications of the proposed framework and end with conclusions.

2. Theoretical framework for ET temporal variance

2.1. Catchment water balance in the Budyko equation

The water balance lumped over a catchment over a time interval ΔT_i is:

$$\Delta S_i = \mathrm{P}_i - \mathrm{ET}_i - Q_i \tag{2}$$

where ΔS is catchment storage change; P is precipitation; ET is actual evapotranspiration; Q is runoff; and the subscript i represents the time interval ΔT_i, which can range from a month to decades. Over a long period when the catchment reaches equilibrium (i.e., flux-in balances flux-out and ΔS is negligible), the sum of ET and Q balances the incoming water flux P. At a small temporal scale (e.g., month), the water availability for ET and Q is adjusted by catchment storage. When catchment storage increases (i.e., ΔS is positive, due to, e.g. snowpack accumulation and aquifer recharge), less available water is left for ET and Q. On the other hand, when catchment storage releases (i.e., ΔS is negative, such as snow melting and aquifer discharge), it provides additional water for ET and Q [20]. As time scale becomes smaller, the role of catchment storage in water balance becomes significant in Eq. (2). To account for the complementary effect of catchment storage, the total available water (P′) for ET and Q is defined by rearranging Eq. (2), which yields:

$$\mathrm{P}'_i = \mathrm{P}_i - \Delta S_i = \mathrm{ET}_i + Q_i \tag{3}$$

The total available water for ET not only depends on the system input (i.e., atmospheric water supply), but is also determined by catchment storage. Vegetation, soil moisture condition, groundwater table, and catchment management practices all affect the total water availability. In a catchment with significant subsurface lateral flow and/or trans-boundary water delivery, the inflow into the catchment or the outflow to another catchment can be added to or subtracted from P′ in Eq. (2) to account for the total water availability.

The original Budyko hypothesis focuses on geographical zonality (i.e., spatial comparison) and is validated for long-term average over many catchments. Fu [10] and Yang [11] derived analytical solutions expressed as the long-term aridity index ($\bar{\phi} = \overline{\mathrm{PET}}/\bar{\mathrm{P}}$) and evaporation index ($\overline{\mathrm{ET}}/\bar{\mathrm{P}}$) based on dimensional analysis and mathematical reasoning. Hereinafter, variables with over-bar denote long-term average. For example, the analytical solution obtained by Fu [10] is:

$$\frac{\overline{\mathrm{ET}}}{\bar{\mathrm{P}}} = F(\bar{\phi}) = F\left(\frac{\overline{\mathrm{PET}}}{\bar{\mathrm{P}}}\right) = 1 + \frac{\overline{\mathrm{PET}}}{\bar{\mathrm{P}}} - \left[1 + \left(\frac{\overline{\mathrm{PET}}}{\bar{\mathrm{P}}}\right)^{\varpi}\right]^{1/\varpi} \tag{4}$$

where ϖ is a parameter representing catchment characteristics. Since Eq. (4) is based on long-term average, it assumes negligible catchment storage change (i.e., $\overline{\Delta S} = 0$) and atmospheric water is the only source for ET and Q. Although some studies have applied Fu's equation to annual scale and found a reasonable fit to observed data [8], the assumption on negligible storage change is not valid at shorter time scales. As time scale becomes finer, model complexity should be extended to represent additional processes [28]. For example, Zhang et al. [29] introduced an additional partition of