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Assessment of Evaporative Demand Drought Index for drought analysis in Peninsular Malaysia

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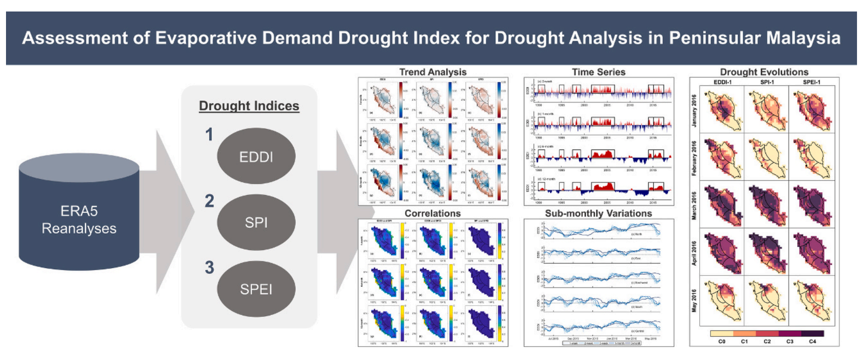
HIGHLIGHTS

- Evaluation of EDDI as a drought monitoring tool in tropical Peninsular Malaysia
- EDDI shows comparable performance in historical drought events identification.
- Consistent drought signals among EDDI, SPI and SPEI at monthly timescales
- EDDI has shorter application timescales for early detection of droughts.
- EDDI is more sensitive to drought signals when rainfall deficits are normalized.

GRAPHICAL ABSTRACT



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ABSTRACT

An effective drought monitoring tool is essential for the development of timely drought early warning system. This study evaluates Evaporative Demand Drought Index (EDDI) as a drought indicator in measuring spatiotemporal evolution of droughts over Peninsular Malaysia during 1989–2018. The modified Mann–Kendall and Sen's slope tests were performed to detect the presence of monotonic trends in EDDI, Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and their related climate variables. The performance of EDDI in capturing the drought onset, evolutions and demise of historical severe droughts was also compared with SPI and SPEI at multiple timescales. EDDI demonstrates strong spatiotemporal correlations with SPI and SPEI and comparable performance in historical drought events identification. At sub-monthly timescale, 2-week EDDI displays equivalent drought severities and durations for all historical severe droughts corresponding to the monthly EDDI. In the case when rainfall deficits are normalized in an otherwise warm and dry month, EDDI may serve as a great alternative to SPI and SPEI due to it being sensitive to the changes in prevalent atmospheric conditions. Collectively, the results fill in the knowledge gaps on drought evolutions from the evaporative perspective and highlight the efficacy of EDDI as a valuable drought early warning tool for

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Peninsular Malaysia. Future study should explore the physical mechanisms behind the development of flash drought and the role of evaporation in the drought propagation processes.

1. Introduction

Drought is defined as deficits in moisture fluxes/states relative to its local long-term normal conditions. It is a complex and recurring natural disaster with adverse impacts on ecological and socioeconomical sectors by disrupting the food supply chain and threatening water security (Cardil et al., 2019; De Silva and Kawasaki, 2018; Kapoor et al., 2020). Over the past century, Asia has had the largest populations affected by drought, with total damages amounting to 90 billion USD (Guha-Sapir et al., 2021). These damages and losses could be amplified in the future, as the recent report by the Intergovernmental Panel on Climate Change (IPCC) reveals that severe dry events are expected to be more severe due to the intensified water cycle under global warming (IPCC, 2021).

Despite the widespread influences of drought on human livelihood, there are difficulties in identifying and monitoring its onset and demise. One of the most common monitoring tools utilized to quantify dry conditions is drought index derived from atmospheric variables. Drought index provides a clearer picture of drought levels and severities that is more suitable for decision-making compared to the use of raw magnitude of the atmospheric variable (Hayes, 2006). Major operational drought indices employ either rainfall alone or in combination with other meteorological variables in their assimilations. For example, the Standardized Precipitation Index (SPI) developed by McKee et al. (1993) measures meteorological drought solely based on rainfall data. It was recommended by the World Meteorological Organization (WMO) to be used in drought monitoring due to its ease of use and flexibility (WMO, 2012), which is particularly important for regions with limited data availability. Integrating rainfall with other variables, such as evaporative demand (ET_0), which has a great effect on soil moisture depletion (Otkin et al., 2018; Pendergrass et al., 2020), can provide more insights on how drought conditions change over time. The exclusion of ET_0 effects as a part of the hydrological process can significantly underestimate soil moisture deficits and decline in runoff during extended drought, especially in a warming climate (Massari et al., 2022). To include ET_0 for its relevance in the hydrological cycle, Vicente-Serrano et al. (2010) developed a multivariate drought index named the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates both rainfall and ET_0 to describe drought condition. A similar approach in describing drought is the Palmer Drought Severity Index (PDSI), which measures the moisture availability using the water balance equation based on the supply and demand concept (Palmer, 1965). The applications of SPEI and PDSI have been extensively studied for tropical climates; they often reveal different drought severity, frequency or trend compared to those estimated by SPI (Balbo et al., 2019; Fung et al., 2020; He et al., 2021; Uddin et al., 2020). While the SPEI and PDSI have been proven useful in measuring drought, most of the studies adopted simple formulations of ET_0 based on air temperature alone such as the Thornthwaite, Blaney-Criddle and Hargreaves-Samani methods (Al-Faraj and Al-Dabbagh, 2015; Ortiz-Gómez et al., 2022; Zaki and Noda, 2022). These methods may create uncertainties in the derived drought index as the effects of solar radiations, humidity and wind speed, which govern the background aridity and moisture depletion from the upper soil layers, are excluded from the calculation (Feng et al., 2017; Sherwood and Fu, 2014; Wang et al., 2022). As such, more physically-based ET_0 formulation, such as the Penman–Monteith equation (Monteith, 1965), should be adopted in the computation of ET_0-based drought index to accurately reflect the drought conditions under warming climate (Sheffield et al., 2012). In view of this, the Penman–Monteith method has been endorsed by the Food and Agriculture Organization of the United Nations and the American Society of Civil Engineers (ASCE) as the standard method for ET_0 estimation.

Although various drought indices have been proposed to objectively quantify drought characteristics and spatial extent, effective drought management still depends on indices that are drought response oriented – appropriately address different drought severities and provide timely warnings. Traditionally, drought indices are designed to measure drought over months or years, as drought is usually thought of as slow-evolving and sustained (Mishra and Singh, 2010). However, the rapid development of several drought events at a shorter timescale have heightened the interests of researchers in recent years as they present a new challenge for drought early warning (Hoerling et al., 2012; Li et al., 2019; Nguyen et al., 2019). When weather anomalies such as rainfall deficits, warm surface temperature, strong and dry winds and sunny skies persist, soil moisture can quickly deplete, escalating water stress to vegetation and inducing rapidly developing drought, or known as "flash drought" (Otkin et al., 2013). Such flash drought can occur in a period of days or weeks and has detrimental impacts on agriculture and food supply, especially when it occurs during the growing season, which is the critical stage for sufficient yield gains (Lobell et al., 2014). In theory, SPI, SPEI and PDSI can be computed for shorter time periods (daily or weekly) to better capture short-term moisture deficits. However, they may be less reliable for the monitoring of flash drought as they do not account for other atmospheric variables, such as wind and radiation anomalies, that are typically associated with flash drought development (Otkin et al., 2013; WMO, 2012; Zhang et al., 2017). To address these shortcomings, Hobbins et al. (2016) formulated a physically based drought index named Evaporative Demand Drought Index (EDDI). EDDI provides valuable information on anomalous ET_0 at 1-week to 12-month timescales and has been proven useful as an indicator for flash drought in the continental United States (CONUS) and mainland China (Hobbins et al., 2016; McEvoy et al., 2016a; Yao et al., 2018). In addition, seasonal forecasts of ET_0 are found to be more skillful than for precipitation (McEvoy et al., 2016b). Being independent of precipitation, EDDI can be valuable for seasonal drought forecasts and early warning. However, very little is known about the applicability of EDDI on drought monitoring in tropical Southeast Asia, which has a different climate profile compared to the aforementioned regions. Previous study by Gevaert et al. (2018) found that drought signals in tropical climates tend to be more responsive to rainfall deficits at sub-seasonal scale, indicating more frequent occurrence of flash drought against long-term drought. Nonetheless, the hazards and spatiotemporal variabilities of droughts in Southeast Asia have often been evaluated using the SPI, SPEI and PDSI (He et al., 2021; Prabnakorn et al., 2018; Räsänen et al., 2016; Salvacion, 2021; Suroso et al., 2021), while the use of EDDI for flash drought monitoring has not been fully understood.

Before EDDI is adopted for operational drought monitoring, a few pertinent questions need to be addressed: (a) Is EDDI suitable for drought trend analysis in the Tropics? (b) How well is EDDI in drought detection against other commonly used drought indices? (c) Can EDDI capture the drought stress during extreme droughts? As the knowledge gaps on the application of EDDI remain large, this study intends to evaluate the effectiveness of EDDI in drought monitoring application for the tropical Peninsular Malaysia. The performance of EDDI in drought monitoring is compared to those of SPI and SPEI. In the following sections, spatial distribution of drought trends for Peninsular Malaysia is presented. The strength of associations between drought indices is derived by cross-correlating EDDI, SPI and SPEI at various temporal scales. The evolutions of two severe drought events are investigated using EDDI in the case studies.