The Development of Atmospheric Crop Moisture Index for Irrigated Agriculture

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Abstract—This paper develops the Atmospheric Crop Moisture Index (ACMI), an indicator of atmospheric drought. Levels in the index represent the possibility of rainfall or the lack of moisture needed at various stages of crop growth. The lack of moisture is determined with the ratio between water supply and demand, where the supply indicator is Precipitable Water Vapor (PWV). The ACMI was calculated from data collected between February 2010 and September 2014. The example of calculation of 10-day values of ACMII\textsubscript{10} for rice is provided. The comparison of ACMI and other indices shows poor correlation with the SPI, the SPEI, and the scPDSI; however, it displays high correlation with precipitation, the PE, and the MAI. The ACMI is a parameter affected by surface temperature, relative humidity, wind speed, atmospheric pressure, and solar irradiation; all these parameters are included in the study of drought. The ACMI is an effective tool for agricultural water management.

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1. INTRODUCTION

Most farms in Northeast Thailand get water through the natural cyclic movement of water (rain) driven by the Sun energy. Water vapor movement governs global weather patterns [22]. The role of moisture is more essential in tropical areas, where monsoons occur. We appreciated the relationship between atmospheric moisture and crop yield and developed the atmospheric crop moisture index (ACMI) computed from moisture supply (Precipitable Water Vapor, PWV) and crop water requirement. So, ACMI reflects atmospheric moisture deficit or surplus in comparison with plant water requirements and can be used to determine the most suitable time for planting. This paper discusses PWV estimation using data from GPS as well as calculation of crop water requirement and ACMI.

2. MATERIALS AND METHODS

2.1. Precipitable Water Vapor

The amount of moisture in the air at a given time is the factor that determines the probability of rain: high amounts of water correspond to high possibility of rain. There are several ways of determining and expressing the amount of atmospheric water vapor. Absolute humidity is the mass of water vapor in a volume of air; mixing ratio is the ratio of water vapor mass to dry air mass; specific humidity is the ratio of water mass to air mass; relative humidity is the ratio of water vapor pressure to saturated water vapor pressure; PWV is the amount of water vapor in the air column.

PWV has been used widely in weather models and weather tracking [24], studies of drought [5] and El Niño [24, 26]. Analytically, PWV can be computed as an integration of the mixing ratio $x$ divided by gravitational acceleration $g$. The mixing ratio is integrated between the top and bottom of the atmosphere:

$$\text{PWV} = \frac{1}{\rho_w g} \int_{P_t}^{P_s} x dP$$  \hspace{1cm} (1)
where $\rho_w$ is the density of water; $g$ is the acceleration of gravity; $P_{\text{toA}}$ is pressure at the top of the atmosphere; $P_s$ is surface pressure; and $x(P)$ is the mixing ratio at pressure $P$. It is more practical to determine PWV using the integral water vapor (IWV) density and water density $\rho_w$.

$$\text{PWV} = \text{IWV}/\rho_w$$

(2)

where IWV is the sum of the average values of water vapor density $\rho_v$ at different heights in the atmosphere:

$$\text{IWV} = \sum \rho_v \, dz.$$  

(3)

If the atmosphere is in the equilibrium, water vapor density can be obtained using the ideal gas law

$$\rho_v = P_v / R_v T,$$  

where $R_v$ is the gas constant of water vapor; $T$ is temperature; $P_v$ is the partial water vapor pressure obtained by rawinsondes.

The mentioned method for determination of PWV uses rawinsonde data. Alternatively, PWV can be estimated with satellite data [9] or computed via numerical methods of weather prediction [7]. It is also possible that such data as specific humidity, relative humidity, and water vapor pressure obtained from surface meteorology stations can be used to estimate PWV; however, this approach leads to great errors. Alternatively, PWV can be measured using atmospheric microwave radiometers [12].

The discrete method is to estimate PWV using data from GPS. The method estimates the delay of a dual-frequency microwave signal (bands $L_1 = 1574.42$ MHz and $L_2 = 1227.60$ MHz) sent from GPS satellites to ground stations [2]. This method provides accuracy comparable to that of the atmospheric microwave radiometer [7, 20, 23] and ERA-Interim analysis data [6]; it is relatively inexpensive, all-weather, and around the clock.

The signal propagation delay has two components: Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). As the names suggest, the first component refers to the delay that occurs in dry air, and the second, to the delay in wet air. The combined effect is called Zenith Total Delay (ZTD) [8, 21].

$$\text{ZTD} = \text{ZHD} + \text{ZWD}.$$  

(5)

The ZTD can be analytically computed by integrating total refractivity $N$ across the atmosphere $Z$ [4]:

$$\text{ZTD} = \int N(z) \, dz.$$  

(6)

(the integration occurs from the surface to the top of the atmosphere).

However, it is difficult to calculate total reflectivity at a certain time moment, so, the ZTD calculation accuracy is quite low. Besides, ZTD value can be determined through the GPS data analysis using GPS program tools such as GAMIT, GIPSY, or Bernese.

The ZHD parameter depends on pressure $P_s$ at a certain region, latitude $\lambda$, and ellipsoid height $H$. The ZHD value can be calculated from the following formulae:

$$\text{ZHD} = (2.2779 \pm 0.0024) \frac{P_s}{f(\lambda, H)}.$$  

(7)

$$f(\lambda, H) = 1 - 0.0026 \cos 2\lambda - 0.0028 H.$$  

(8)

The values of delay in wet air ZTD is determined from the formulae:

$$\text{ZWD} = 0.00227 \left(0.005 + \frac{1255}{T_s}\right) e_v.$$  

(9)

$$\text{ZWD} = -74.3288 + 17.123e_v - 0.5955T.$$  

(10)

$$\text{ZWD} = \text{ZTD} - \text{ZHD}.$$  

(11)

There are several methods for determining ZWD. According to the model by Saastamoinen (9) and Uang-aree (10), water vapor pressure $e_v$ and temperature $T_s$ can be used to find ZWD [21, 27]. To improve accuracy, equation (5) was adapted to find ZWD from ZTD and ZHD (11) [14]. Estimating PWV from GPS data can be done using ZWD and the dimensionless constant of proportionality $\Pi$:

$$\text{PWV} = \text{ZWD} \times \Pi.$$  

(12)