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Exploring Subsurface Thermal Dynamics at the Astronomical Observatory in Thiruvananthapuram

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Abstract

The study involves the analysis of soil temperature data collected at various depths with an hourly interval using a hydro-meteorological data acquisition system at the Astronomical Observatory in Thiruvananthapuram. The research reveals that the highest diurnal fluctuation occurs at the surface, with the amplitude of the thermal wave decreasing exponentially with depth. Parameters such as damping depth and the velocity of the diurnal thermal wave are calculated. Additionally, thermal diffusivity of the soil over a six-month period (January 2008 to June 2008) is estimated using the amplitude method (Kaushik et al., 1965). The study investigates the variation of thermal diffusivity with average soil moisture, highlighting that the minimum diffusivity aligns with the period of minimum soil moisture, and an increase in diffusivity is observed with higher moisture content.

Key words: Soil temperature, soil thermal diffusivity, damping depth

1. Introduction

The investigation of temperature, moisture, and thermal properties of soil constitutes a vibrant domain within applied physics research. Soil temperature, a pivotal physical attribute, significantly influences the rate of energy exchange at the soil-air interface. Understanding the heat flow through the soil is crucial for comprehending plant growth dynamics. Extreme soil temperature levels have a profound impact on plant life. By monitoring temperatures at various soil depths, the damping and propagation of thermal waves within the soil can be observed. This research aims to scrutinize the diurnal and annual fluctuations in soil temperature, examining the amplitude variation of the diurnal thermal wave with depth. Furthermore, the study explores the influence of soil moisture on soil thermal diffusivity, calculated from monthly mean soil temperature data.

2. Method and Measurement

The diurnal temperature wave, generated by the sun's heating of the Earth's surface during the day and subsequent cooling at night, exhibits a periodicity of 24 hours. The conductive heat transfer equation for a one-dimensional isotropic medium describes the thermal dynamics of this process. (Kaushik et al. 1965) is

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$$\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

The provided equation (1) describes the relationship between soil temperature (T), soil thermal diffusivity (k), time (t), and depth (z). The thermal diffusivity (k) can be determined by analyzing the amplitude decrement and phase difference of temperature waves at different depths in the soil. The solution to equation (1) provides the amplitude (A) of the temperature wave at any given depth (z).

$$A = A_o \exp\left[-\sqrt{\frac{\omega}{2k}} z\right] \qquad (2)$$

The equation (2) introduces additional parameters, where A_0 represents the amplitude of the thermal wave at the surface, and ω is the angular velocity of the Earth's rotation (7.292 X 10^{-5} rad/sec). Consequently, equation (2) provides the amplitude equation for calculating thermal diffusivity given in equation (3)

$$k = \frac{\omega}{2}\left[\frac{z}{\ln(A/A_o)}\right]^2 \qquad (3)$$

The research was carried out at the Astronomical Observatory (76° 59' E longitude and 8° 30' N latitude), part of the University of Kerala and situated adjacent to the India Meteorological Department in Thiruvananthapuram, South Kerala. The soil characteristics at the experimental site include a surface color ranging from dark brown to dark reddish-brown, with a texture ranging from gravelly sandy loam to gravelly loam. The landscape reflects laterite development under a tropical climate with distinct wet and dry seasons. Utilizing a hydro-meteorological data acquisition system installed at the site, soil temperature and moisture data were recorded at one-hour intervals. The study focused on the diurnal temperature variations, selecting monthly mean data for June 2008. Thermal diffusivity calculations were performed over a six-month period (from January 2008 to June 2008), using monthly mean soil temperature data. Unfortunately, data for April 2008 is unavailable due to technical issues.

3. Results and Discussion

Figure 1 illustrates the diurnal variation in the measured soil temperature profile throughout the month of June 2008, considering both time and soil depth. The soil surface exhibited the highest temperature fluctuation compared to deeper soil layers. In contrast, the soil temperatures at greater depths showed relatively constant changes over time. Beyond a depth of 30 cm, the soil experienced minimal daily temperature fluctuations, indicating damping of the diurnal variation.

In Figure 2, the amplitude of the thermal wave is graphed against depth. Assuming the soil's thermal characteristics remain constant with depth and time of day, and modeling soil temperature as a sine wave solution to the heat equation, we can expect the amplitude of the diurnal soil temperature wave to decrease exponentially with greater soil depth. This exponential decrease is characterized by a specific length referred to as the damping depth.

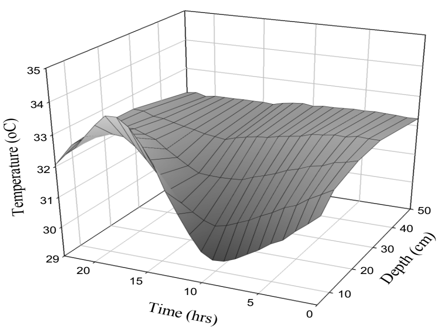

Fig.1 Diurnal soil temperature fluctuation with respect to time and soil depth

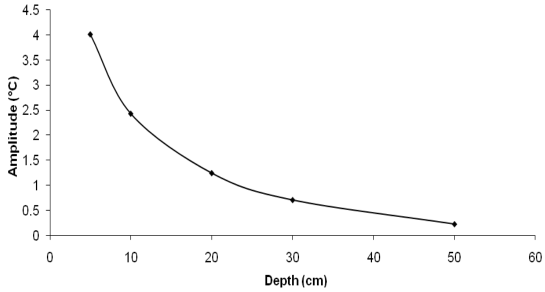

Fig 2. Variation of amplitude of thermal wave with depth

Figure 2 is an exponential curve with the data fitting in the following equation.

$$A = 6.626\exp(-0.1004d) \tag{4}$$

The fitting curve provides the relevant damping depth as an outcome. In the case of the monthly mean data depicted in Figure 2, the determined damping depth is 9.96 cm. This depth serves as an approximation of the distance over which diurnal temperature variations extend into the soil.

The velocity of the thermal wave, υ_T can be calculated by measuring the time difference between the temperature maxima at various depths. It represents the velocity of the temperature maximum into the soil. υ_T is given by, υ_T = (depth difference)/(time between maximum temperature at the depths). For the month of June, the average velocity of thermal wave is found to be 2.5 cm/h for the depth 5-10 cm. In order to see the variation through the twelve months, hourly observations of a day were averaged to get the daily mean. From figure 3, it can be seen that soil temperature is minimum during rainy seasons and maximum during dry seasons. Amplitude of annual thermal wave diminishes with depth, but less rapidly than the diurnal (Fig 4). The behaviour of annual thermal wave is discernible down to a few meters.

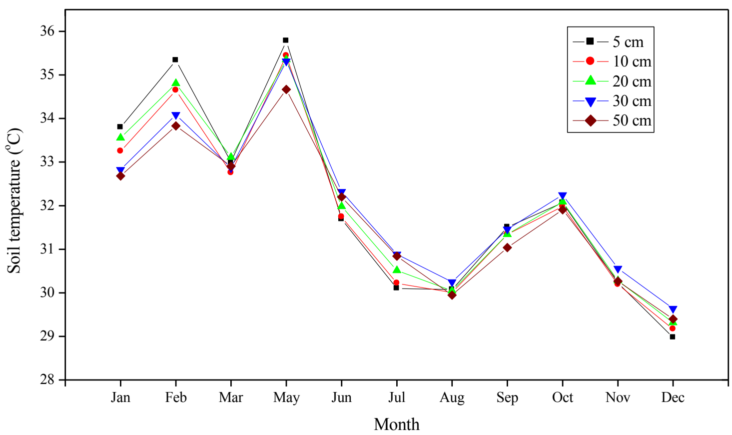

Fig.3: Monthly variation of Soil temperature

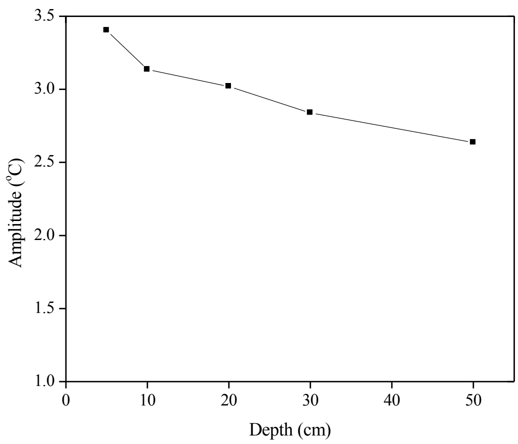

Fig.4: Variation of amplitude of thermal wave with depth

Thermal diffusivity of the soil is calculated for the layer 5-10 cm using the equation (3) for six months from January 2008 to June 2008 to study the effect of soil moisture. The calculated values are shown in table 1. The results shown in the table 1 gives a feeling about the influence of soil moisture on soil thermal diffusivity. Minimum soil thermal diffusivity of 0.216 $X10^{-6}$ m^2 sec^{-1} is observed in February 2008 when the average soil moisture is 12.54 %. The plot of soil thermal diffusivity versus soil moisture is shown if figure 3. It is seen that thermal diffusivity increases with increase in moisture content and maximum diffusivity is observed in June 2008 when the average soil moisture content is 28.41 %. Heat capacity of water is higher than that of dry soils. Hence more heat is conducted by the soil in the presence of higher moisture. Oke (1978) indicated that thermal diffusivity of the soil initially increases with increase of moisture content and begins to decline when the moisture content exceeds 20 %. The variation of thermal diffusivity due to wetting of the soil has been studied by Anandakumar *et al* (2001) and reported a soil thermal diffusivity value of 1.06 X 10^{-6} m^2 s^{-1} on a wet day.

Month	Thermal diffusivity $X10^{-6}$ m^2 sec^{-1}	Average Soil moisture (%)
January	0.223	12.98
February	0.216	12.54
March	0.285	22.66
April	Data not available	
May	0.264	17.53
June	0.361	28.41

Table 1: Thermal diffusivity and soil moisture from January 2008 to June 2008

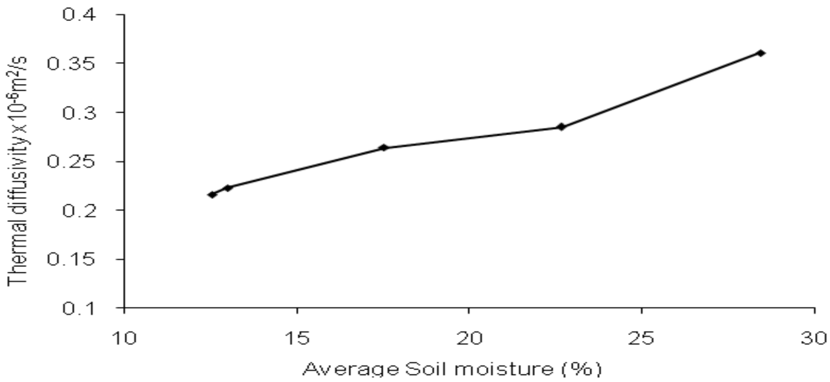

Fig 5. Variation of soil thermal diffusivity with average soil moisture

Conclusion

The study examines the diurnal variation of soil temperature at various depths, revealing that the maximum fluctuation occurs at the soil surface compared to deeper layers. The exponential decrease in the amplitude of the thermal wave with depth is observed. The calculated damping depth for the diurnal thermal wave in June 2008 is 9.96 cm, signifying the distance over which temperature variations extend into the soil. The velocity of the thermal wave at a depth of 5-10 cm is calculated to be 2.5 cm/h. Additionally, the investigation explores the relationship between soil thermal diffusivity and monthly average soil moisture, indicating that higher soil moisture correlates with greater thermal diffusivity. This suggests that soil conducts more heat in the presence of higher moisture due to the larger heat capacity of water, resulting in increased diffusivity.

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