Spatial variability of soil temperature under greenhouse conditions

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Abstract

The spatial variability of surface temperature has been examined under greenhouse conditions at Al-Mada’in Research station. Soil temperatures were measured at 14:00 h on 3 consecutive days after a trickle irrigation. Measurements were made every 0.5 m along a 55-m transect with copper–Constantan thermocouples. In addition, soil samples were collected to determine the thermo-gravimetric water content between the soil surface and 0.05 m depth. Cross semi-variograms and cross-correlation functions were determined and the measurements were found to be correlated over space. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Soil temperature; Geostatistics; Cross semi-variogram; Cross-correlogram; Greenhouses

1. Introduction

Soil physicists [1–3] studied the variability of soil properties in conventional statistical terms (i.e. probability density function with associated moments and coefficient of variation). Classical statistical procedures assume that variation is randomly distributed within sampling units. Actually, soil properties are continuous variables whose values at any location can be expected to vary according to direction and distance of separation from neighboring samples [4]. Recently, emphasis has been placed on the fact that the variations of a soil property are not completely disordered over the field and this spatial structure must be taken into account in the treatment of the data. During the last few years there has been considerable research reported in the literature on the spatial variability of several soil properties [5–13].

Investigators have shown increasing interest in analyzing measured soil parameters for their interdependency over space, i.e., to study the dependency of a measured parameter on location in the field. Typically semi-variograms and outocorrelograms
have been used to study the spatial structure of soil properties. A literature search revealed limited published studies on spatial behavior of temperature in soils. One of the few papers is that by Vauclin et al. [11], who studied the spatial variability of soil surface temperature and soil surface water content and investigated the presence of a trend in their data using a method proposed by David [14]. Semi-variograms and autocorrelation functions for soil temperature observations were found to be correlated over space [11,13].

Surface temperature of a bare soil is a complex function of many parameters, some of them pertaining to the soil itself (thermal properties, moisture content, albedo, emissivity) others being related to atmospheric behavior [15–18]. Being functions of both soil and atmosphere, the surface temperature can be expected to have spatial structures characteristics of both soil and atmosphere. Under greenhouse conditions, the atmosphere plays an important role in governing the soil temperature rather than the soil properties [19].

The objective of this study was to define the spatial variability of soil temperature conjugated with moisture content along transect under greenhouse conditions. Analysis of the spatial structure was based on the cross semi-variogram and cross autocorrelation functions.

2. Materials and methods

Soil temperature data was collected on a greenhouse at Al-Mada’in Research Station of the solar Energy Research Center. The station is located 30 km south of Baghdad, Iraq, at 33°14′N latitude and 44°14′E longitude at an elevation of 34 m above mean sea level. The climate of the study area is semi-arid and sub-tropical with very little rainfall. The soil of the site is a Typical (Torrifluvents) clay soil, composed of 18% sand, 39% silt and 43% clay. The greenhouse was semi-cylindrical tunnel type, 55×10×3.5 m³ in size, with its longer axis aligned in the north–south direction. The greenhouse was covered with a 180 μm transparent polyethylene film and planted with cucumber plants, 0.85 m in height. Trickle system was used for irrigation.

Soil temperatures at 0.05 m depth along a 55-m transect were monitored by means of shielded copper–constantan thermocouples. The analog signals from the sensors were converted into digital signals for the Hewlett-Packard Automatic Data Acquisition/Control System Model 3054 A. The output data were printed using a Hewlett-Packard Model 9845 B computer connected on-line with the data acquisition system. Temperature data were collected under cloudless conditions at 14:00 h CST on January 15, 1999. During the experiment, soil moisture content measurements were taken by thermo-gravimetric method for the depth 0.00–0.05 m near the thermocouple installation without upsetting the thermal distribution.

The spatial variability of soil temperature and its relationship to moisture content was studied by means of cross semi-variograms, and cross-autocorrelation functions. So, for any pair of the variables $T$ (soil temperature) and $M$ (volumetric soil moisture content) there is a cross semi-variance $\gamma_{TM}(h)$ at lag distance $h$ defined as:
\[
\gamma_{TM}(h) = E[(Z_T(x) - Z_M(x+h))(Z_M(x) - Z_M(x+h))]
\] (1)

where \(Z_T, Z_M\) are the values of \(T\) and \(M\) at places \(x\) and \(x+h\).

Before proceeding to estimate the cross semi-variogram we should examine briefly its connection with the cross-covariance and correlation. Assuming second order stationarity and one dimension, the cross-covariance \(C_{TM}(h)\) at lag \(h\) is defined as:

\[
C_{TM}(h) = E[(Z_T(x) - Z_T(x+h))(Z_M(x+h) - Z_M(x+h))]
\] (2)

and the cross-correlation \(\rho_{TM}(h)\) as:

\[
\rho_{TM}(h) = \frac{C_{TM}(h)}{\sqrt{C_{TT}(0) \cdot C_{MM}(0)}}
\] (3)

The cross semi-variance is estimated in a way analogous to that for the auto semi-variance. For a lag, \(h\), the average semi-variance of all pairs of observed values separated by that lag, \(N(h)\), are computed as:

\[
\gamma_{TM} = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Z_T(x_i) - Z_T(x_i+h))(Z_M(x_i+h) - Z_M(x_i+h))
\] (4)

In order to define the spatial structure of soil temperature only, the semi-variogram, \(\gamma(h)\), was estimated using:

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (T_i - T_{i+h})^2
\] (5)

The experimental covariance function of \(T\) was estimated as follows:

\[
C(h) = \frac{1}{N(h)-1} \sum_{i=1}^{N(h)} (T_i - \bar{T})(T_{i+h} - \bar{T})
\] (6)

The autocorrelation function \(\rho(h)\), was estimated as follows:

\[
\rho(h) = C(h)/\sigma^2
\] (7)

with \(\bar{T}\) and \(\sigma^2\) as estimates of the mean and variance.

3. Results and discussion

3.1. Surface temperature and moisture content measurements

Figs. 1 and 2 show the variation of measured soil temperature and volumetric moisture content along the transect, respectively. It can clearly be seen from Fig. 1 that the soil temperature was increased from one end of the transect over a distance up to about 40 m and appeared to level off thereafter. The lower soil temperatures recorded at the beginning of the transect could be explained according to the influence of greenhouse ventilation by free convection during the daytime.
Despite erratic fluctuation of the soil temperature, preliminary analysis of data revealed that the coefficient of variation is relatively high (12.11%). The soil temperature had a range of 6°C with variance of 5.71°C. The frequency distribution for soil temperature (Fig. 3) exhibited a light negative skew with a coefficient of skewness of −0.229. Nevertheless, tests for normality showed that soil temperature observations can be considered to be normally distributed. A look at Fig. 3 quickly reveals that maximum frequencies were confined between the soil temperatures 19°C and 21°C. In Fig. 4, it may be seen that values of soil moisture content fluctuate about their respective means apparently independent of transect distance, and manifest smaller standard deviation of 2.092% and lower coefficient of variation (7.33%). The soil moisture content had a range of 10.1% with variance of 4.339%. The frequency distribution for soil moisture content (Fig. 4) exhibited a positive skew with a coefficient of skewness of 0.75. Maximum soil moisture content frequencies were confined between 26 and 29 m³ m⁻³.
3.2. Analysis of semi-variogram and cross semi-variogram functions

Fig. 5 shows the semi-variogram of soil temperature calculated for separation distances up to two-thirds of the total length of the transect. The semi-variogram shows a general increase with increasing separation distance up to about 34 m. At longer spacing the semi-variogram appears to reach a sill larger than the sample variance (dashed line in Fig. 5). The semi-variogram thus indicates a spatial interdependency among soil temperature observations measured at separation distances <34 m (=70 lags).

By definition, $\gamma(h)=0$ for $h=0$; however, extrapolation of the semi-variogram to the origin resulted in a nugget effect of 0.292 indicating that approximately 3% of variance is due to random fluctuation, sampling error, soil moisture content variation along the transect, or the presence of spatial structure at scale <0.50 m.
A spherical model in the form of:

$$\gamma(h) = C_0 + \left(C_1 - C_0\right)\frac{3}{2}(h/a) - \frac{1}{2}(h/a)^3$$  \hspace{1cm} (8)

for \( h \leq a \) and \( = C_1 \) for \( h > a \)

was fitted to the semi-variogram data (Fig. 5), where \( C_0, C_1, \) and \( a \) are the nugget, sill and range of influence, respectively. The value of \( C_0 \) was calculated from the intercept of a linear regression of the first 70 data points. The sill was also obtained using linear regression of the data at separation distance exceeding 12.46 m (flat part in Fig. 5). The range of influence \( (a=35.50 \text{ m}) \) is estimated by noting that the linear regression should intersect the sill of the semi-variogram at a separation distance roughly equal to two-thirds of \( a \) [20,21]. Estimates of the model parameters are given in Table 1.

The cross semi-variogram of soil temperature and moisture content for separation

<table>
<thead>
<tr>
<th>Variogram</th>
<th>( C_0 )</th>
<th>( C_1 )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-variogram (( T ))^a</td>
<td>0.292</td>
<td>12.46</td>
<td>71</td>
</tr>
<tr>
<td>Cross semi-variogram (( T ) and ( M ))^b</td>
<td>0.028</td>
<td>10.66</td>
<td>60</td>
</tr>
</tbody>
</table>

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*a* Soil temperature (°C).

*b* Soil moisture content (m³ m⁻³).
distances up to two-thirds of the total length of the transect is shown in Fig. 6. The graph has much the same form as the semi-variogram. Three features are worth noting at the cross semi-variogram (Fig. 6). First, the nugget variance, i.e. the intercept value, was 0.028 indicating that approximately 0.3% of variance is due to random fluctuation, sampling error or the presence of spatial structure at scale <0.50 m. This value is ten times lower than that obtained for the semi-variogram. The second feature is the sill obtained at separation distance exceeding 10.66 m, which is lower than the sill value of the semi-variogram by approximately 15%. Finally, the range of influence was 30.00 m. Estimates of the cross semi-variogram spherical model parameters are given in Table 1. Generally, these results are inconsistent with other published semi-variograms of soil temperature [11,13]. This inconsistency is due to:

1. the published semi-variograms concerned the spatial variation of soil temperature in bare soils and uncladed conditions;
2. the variation of soil moisture content was not taken into account in these semi-variograms.

3.3. Analysis of autocorrelation and cross correlation functions

The autocorrelation for temperature data is shown in Fig. 7. The correlation was not significantly different from zero (at $\alpha=0.05$) for separation distances up to 7.5 m. Thereafter, the correlation seems to be significantly different from zero for separation distances more than 8 m. The 95% confidence interval indicated by the two dashed lines (calculated according to Haan [22]) signifies correlation coefficients that are significantly different from zero ($\rho(h) \neq 0$). Thus, the autocorrelation of temperature measurements indicates poor or limited spatial structure for separation distances <8 m.

![Experimental cross semi-variogram for temperature vs. volumetric moisture content along transect for 0.0–0.05 m soil depth (horizontal dashed line represents the sample variance).](image)
Fig. 7. Autocorrelogram of soil temperature along the transect at 0.05-m soil depth under greenhouse conditions.

The correlation sharply decreased and reached $-1$ after approximately a separation distance of 15 m.

The cross correlations (Fig. 8) exhibit a similar scheme to the autocorrelation (Fig. 7). The cross correlation resulted in a significant decrease of spatial interdependency of temperature observations. Hence, the significant cross correlation coefficients are manifested for separation distance $>2.5$ m. Moreover, the cross correlation gradually decreased and reached $-1$ after approximately 17.5 m. Thus, it seems necessary to take into account the soil moisture content in spatial variation studies of soil temperature.

Fig. 8. Cross-correlogram for soil temperature vs. volumetric moisture content along the transect at 0.0–0.05 m soil depth under greenhouse conditions.
4. Summary and conclusions

Spatial variability of soil temperature at depth of 0.05 m along a 55 m transect under greenhouse conditions was studied by means of cross autocorrelation and cross semi-variogram functions between $T$ and $M$, as well as autocorrelation and semi-variogram functions. Spatial cross correlation coefficient between $T$ and $M$ manifested significant values for distances more than 2.5 m up to 17.5 m. The spatial autocorrelation coefficient for $T$ was significantly correlated for distances more than 8 m up to 15 m. Moreover, the cross semi-variogram of $T$ and $M$ represents a range of influence 5 m lower than that for the semi-variogram of $T$. Thus, cross-correlation and cross semi-variogram between $T$ and $M$ proved useful for identifying the variation in soil temperature under greenhouse conditions. This utility is based upon the fact that small differences in soil moisture content yield significant differences between soil temperature measurements. This could be due to the influence of moisture content on soil thermal properties (thermal conductivity, heat capacity, etc.).

References


