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INVESTIGATIONS AND ANALYSES OF SPATIAL VARIABILITY OF SOIL TEMPERATURE

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A b s t r a c t. We studied the spatial variability of soil temperature in two square grids, small and large, on a bare field, on silt loam soil located in Felin near Lublin. The soil temperature was measured every 1 m over a 3 by 3 m area for the small square grid and every 10 m over a 30 by 30 m area for the large square grid and at various soil depths. The spatial structure of soil temperature data was examined by semivariograms and classical statistics. Structural analysis of semivariograms for some depths consisted of pure nugget effect for different lag distances. This implies that the data are independent for our sampling scale and statistical properties could well be characterized by the mean and variance. Except for several soil depths which exhibited a pure nugget effect, the temperature observations were found to be spatially interdependent. The spatial structure was found at two scales: 18 m for depths of 2 - 25 cm and 4.5 m for depths of 50 - 100 cm.

INTRODUCTION

In soil physics, observables are usually interdependent. Yet, statistical methods widely applied to the description of soil system assume their independency. This produces a bareer against the exact description and analyses of soil systems. Recently, methods and models have been developed which take into account the interdependency of observables and their variability. They are also able to estimate the investigated quantity at every spatial site. These advantages improve the applicability of the above methods to agrophysics since they give a more detailed picture of the investigated system.

It is appropriate to treat soil systems, studied in their natural state, as systems interrelated with their environment and describable by appropriate functions of time and/or functions of time and spatial coordinates. The complete physical description of the reaction between the soil and the environment may not be fully known. Yet these interactions may be analysed in categories of stationary random processes or treated as forms of interrelated random fields [9]. The charateristic of experimental data sets - treated stochastically or as random fields - requires the redistribution of their variability into random (noise) and deterministic (trend and periodical variation) components [15]. The purpose of this redistribution is also for the specification of autoregression mathematical models (ARMA, ARIMA and others) to generate series of measurements and their prognosis in time [1,11]. Investigation of spatial variability of given physical parameters lead to a better understanding of soil physical processes. Such investigations with automatic measuring systems and spatial analyses methods are directed toward objective descriptions of the main properties of the soil environment. They give the basic information about anisotropy of the soil system and distance correlation between observable properties. By this, they precisely define the soil physical conditions using a minimal amount of experimental data. The variogram is a basic tool for investigations of the variability of soil parameters. Kriging is a basic tool for the estimation of the value of a given parameter [2,3,7,10,13,14].

THEORY

Variogram

The basic tool for investigation of spatial variability of soil physical properties is the variogram - more correctly the half of the variogram known as the semivariogram. The semivariogram will be used here; and for practical purposes it will be referred to later as a variogram [13].

A variogram is defined as the sum of squares of the differences of an investigated parameter between points x_i and $x_i + h$, where h is a vector. For a discrete distribution of observed points with isotropic conditions, the empirical estimate of a variogram is given by:

$$\gamma^*(h) = \frac{1}{2N_h} \sum_{i=1}^{N_h} (f(x_i + h) - f(x_i))^2 \quad (1)$$

where $f(x_i)$ and $f(x_i + h)$ are the investigated parameter values at points x_i and $x_i + h$, respectively, N_h is the number of couples of observation points whose distance is equal to h. The value of the variogram depends on the direction and value of h. When the direction influences the value of the variogram, the investigated environment is anisotropic. As shown in Fig. 1 as h increase the variogram value increases from zero to a constant value called a 'sill'. The sill is approximately equal to the variance of the test. The distance in which the variogram value reaches the sill is called the 'range'. It is commonly observed that the value of the variogram when the vector h goes to zero has a non-zero value called a 'nugget'. This expresses changes in small scale testing range. The value of h when the variogram reaches its 'sill' approximates the maximum distance within which the samples are correlated. If a variogram has a constant value within the whole range, the so-called 'pure nugget' effect occures. In this case, the investigated parameter can be adequately described by its mean value and variance. As a basic source of information about anisotropy and distance correlation the variogram can be used in the interpolational method, kriging.

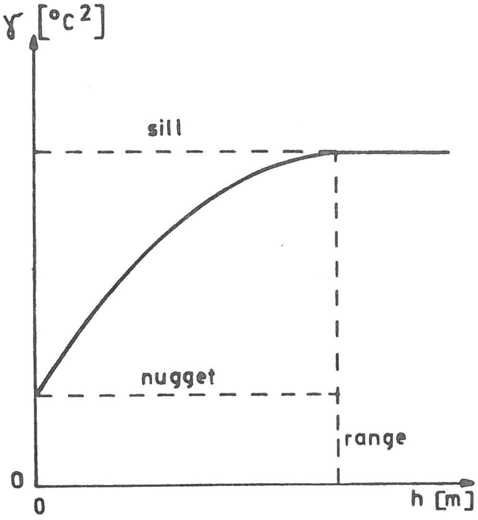


Fig. 1. Graphical presentation of the variogram.

Kriging

The basic assumption of kriging is that the (unknown) estimator Z^* of a soil parameter depends linearly on the random variables $f(x_i)$ [12,13,14]:

$$Z^* = \sum_{i=1}^{N} a_i f(x_i) \quad (2)$$

where $f(x_i)$ is the value of the parameter at point x_i, a_i is a weighting coefficient for x_i and N is the number of experimental points. The unknown values a_i are determined from the conditions that the estimator Z^* is unbiassed, i.e., $E[Z^*(x_o) - Z(x_o)] = 0$ and effective, i.e., the variance is minimal σ_k^2= var $[Z^*(x_o)-Z(x_o)=$ min.)].

From these conditions, the following system of equations can be obtained:

$$\sum_{j=1}^{N} a_j \gamma (x_i - x_j) - \lambda = \gamma (x_i - x_o)$$

$$i = 1, 2, 3.....,N$$

$$\sum_{j=1}^{N} a_j = 1 \qquad (3)$$

where $\gamma(x_i-x_j)$ is the half of the variogram value for the distance between points x_i and x_j, $\gamma(x_i-x_o)$ is the half of the variogram value for the distance h between point x_i and the interpolated point x_0, λ is the Lagrange multiplier.

The solution of Eq. (2) leads to values for the interpolator weights, a_j. This permits the extrapolation and prognosis of values of soil properties investigated either in time or in time and space.

In a number of papers, it was stated that the spatial variability of soil temperature depends on soil type and moisture [4,5,12,16]. Vauclin *et al.* [12] determined a range of spatial dependence from 10 to 15 meters. Davidoff and others [4,5], however, stated that for their conditions, spatial dependence occurred in the range of 25 to 50 m; and, that for 0.2-0.3 m horizons, the pure nugget effect existed. Yates *et al.* [16] examined soil temperature for bare and plant covered soils. Their range determined for dry soil with and without plants was from 18 to 40 m. When the soil was humid, the range decreased to 6-16 m for bare soil and to 2-15 m for plant covered soil.

RESULTS

Results and the analyses of selected soil temperature fields

Measurements of soil temperature and moisture were performed at different depths

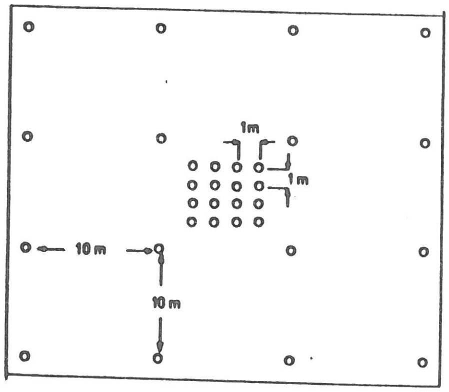


Fig. 2. Scheme of measurements.

of an Eutric Cambisol soil located in Felin near Lublin. Experimental data were taken at points which were nodes of square nets of 1 x 1 m and 10 x 10 m, covering the squares of 3 x 3 m and 30 x 30 m, according to the scheme presented in Fig. 2.

Examples of the dynamics of the soil temperature variability at different depths are presented in Fig. 3. This figure shows temperatures at 16 different points from the 3 x 3 m area. The highest differences were observed in upper soil layer up to 6°C at noon and up to 2°C at night. The temperature dynamics diminishes with depth and a phase shift is observed for the deeper levels. As additional example, four temperature profiles and one moisture profile taken on the 15/16th of July 1985 are presented in Fig. 4. Temperature profiles were recorded at 12.00 h (intensive sunlight), at 22.00 h (at sunset), at 1.30 h (night) and at 5.00 h (sunrise). The mean values for the different depths and the standard deviations are also presented in Fig. 4. In Table 1 results are presented for two selected days for given depths. This contains the mean value and variance, the variability coefficient and the maximum and minimum values.

The variability of soil temperature was analysed in two ways: first in the classical way, by the variability coefficient, c.v., defined as the ratio of the standard deviation and the mean; and, second, by a variogram as a base of geostatistics [13, 14].

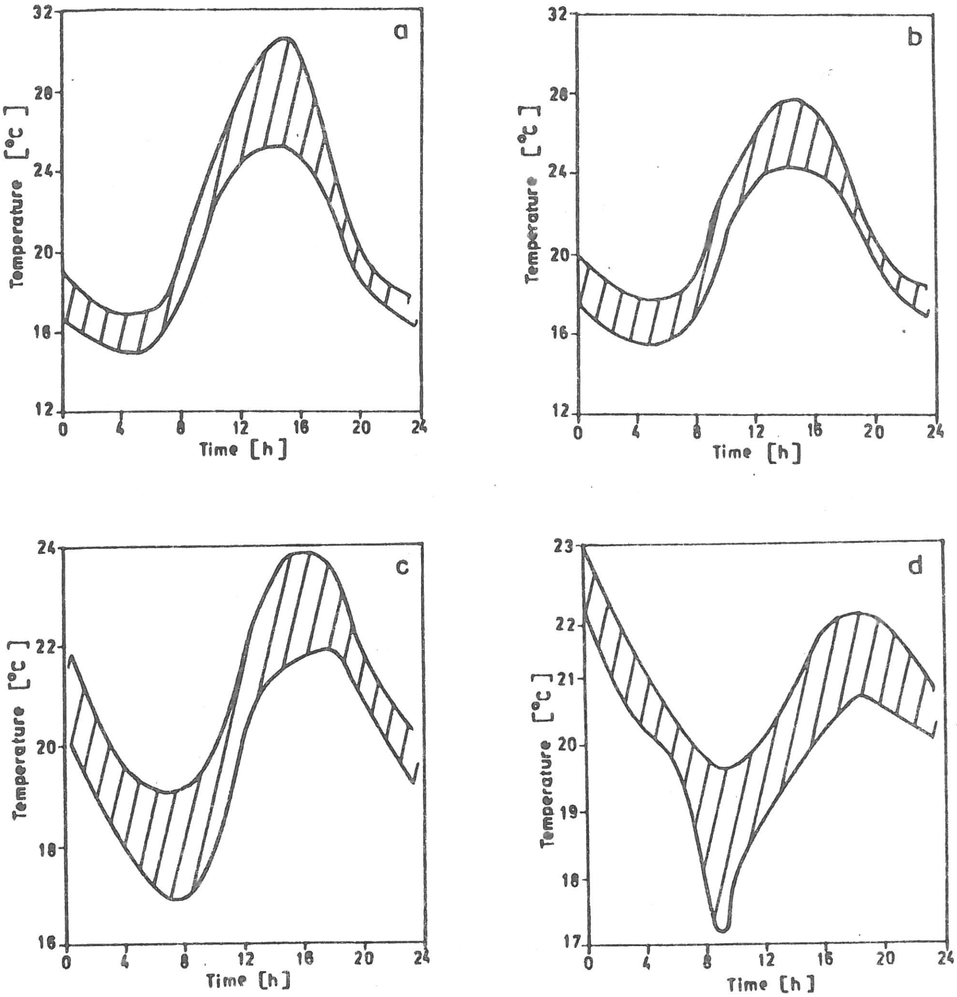


Fig. 3. Temperature readings in time, taken at 16 locations from the 9 m^2 area. Levels: a - 0.005 m, b - 0.02 m, c - 0.1 m, d - 0.2 m. Date 20.08.1989.

The determination of the variogram and the estimation of the field of temperature were performed using the files of GEO-EAS (Geostatical Environmental Assessment Software) [6] for the IBM PC/XT computer.

The mean values (Table 1) for every depth investigated ranged from -1.3°C to 23.2°C and the coefficients of variability ranged from 2.1 to 1 002 %. The extreme value occurred when the mean value of the temperature was close to zero. Data from the literature show that, for days when soil temperature is above zero, the coefficient of variability is in the range of 1.3-10% [4, 8, 16].

The analysis of the soil temperature field variability was performed on the basis of a variogram and the experimental data from 23.09.1987 and 29.10.1987, both taken at noon (12.00). The day 23.09.1987 was sunny with air temperature above 20°C. The day 29.10.1987 was also sunny but the air temperature was below zero.

The analytical functions of the variogram were selected by fitting given mathematical functions to the values calculated on the basis of the experimental data. The results of the above procedure for different depths are presented in Fig. 5. It is seen that

Table 1. Statistics of the soil temperature

	23.09.1987					29.10.1987				
Depth	$\overline{T}$	var	c. v.	max	min	$\overline{T}$	var	c. v.	max	min
cm	°C	°C²	%	°C	°C	°C	°C²	%	°C	°C
0.5	23.2	0.71	3.7	25.8	21.0	0.27	0.44	247.0	1.6	-0.9
2	21.8	0.54	3.4	23.5	19.9	-0.50	0.30	108.0	0.7	-1.3
5	19.7	0.49	3.6	21.1	17.8	0.07	0.32	1 002.0	1.1	-1.1
10	17.2	0.30	3.2	18.2	15.9	1.70	0.38	35.7	2.9	0.6
15	14.9	0.23	3.2	16.0	13.9	2.60	0.27	19.0	3.7	1.9
20	13.7	0.19	3.1	14.5	12.8	2.10	0.34	28.2	3.4	0.9
25	13.0	0.17	3.1	13.6	12.1	1.50	0.34	40.9	3.0	0.4
30	12.7	0.15	3.0	13.3	11.8	1.50	0.40	42.2	2.4	0.4
40	12.7	0.15	3.0	14.1	12.1	4.00	0.40	15.4	5.6	3.1
50	12.8	0.10	2.4	13.7	12.3	5.00	0.28	10.6	6.5	4.1
70	13.1	0.16	3.1	14.0	12.3	6.30	0.26	8.1	7.7	5.3
100	13.7	0.08	2.1	14.5	13.2	7.90	0.34	7.3	9.1	6.9

Explanations: $\overline{T}$ - average temperature, var - variance, c.v. - coefficient of variability, max - maximal temperature, min - minimal temperature.

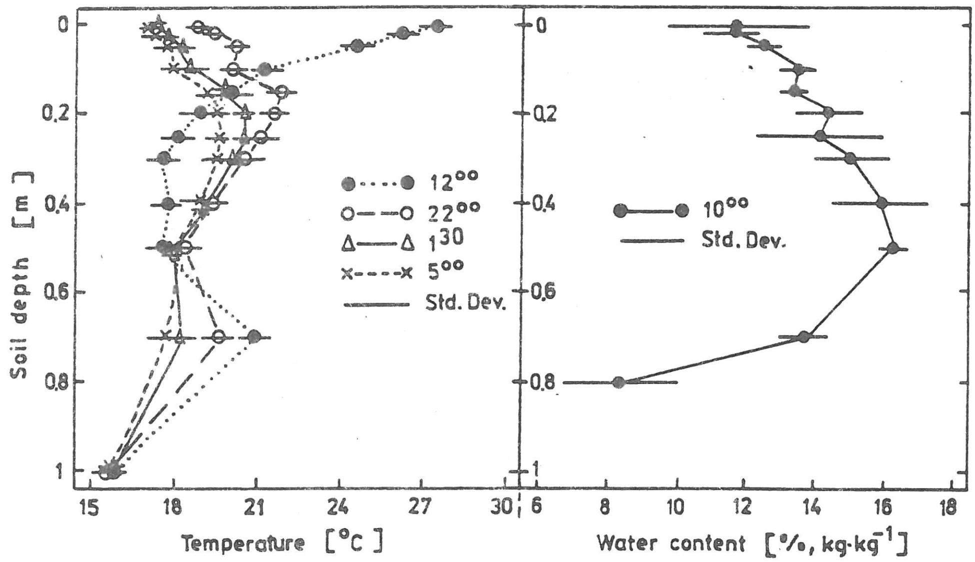


Fig. 4. Temperature profile and moisture profile from the 15th and 16th of July, 1985.

values of the variogram change stepwise which means that the pure nugget effect occurrs in particular ranges. Considering the previous suggestion that for the soil temperature description in such a case only the mean value and variance are needed, these values were calculated for the different steps. The results for 0.005 m the depth are presented below (the range, the mean and the variance are given, respectively):

0 - 9 m	$\overline{T}$ = 23.13	var = 0.269
9 - 18 m	$\overline{T}$ = 23.13	var = 0.774
18 - 40 m	$\overline{T}$ = 23.43	var = 0.963.

Mean values and variances calculated for the different steps do not surpass the values calculated for the whole range. In the second range, where the value of the variogram doubles, the variance increases almost threefold, but the mean remains that same. Similar dependences are noted in the third range. The pure nugget effect occurs also for the deeper levels; however only two ranges occur and the value of the first range is half the value of the 0.005 m soil layer. The values of range, mean and variance for 0.3 m depth are given below:

0 - 4.5 m	$\overline{T} = 12.9$	var = 0.045
4.5 - 40 m	$\overline{T} = 12.7$	var = 0.15.

Between levels spatial correlation was observed, as seen in Fig. 5b. The range of correlation was 18 m. Below the 0.5 m depth space correlation also occurred but with a range of 4.5 m which can be seen in Fig. 5d. For the 29th of October, 1987, two Figs 5e and 5f are presented. Space correlation is observed only for the upper soil layer with a range of 4.5 m. For the deeper layers the pure nugget effect occurred with no space correlation (Fig. 5f). It can be concluded that the variability of the field of soil temperature is influenced not only by the type and moisture content of the soil but also by meteorological conditions.

The mathematical functions which were fitted to the empirical variograms are presented below.

Linear model:

$$\gamma(h) = c_0 + c \left(\frac{h}{a}\right) \quad (4)$$

$0 < h \le a$

$\gamma(h) = c_0 + c \quad h > a$

$\gamma(0) = 0$

Gaussian model:

$$\gamma(h) = c_0 + c\ [1 - \exp(-h^2/a^2)] \quad (5)$$

$0 < h$

Exponential model:

$$\gamma(h) = c_0 + c\ [1 - \exp(-h/a)] \quad (6)$$

$0 < h$

Spherical model:

$$\gamma(h) = c_0 + c * \left\{ \left[\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \right. \quad (7)$$

$0 < h \le a\}$

$\gamma(h) = c_0 + c \quad h > a$

$\gamma(0) = 0$

where h is the spatial step, a is the range, c_0 is value of the variogram at h=0, i.e., the nugget, and c is a parameter.

Estimation of the soil temperature field

The estimation of the field of soil temperature was performed using kriging where the previously determined models of variogram were applied and were adjusted to the empirical data of the different soil depths investigated. The models of the variogram and its parameters for different depths are

Table 2. Models of variograms and their parameters for given depths

Date	Depth (m)	Model type	Nugget value	Sill	Range (m)
23.09.1987	0.005	Gaussian	0.2	1.2	25.0
	0.15	exponential	0.0	0.3	18.0
	0.30	Gaussian	0.04	0.19	6.0
	1.0	exponential	0.0	0.07	4.5
29.10.1987	0.005	spherical	0.0	0.5	4.5
	0.15	linear	0.31	0.01	40.0

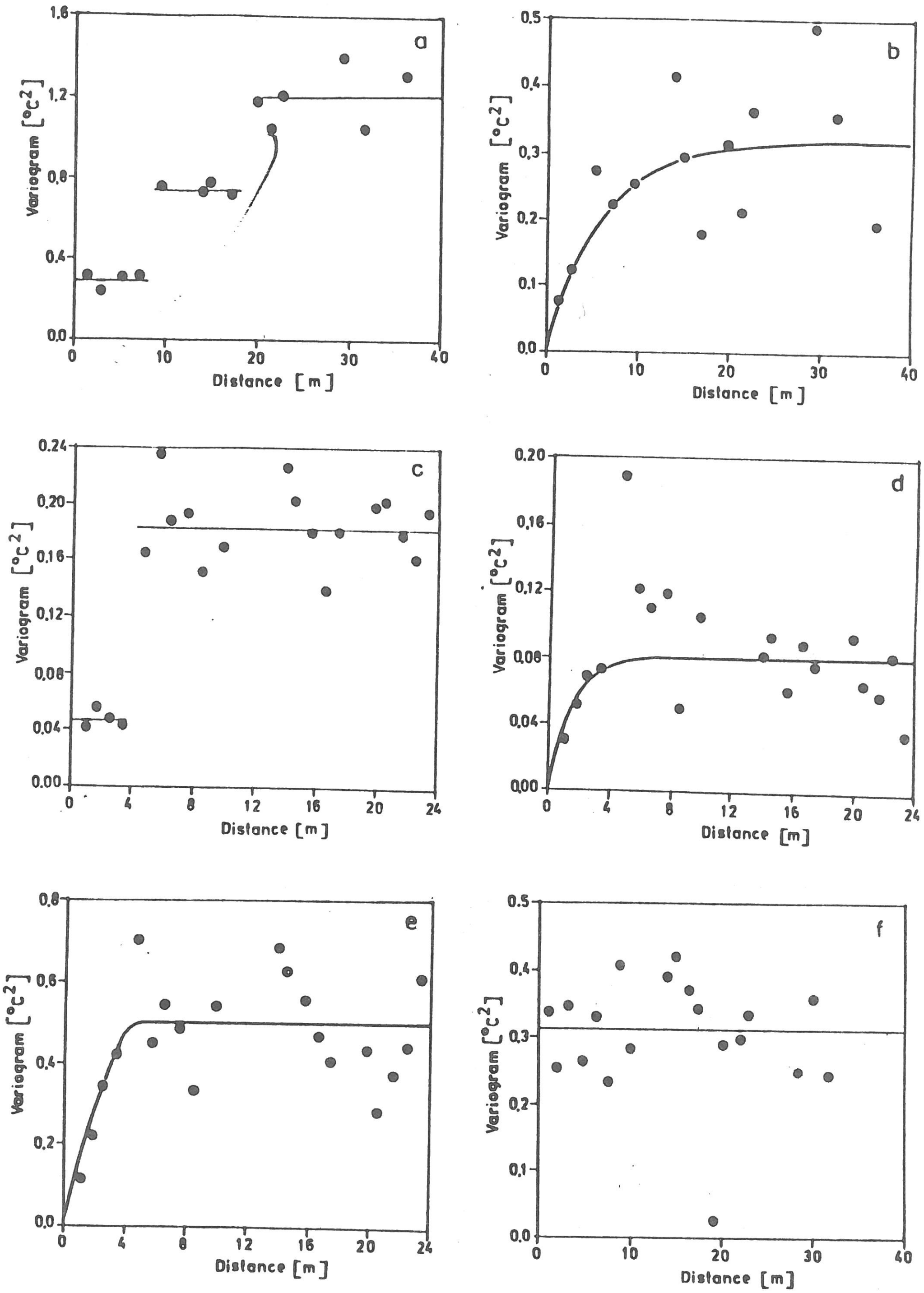


Fig. 5. Variogram of soil temperature from the 23th of September, 1987, for levels: a - 0.005 m, b - 0.15 m, c - 0.3 m, d - 1 m and from the 29th of October, 1987, for levels: e - 0.005 m and f - 0.15 m.

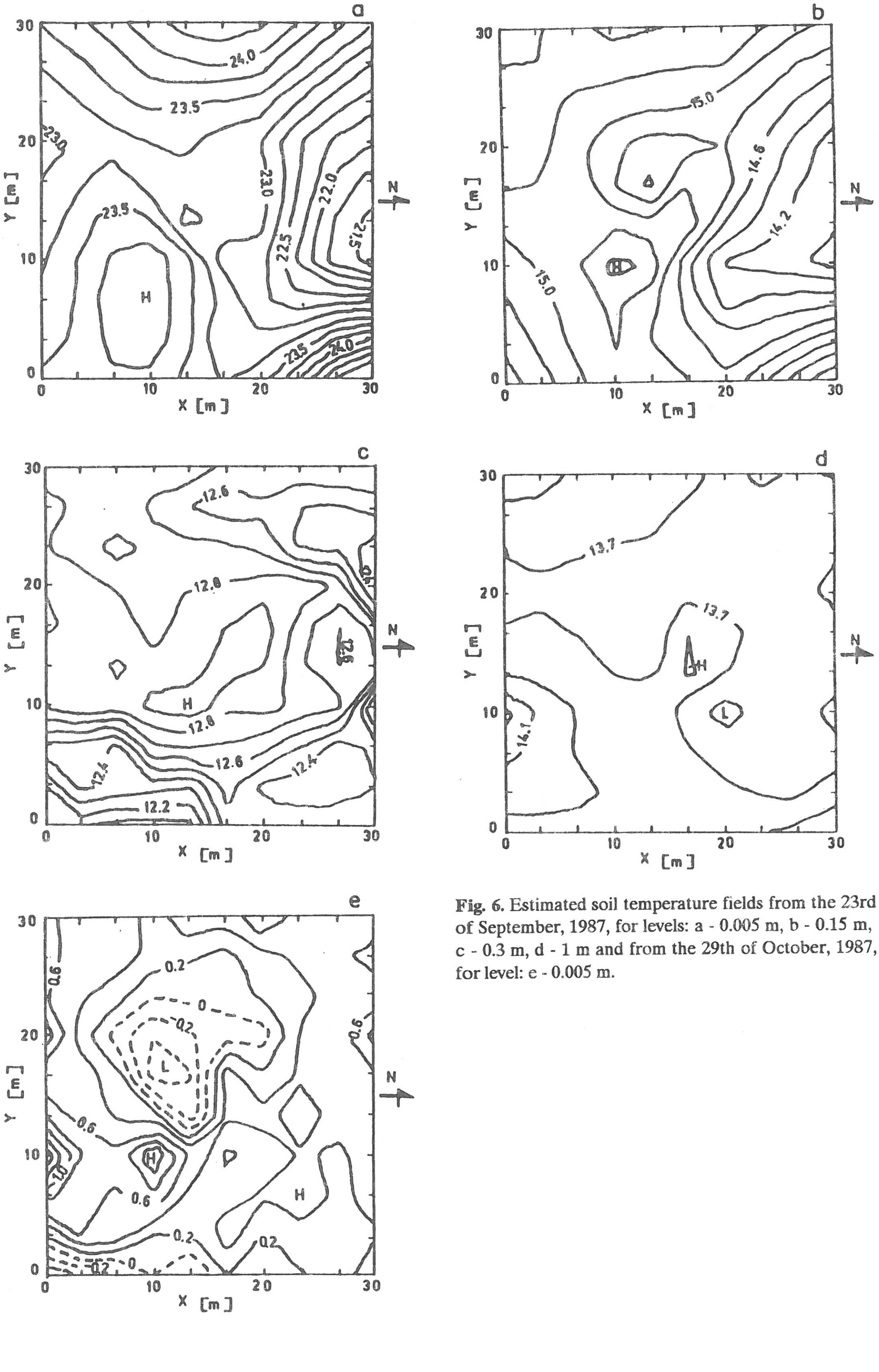
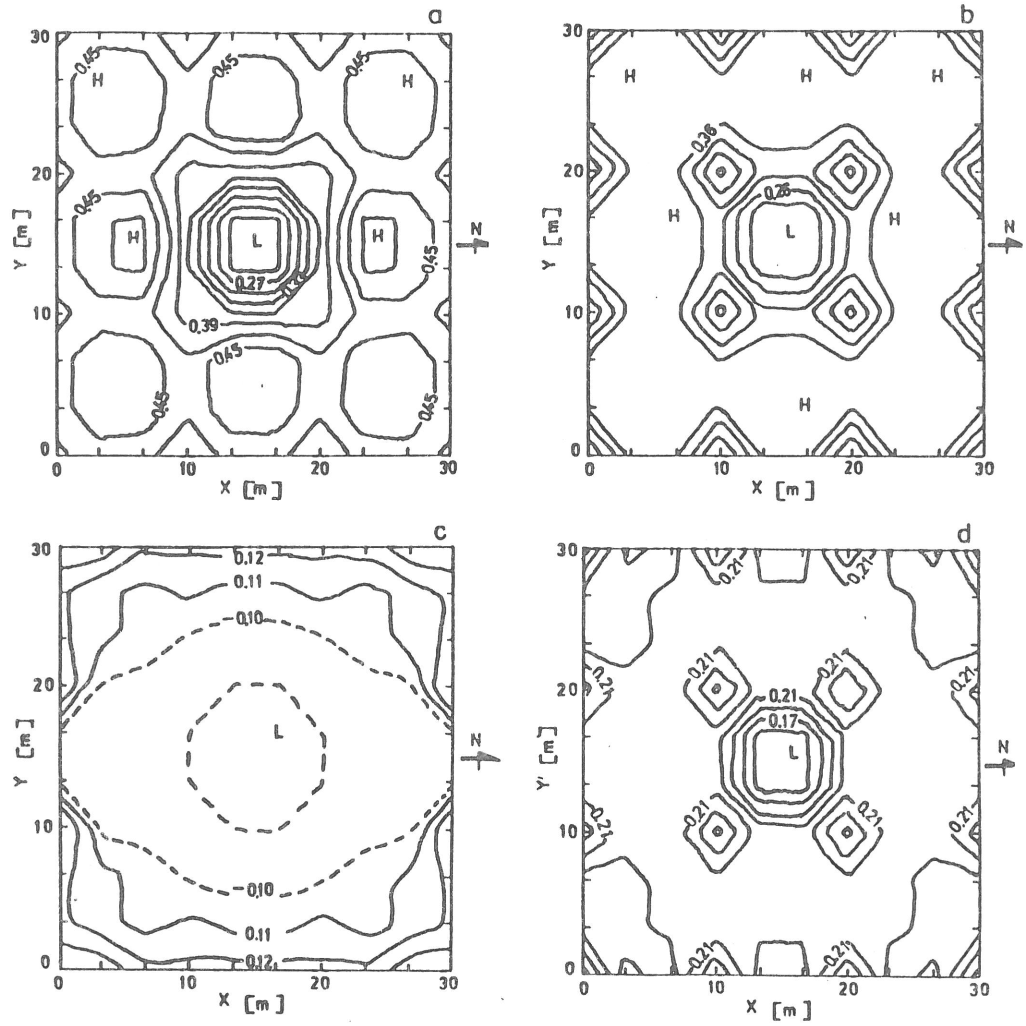


Fig. 6. Estimated soil temperature fields from the 23rd of September, 1987, for levels: a - 0.005 m, b - 0.15 m, c - 0.3 m, d - 1 m and from the 29th of October, 1987, for level: e - 0.005 m.



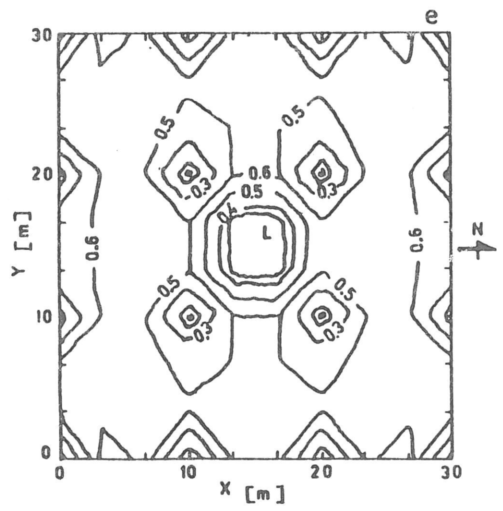


Fig. 7. Estimated maps of soil temperature errors from the 23rd of September, 1987, for levels: a - 0.05 m, b - 0.15 m, c - 0.3 m, d - 1 m and from the 29th of October, 1987, for level e - 0.005 m.

presented in Table 2. For the depths where the stepwise changes of values of the variogram occurred the Gaussian type models were chosen because they gave the closest match of measured and estimated data. Application of the step functions did not succeded in this case.

Estimations of the field of soil temperature for given soil depths are shown in Fig. 6. The solid lines are the isotherms surrounding areas of the same temperatures. Dashed lines mark the areas below 0^{o}C. Analysing the field of soil temperature at various time of day, one can observe its dynamics. The 'H' and 'L' mark the warmest and the coldest places in the figure, respectively.

Figure 7 shows maps of errors for the areas of differences between measured and estimated values. Solid lines mark areas of equal errors. The error value is given on the appropriate line. 'H' marks the area of major error and 'L' - of minor error. The major estimation error occurs for the surface soil layer and it is $\pm 0.8\ ^{o}$C. The minor error equals to $\pm 0.2\ ^{o}$C is observed for the 0.3 m depth. For the 1m depth the error equals $\pm 0.3\ ^{o}$C. As can be seen, kriging allows one to perform error analysis and because of this it is a good tool for minimizing the number of measurements.

CONCLUSIONS

The methods of investigations that were used and the method of analysis of spatial variability of soil temperature permitted the calculation of basic quantities characterizing the soil system, i.e., the length of the vector with the pure nugget effect. By this, the maximum step of sampling of soil temperature with a given mean and variance can be determined. Furthermore, it can be concluded that:

1. Anisotropy of the temperature field was not observed and spatial correlation with a range of 4.5-18 m occurred.

2. Pure nugget effects were observed within the investigated area in the definite ranges: 9 m from the surface to the 0.05 m depth and 4.5 m from 0.25 to 0.5 m depths. A spatial correlation between these depths was observed.

3. The range of spatial correlation as well as the occurrence of the pure nugget effect depended not only on the soil type and moisture but also on meteorological conditions.

4. The method of estimation of the field of soil temperature from at-point measurements allowed the calculation of this field on the one hand and error analysis on the other. Because of this, it is a good tool for the measurement minimization.

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