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AN EXPERIMENT ON THE QUANTITATIVE DESCRIPTION OF CLIMATIC ELEMENT FIELD BY ORTHOGONAL FUNCTIONS

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ABSTRACT

In this paper, the author first proposes the generalized problem of the quantitative description of climatic field by means of approximate analytic expression. It is submitted that the application of the linear combination of orthogonal functions in approximate expression has many advantages. A formula to measure the precision of the calculation is also proposed. Two calculated examples are given.

I. INTRODUCTION

In the theory of climatology, for the study of the relations between the various climate-forming factors and the climatic element field, how to describe objectively and quantitatively the space time distribution of these factors and the elements is a very important basic problem.

Obviously, although the raw data and the contour maps from various stations are objective, they are not very convenient to handle theoretically, and therefore difficult to be applied directly. The average values or other indices obtained from the raw data or the contour maps frequently do not contain enough details to represent the characteristics of the distribution; some of them even lose all their representative values. Therefore, the most ideal method is to find an analytical expression represented by a mathematical function $\hat{f}_n(x, y, z; t)$ to approximately describe quantitatively, according to our required accuracy, the climatic element field $f(x, y, z; t)$, the expression of which is not known but which exists objectively.

From the viewpoint of the statistical theory of climatology, such a problem is just the problem of finding the regression. However, if the method of solving a set of normal equations is used, it becomes very tedious even for finding the regression of one variable along a curve.. Furthermore, if it is found that the calculated result is not satisfactory enough according to the required accuracy and terms have to be added, all the coefficients must be recalculated. As to the regression on a surface in a multidimensional space, it is of course a very tedious matter.

If the orthogonal functions in mathematics are used, we could avoid or lessen the defects and difficulties mentioned above. Also, a most advantageous choice of the set of orthogonal functions can be made (to simplify the equations and hasten the convergence) for each different problem. It is just because of this that there exist already many examples in meteorology in which use is made of the linear combinations of orthogonal functions to describe quantitatively the element field, such as: use of trigonometric functions to perform harmonic analysis of the atmospheric temperature and the earth temperature[1,2] and use of equidistant point orthogonal polynomials to represent the longitudinal distribution[4,5,6] of the elements or climatic-forming factors. All these examples belong to the application of one-dimensional orthogonal functions to describe the time variation or the one-dimensional spatial distribution of climatic elements. Also, two-dimensional orthogonal functions such as the spherical functions[7], the two-dimensional equidistant point orthogonal polynomials[8,9,10,11,12], the mixed functions[12] of trigonometric functions and orthogonal polynomials have already been applied to describe the horizontal distribution of the element field or the climate-forming factors. In the series of papers by E. N. Blinova, spherical functions or the mixed functions[13] of the trigonometric functions and spherical functions are often used to describe the spatial distribution and the time variation of the climate elements and its formation factors.

II. THE TENDENCY OF THE CLIMATIC VARIATION OF THE AVERAGE HIGHEST TEMPERATURES

According to the opinion of S. K. Pramanik et al.[3], for the study of the tendency of climatic variation of temperature, it is best to obtain the separate equations for the variation curves of the highest and lowest temperatures. To confirm whether the variation from year to year is purely accidental or it may include some regular variation, the method of inflection point can first be used to perform random tests with respect to the series of the highest or the lowest temperatures. From the results of random tests by the inflection point method on the series of highest daily temperatures (averaged over many years) and of the lowest daily temperatures (averaged over many years) as recorded by the eight stations which are distributed over the entire country and which have records over long periods of time, only the continuous series of average highest temperatures of Shanghai (1904-1958, a total of 55 years) and of the average highest temperature of Shen-Yang (1906-1940, a total of 35 years) are not random. This is to say that although one can use mathematical methods coupled with the method of least square to obtain an equation for the tendency curves, these curves have no practical meaning since the rise and fall of the annual average of the highest or the lowest temperatures may be purely accidental. Therefore, we shall only obtain the tendency variation curve for the two series which are not random in nature.

Here, the climatic element field under consideration is only a one-dimensional function of time and the values of t taken are discrete and equidistant. Clearly, the best choice of the set of orthogonal functions shall be one-dimensional, equidistant point orthogonal polynomials.

According to R. A. Fisher's method[15]: let N be the number of equidistant points (the number of years for the series of temperatures). When N is odd, the year in the middle can be taken as the origin ($t = 0$). With an increase or a decrease of one year, t also increases or decreases by 1. When N is even, the two middle years can be taken respectively as $t = -1/2$ and $t = +1/2$; t increases or decreases by 1 with the increase or decrease of one year. When the coordinate of t is chosen in this manner, the normalized, one-dimensional equidistant point orthogonal polynomials $\Phi_\nu(t)$ can be expressed as

$$\Phi_\nu(t) = \frac{P_\nu(t)}{\sqrt{\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_\nu^2(t)}} \tag{1}$$

where

$$\left.\begin{aligned} P_0(t) &= 1, \\ P_1(t) &= t, \\ P_2(t) &= t^2 - \frac{N^2-1}{12}, \\ P_3(t) &= t^3 - \frac{3N^2-7}{20}\,t, \\ &\cdots\cdots\cdots \end{aligned}\right\} \tag{2}$$

In general, there is the recursion formula:

$$P_{r+1}(t) = P_1(t)\,P_r(t) - \frac{r^2\left(N^2 - r^2\right)}{4 \times \left(4r^2 - 1\right)}\,P_{r-1}(t) \quad . \tag{3}$$

and the formulae:

$$\left.\begin{aligned}
&\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_0^2(t) = N, \\
&\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_1^2(t) = \frac{N\left(N^2-1\right)}{12}, \\
&\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_2^2(t) = \frac{N\left(N^2-1\right)\left(N^2-4\right)}{180}, \\
&\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_3^2(t) = \frac{N\left(N^2-1\right)\left(N^2-4\right)\left(N^2-9\right)}{2800}, \\
&\ldots\ldots\ldots\ldots\ldots\ldots
\end{aligned}\right\} . \qquad (4)$$

In general, one has

$$\sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} P_r^2(t) = \frac{(N-1)^{(r)}\,(N+r)^{(r+1)}}{(2r+1)\binom{2r}{r}^2}, \qquad (5)$$

where

$$(N-1)^{(r)} = (N-1)(N-2)\ldots(N-r+1)(N-r),$$

$$(N+r)^{(r+1)} = (N+r)(N+r-1)\ldots(N+2)(N+1)\,N,$$

$$\binom{2r}{r}^2 = \left[\frac{(2r)!}{r!\,r!}\right]^2 .$$

The values of $P_\nu(t)$ and $\sum_t P_\nu^2(t)$ which vary with the values of N, ν, t can be found from tables[16]. Therefore, it is very convenient to find the coefficient C_ν ($\nu = 0, 1, 2, \ldots$):

$$C_\nu = \sum_{t=\frac{1-N}{2}}^{\frac{N-1}{2}} T_M(t)\, \varphi_\nu(t) \ . \qquad (6)$$

where $T_M(t)$ denotes the annual average highest temperatures in the series.

When n is fixed,

$$\hat{T}_{Mn}(t) = \sum_{\nu=0}^{n} C_\nu \varphi_\nu(t) \ . \qquad (7)$$

which is the best quantitative description of the highest temperature series in the sense of least squares. It represents the parabolic tendency of the climatic variation of the highest temperatures.

The ρ_n defined below can be taken as the degree of accuracy when $\hat{T}_{Mn}(t)$ is used to describe $T_M(t)$:

$$\rho_n^2 = \frac{\sum_{\nu=1}^{n} C_\nu^2}{N\sigma^2} \qquad (8)$$

where σ^2 is the squared difference of the $T_M(t)$ series.

From the statistical point of view, ρ_n is actually the related index of $T_M(t)$ relative to the tendency curve $\hat{T}_{Mn}(t)$. The advantages of adopting the related index ρ_n as degree of accuracy are that its meaning is clear and that it is convenient for calculation. Substituting the $C_\nu(\nu = 1, 2, \ldots, n)$ already obtained into Equation (8), one can obtain ρ_n very quickly. When $\hat{T}_{Mn}(t)$ and $T_M(t)$ are completely the same, $\rho_n = 1$. The closer $\hat{T}_{Mn}(t)$ is to $T_M(t)$, the closer is ρ_n to 1. On the other hand, if the required accuracy ρ_n is first given, then the C_1, $C_2, \ldots, C_n$ which are found by steps can be substituted into Equation (8) until the requirement is satisfied. Then, n is the most appropriate number of terms.

From ρ_n^2 the standard deviation S can be found when $\hat{T}_{Mn}(t)$ is used to describe $T_M(t)$ quantitatively:

$$S = \sigma\sqrt{1 - \rho_n^2} \quad . \tag{9}$$

In addition, the method of the analysis of difference square can be used to test the distinguishability of the analytic expression which is obtained and used for quantitative description. Here, the difference square ratio F can be calculated with the formula below:

$$F = \frac{\frac{\rho_n^2}{n}}{\frac{1 - \rho_n^2}{N - n - 1}} \tag{10}$$

The degree of freedom of F is: (n, N - n - 1).

Calculated results:

(1) Shen-yang (1906-1940)

The squared difference of the annual average highest temperature series: $\sigma^2 = (0.67°C)^2$.

Coefficient C_ν

C_0	C_1	C_2	C_3
81.0	1.95	-0.428	0.063

On substituting the C_ν values from the above table and the $\Phi_\nu(t)$ of Equation (1) into Equation (7), and on combining terms of the same power, the tendency equation can be obtained:

$$\hat{T}_{M3}(t) = 13.8 + 0.0132t - 0.000795t^2 + 0.0000159t^3 \quad . \tag{11}$$

The related index ρ_n calculated according to Equation (8) can then be used to examine how close the tendency equation is to the original series:

$$\rho_3^2 = \frac{1.95^2 + 0.428^2 + 0.063^2}{35 \times 0.67^2} = 0.26 \quad .$$

i. e. :

$$\rho_3 = 0.51$$

The related index of the original series relative to the cubic parabola (11) is 0.51. It is clearly seen that C_1 contributes most to the related index. If the tendency equation is taken to be:

$$\hat{T}_{M1}(t) = C_0\,\varphi_0(t) + C_1\varphi_1(t) = 13.7 + 0.0326t. \qquad (12)$$

then the related index can also reach:

$$\rho_1 = \sqrt{\frac{1.95^2}{35 \times 0.67^2}} = 0.49 \ .$$

According to Equation (19), when Equation (11) is used to describe the original series, the standard deviation can be calculated:

$$S = 0.67 \times \sqrt{1 - 0.26} = 0.576°C \ .$$

According to Equation (10), the difference square ratio is calculated to be:

$$F = \frac{\frac{0.26}{3}}{\frac{1 - 0.26}{35 - 3 - 1}} = 3.63 \quad .$$

If the distinguishability level is taken to be 5 percent, then the critical F value for the degree of freedom (3, 31) is: [16] $F^* = 2.91$. Therefore, it is at least 95 percent sure that one can consider the agreement in Equation (11) as non-random.

(2) Shanghai (1904-1958)

The squared difference of the annual average highest temperature series: $\sigma^2 = (0.74°C)^2$.

Coefficient C

C_0	C_1	C_2	C_3
154.9	0.735	-3.32	1.89

On substituting C_ν into Equation (7), the tendency equation can be obtained:

$$\hat{T}_{M3}(t) = 21.4 + 0.0511\,t - 0.00199\,t^2 - 0.0000979\,t^3 \quad . \qquad (13)$$

The related index:

$$\rho_3 = \sqrt{\frac{0.735^2 + 3.32^2 + 1.89^2}{55 \times 0.74^2}} = 0.71 \quad .$$

Therefore, Equation (13) agrees even better with the original series than the corresponding case of Shen-yang. However, in the related index the main contributions come from the coefficients of the quadratic and cubic terms. Therefore, in the tendency equation for the climatic variation of highest temperatures of Shanghai, the quadratic and the cubic terms have to be considered. If only the linear term is considered, the related index is:

$$\rho_1 = \sqrt{\frac{0.735^2}{55 \times 0.74^2}} = 0.13 \quad .$$

If the consideration stops at the quadratic term, the related index is:

$$\rho_2 = \sqrt{\frac{0.735^2 + 3.32^2}{55 \times 0.74^2}} = 0.62 \quad .$$

The standard deviation of Equation (13) is:

$$S = 0.74 \times \sqrt{1 - 0.71^2} = 0.52°C.$$

The ratio of the squared difference is:

$$F = \frac{\frac{0.71^2}{3}}{\frac{1 - 0.71^2}{55 - 3 - 1}} = 17.2$$

This F value greatly exceeds the critical[16] F* value for a 0.1 percent distinguishability level and a degree of freedom of (3, 51). Therefore, it is more than 99.9 percent sure to consider the arrangement in the tendency Equation (13) as a non-random. In the figures, the broken lines represent the actual series of annual average highest temperatures of Shen-yang and Shanghai. From the figures, it can be seen that the tendency curve for Shen-yang is very close to being a straight line while the tendency curve for Shanghai obviously possesses the characteristics of a cubic parabola. From the calculations of the related indices we have already confirmed these facts.

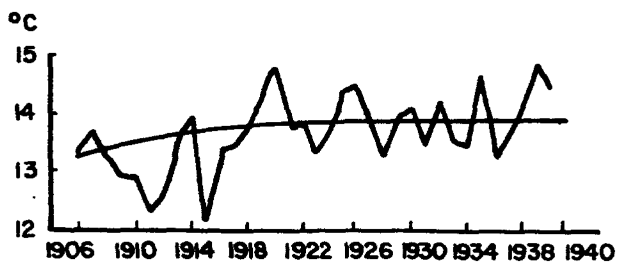

Figure 1. The Variation Tendency of the Annual Average Highest Temperatures of Shen-yang

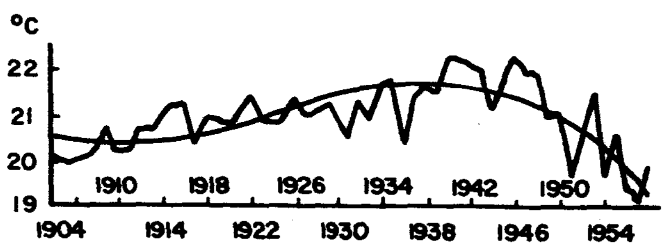

Figure 2. The Variation Tendency of the Annual Average Highest Temperatures of Shanghai.

Judging from these two curves, it is seen that, from the year 1905 to the year 1940, both Shen-yang and Shanghai have the temperature-rising tendency. From the tendency curve for Shanghai, it is seen that, beginning from the forties, there is a temperature falling tendency. The characteristics of these tendency curves are consistent with the conclusion obtained by Wang P'eng-fei[17](3679 7720 7378) who used other methods to study the climatic variations of our country in the last hundred years.

III. QUANTITATIVE DESCRIPTION OF THE TEMPERATURE FIELD ALONG THE COAST OF CHINA

In the equal-area projection map of Albers', the rectangular domain as shown in Figure 3 is chosen to be the object of description. The domain can be divided into 14×20 squares by 15×21 grid points. The coordinate of each grid point is (x, y), x taking on values from 0, 1, 2, ... to 14, y taking on values from 0, 1, 2, ... to 20. (See Figure 3.)

Based on data[19], the temperature contour map for January and July of that district is made. At each grid point, the temperature $T(x, y)$ of the corresponding month can be read off.

Let $X_r(x)$ be the normalized, equidistant point orthogonal polynomial of degree r for 15 points, $Y_s(y)$ be that for 21 points:

$$\left.\begin{aligned} X_r(x) &= \frac{\displaystyle\sum_{i=0}^{r} (-1)^i \binom{r}{i}\binom{r+i}{i} \frac{(x)^{(i)}}{(14)^{(i)}}}{\dfrac{(14+r+1)^{(r+1)}}{(2r+1)(14)^{(r)}}}, \\ Y_s(y) &= \frac{\displaystyle\sum_{i=0}^{s} (-1)^i \binom{s}{i}\binom{s+i}{i} \frac{(y)^{(i)}}{(20)^{(i)}}}{\dfrac{(20+s+1)^{(s+1)}}{(2s+1)(20)^{(s)}}} \end{aligned}\right\}. \qquad (14)$$

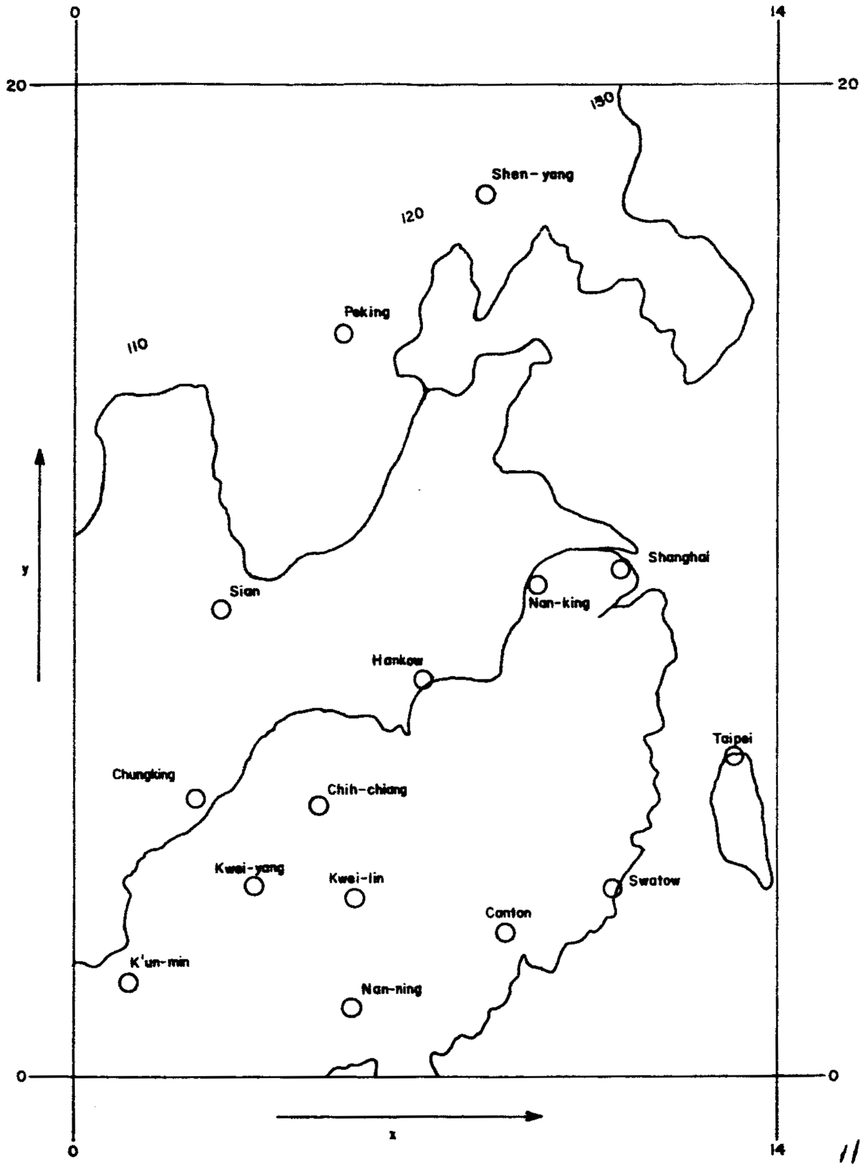

Figure 3. The Domain and the Coordinates of the Quantitatively Described Temperature Field.

where

$$(x)^{(i)} = x(x-1)\ldots(x-i+1),$$

$$(14)^{(i)} = 14 \times 13 \times \cdots \times (14-i+1),$$

$$(14+r+1)^{(r+1)} = (14+r+1)(14+r)\cdots(14+1),$$

$$(14)^{(r)} = 14 \times 13 \times \cdots \times (14-r+1) .$$

Similarly for the rest. Their product $X_r(x)\,Y_s(y)$ is then a normalized orthogonal polynomial of degree $(r+s)$ which is orthogonal at 15×21 grid points. From this, we can obtain the equation which describes quantitatively the temperature distribution of the corresponding month:

$$\hat{T}(x, y) = \sum_{r=0}^{l} \sum_{s=0}^{m} a_{rs} X_r(x)\,Y_s(y) . \tag{15}$$

where the coefficient of each term is:

$$a_{rs} = \sum_{x=0}^{14} \sum_{y=0}^{20} T(x, y)\,X_r(x)\,Y_s(y) . \tag{16}$$

The formula for calculating the related index ρ_n is now reduced to become:

$$\rho_n^2 = \frac{\sum_{r=0}^{l} \sum_{s=0}^{m} a_{rs}^2 - a_{00}^2}{\sum_{x=0}^{14}\sum_{y=0}^{20} T^2(x, y) - \frac{1}{15 \times 21}\left(\sum_{x=0}^{14}\sum_{y=0}^{20} T(x, y)\right)^2} \tag{17}$$

From the contour maps, the $T(x, y)$ value at each grid point can be read off. According to Equation (16), and also by using the numerical table[16], the a_{rs} value, the equation for quantitative description, the related index ρ_n of the raw data relative to the equation, the standard deviation S and the ratio of difference square can be obtained for January and July, respectively, as follows:

(1) January

a_{rs} Value

a_{00}	a_{10}	a_{01}	a_{20}	a_{11}
31.08	-105.24	162.94	17.64	22.67
a_{02}	a_{30}	a_{21}	a_{12}	a_{03}
3.48	- 6.25	3.90	11.25	10.18

Equation for quantitative description:

$$\hat{T}(x, y) = 1.94 + 0.17x - 0.14y - 0.000567x^2 + 0.000666xy$$
$$+ 0.0000114y^2 + 0.0000605x^3 - 0.0000024x^2y$$
$$+ 0.0000034xy^2 + 0.0000117y^3 \quad . \qquad (18)$$

According to Equation (17), the related index of the raw data relative to Equation (18) is:

$$\rho_9 = \sqrt{\frac{105.24^2 + 162.94^2 + \cdots + 10.18^2}{40925.76}} = 0.97$$

Standard deviation:

$$S = \sqrt{\frac{40925.76^2 \times (1 - 0.97^2)}{15 \times 21}} = 2.6°C \ .$$

Ratio of difference square:

$$F = \frac{\dfrac{0.97^2}{9}}{\dfrac{1 - 0.97^2}{15 \times 21 - 9 - 1}} = 591.1 \ .$$

(2) July

a_{rs} Value

a_{00}	a_{10}	a_{01}	a_{20}	a_{11}
456.75	-21.10	26.33	-20.95	-9.34
a_{02}	a_{30}	a_{21}	a_{12}	a_{03}
-20.17	- 7.96	-5.92	- 4.35	-1.87

Equation for quantitative description:

$$\hat{T}(x, y) = 25.65 + 0.0529x - 0.0197y - 0.00251x^2 - 0.000390xy$$
$$- 0.000256y^2 + 0.0000799x^3 + 0.00000392x^2y$$
$$+ 0.00000113xy^2 + 0.00000214y^3 \quad . \tag{19}$$

The related index of raw data relative to Equation (19):

$$\rho_9 = \sqrt{\frac{21.10^2 + 26.33^2 + \cdots + 1.87^2}{1938.80}} = 0.86 \quad .$$

Standard deviation:

$$S = \sqrt{\frac{1938.80 \times (1 - 0.86^2)}{15 \times 21}} = 1.54°C \ .$$

Ratio of difference square:

$$F = \frac{\frac{0.86^2}{9}}{\frac{1 - 0.86^2}{15 \times 21 - 9 - 1}} = 99.1 \quad .$$

By comparing the F value obtained above with the critical F* value[16] for a 0.1 percent distinguishability level and a (9, 305) degree of freedom, it is found that in both January and July, the F value greatly exceeds F*. Therefore, it may be considered that Equations (18) and (19) do not come about randomly.

In addition, from the a_{rs} value for January, it can be seen that the linear term is largely dominant. In fact, if only the linear term is considered:

$$\hat{T}(x, y) = a_{00}X_0(x)Y_0(y) + a_{10}X_1(x)Y_0(y) + a_{01}X_0(x)Y_1(y)$$

$$= 1.90 + 0.182x - 0.145y. \quad (20)$$

Then the related index of the raw data relative to this descriptive Equation (20) is:

$$\rho_z = \sqrt{\frac{105.24^2 + 162.94^2}{40925.76}} = 0.95$$

Hence the temperature distribution of January basically can be considered as a linear function of the horizontal coordinates (x, y).

However, with July it is another matter. From the a_{rs} value, it can be seen that the contribution of the quadratic term is of the same order as the contribution of the linear term. Even the cubic terms also make significant contribution. This demonstrates that in July, the temperature distribution along our coastal areas is much more complicated that that in January.

To confirm the correctness of the Equations (19) and (20) for quantitative description, the temperatures at various points were calculated according to the equations, and temperature contour maps were then made. The result thus obtained was very close to the original temperature contour maps.

Discussed above are just two examples in which the one-dimensional and two-dimensional equidistant point orthogonal polynomials are used for quantitative description.

For different purposes, the experiment of using various orthogonal sets of functions for quantitative description of the climatic element field is still being carried out, the results of which will be published later.

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