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Spatial Analysis of Air Temperature in the Qinghai-Tibet Plateau

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Abstract

The mapping of air temperature in the Qinghai-Tibet Plateau is of practical importance because the meteorological stations are sparse and unevenly distributed in the region. The spatial interpolation methods of inverse distance weight, ordinary kriging, ordinary cokriging, and a combined method were used to estimate the spatial distribution of the 1961–1990 January mean air temperature in the Qinghai-Tibet Plateau. The combined method is a combination of ordinary kriging and correction of altitude effect by using lapse rate of air temperature. Comparison of results showed that the problem of mapping air temperature in the Qinghai-Tibet Plateau cannot be resolved by the simple geometric interpolation method as the inverse distance weight. Ordinary kriging can manifest some spatial pattern but the performance was not improved too much. Cokriging to a certain extent was an improvement of kriging but due to the limited altitude information included in the co-variable, the interpolation results were also not in agreement with the actual situation. The combined method was superior to the other methods. The interpolation result from it was reasonable, proved by both the subjective analysis and by many previous works. The comparison of the four methods leads to the conclusion that for regions with sparse meteorological stations, such as the Qinghai-Tibet Plateau, stochastic interpolation methods must be combined with the altitude-effect correction for estimating the spatial distribution of climatic variables.

Introduction

Surface air temperature is a very important climatic variable in many climate studies. Numerous spatial interpolation methods have been applied to estimate the spatial distribution of surface air temperature (Collins and Bolstad, 1996). Recent trends included the usage of a geostatistical method (Holdaway, 1996; Hudson and Wackernagel, 1994), artificial neural network (Snell et al., 2000), spatiotemporal smoothing spline (Luo et al., 1998), and a method based on atmospheric circulation patterns (Courault and Monestiez, 1999). However, estimating spatial distribution of air temperature from irregular point samples in a mountainous region with complex terrain but very few observations is still a challenge. Some studies showed that spatial interpolation errors are larger in mountainous areas where observations are usually sparse and elevation variability is very large.

In order to reduce the errors, elevation information should be incorporated to account for the effects of elevation on temperature (Dodson and Marks, 1997; Hulme et al., 1995; Robeson and Janis, 1998). The Qinghai-Tibet Plateau is such a region, with very sparse and unevenly distributed meteorological stations. Most of the stations in the plateau are located in the eastern part and in the north margin. In the western part (west of 85°E) of the plateau, there are only four stations (Shiquanhe, Geze, Pishan, and Burang), and there is no station in the Qiangtang Highland of the northwest plateau (Fig. 1). Furthermore, almost all the meteorological stations in the Qinghai-Tibet Plateau are located in river valleys with a mean altitude of 3360 m a.s.l., far below the plateau’s mean elevation of 4320 m. Therefore, obtaining a reasonable spatial distribution of air temperature in the Qinghai-Tibet Plateau from incomplete observations by using spatial interpolation methods is of practical importance (Li and Cheng, 1999).

In this paper we first describe the datasets. We then introduce the principles and algorithms of inverse distance weight, ordinary kriging, cokriging, and the combined method. In the following sections we analyze the results obtained from the different methods and give some concluding remarks.

Data

According to the definition of the World Meteorological Organization (WMO), a 30-yr period is required to establish the climatic baseline, and the present climatic baseline is 1961 to 1990. In this study, the 1961–1990 monthly mean air temperature at 173 meteorological stations on the Qinghai-Tibet Plateau and surrounding regions (of which 90 stations are located on the plateau) were used (Fig. 1). The actual interpolation/extrapolation area was slightly widened beyond the plateau’s extent to encompass the region within 75°–106°E and 25°–41°N.

Other important data used in the study include the DEM (digital elevation model) of the Qinghai-Tibet Plateau derived from the 1:4,000,000 digital elevation data of China (Li and Chen, 1995), with a latitudinal resolution of 1°15’ and a longitudinal resolution of 1°52.5’. In the study, the DEM was resampled into the resolution of 0.5°×0.5° by the cubic convolution method.

Method

Among many spatial interpolation methods (Burrough and McDonnell, 1998; Jarvis and Stuart, 2001; Li et al., 2000; Li and...
Revesz, 2002; Price et al., 2000; Zimmerman et al., 1999), the geo-statistical methods were used in this study because they permit the mapping of the error variance of interpolation. Since the elevation is a main factor affecting the spatial distribution of air temperature in the Qinghai-Tibet Plateau, it must be taken into account in the interpolation. There are two methods to do this: (1) the cokriging method, which uses the elevation data as an additional variable; and (2) the combined method, which is a combination of geostatistics and the correction of the altitude effect. In this second method, after the air temperatures are calibrated to the same altitude, they are kriged and then corrected by using lapse rate of air temperature.

In order to examine the effectiveness of the above two methods, two benchmark methods—ordinary kriging and inverse distance weight—were also used for comparison of the performance of different approaches.

**INVERSE DISTANCE WEIGHT**

This assumes that the points closer to the unsampled point make a larger contribution to the value of it, and the contribution is inversely proportional to the distance between sampled and unsampled points. The power of distance was taken as 2 in this study.

**ORDINARY KRIGING**

The theory of kriging is well documented (Deutsch and Journel, 1998; Haining, 1990; Ripley, 1981). In this paper, ordinary kriging was applied as a benchmark method for comparing the performance of different approaches and also for estimating the corrected observations of air temperature in the combined method. The spatial interpolation software developed by Bogaert et al. (1995) was used.

**COKRIGING**

Cokriging optimizes the estimation by taking more than one variable into account (Goovaerts, 1997; Wackernagel, 1995). For instance, the altitude is considered as an important additional variable when estimating air temperature. We used the ordinary cokriging program developed by Bogaert et al. (1995). The elevation of meteorological stations was used as the co-variable.

Once elevation is incorporated into cokriging, a cross-variogram is established based on the temperature-elevation relationship derived from sample data (air temperature and elevation of meteorological stations). The cross-variogram equation is as follows:

\[
\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)][z^k(x_i) - z^k(x_i + h)]
\]

where \( \gamma(h) \) is the cross-variogram, \( z(x_i) \) is the value at location \( x_i \), \( z^k(x_i) \) is the \( k \)th co-variable, \( h \) is the lag or separation distance, and \( n \) is the number of data pairs at lag vector \( h \). The key to cokriging interpolation is to estimate the cross-variogram and analyze the spatial correlation of variables and between variables.

**THE COMBINED METHOD**

This method is a combination of the stochastic model and the deterministic model (Wang et al., 1996). Assuming that the spatial variable, i.e., monthly mean air temperature in this case, consists of the background value and an analysis increment, the estimation of air temperature \( \hat{T}(x) \) at a certain grid can be expressed as

\[
\hat{T}(x) = T^b(x) + \Delta T(x)
\]

where \( x \) denotes the spatial vector at a grid cell; \( T^b \) means the background value of air temperature and can be calculated by

\[
T^b(x) = \sum_{k=1}^{K} k_i T^b(k)
\]

\[
T^b(k) = T(k) - \delta(h(k) - h^p)
\]

where \( k \) denotes the spatial vector at an observation station; \( \lambda \) is the weight; \( T(k) \) is the observed air temperature at the station \( k \); \( h(k) \) is the

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**FIGURE 1. Meteorological stations on the Qinghai-Tibet Plateau.**

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The elevation of the meteorological station; \(h^b\) is the elevation for correction and (we chose 3000 m a.s.l. for this study); \(\delta\) is the lapse rate, for which the values used for different latitudinal and altitudinal zones in the Qinghai-Tibet Plateau are given in Table 1 (from Xie and Zeng, 1983). The lapse rates were obtained by regression analysis, using all the air temperature measurements on the Qinghai-Tibet Plateau from 1950 to the 1980s (Xie and Zeng, 1983). In Equation 3, since the air temperature is corrected to the same altitude, we can assume that the spatial distribution of air temperature no longer contains any altitude information and can be estimated using ordinary kriging.

\[
\Delta T(x) = \delta (h(x) - h^b)
\]

where \(h(x)\) is the elevation of the grid, which is obtained from DEM.

In principle, the core of the combined method is ordinary kriging with corrected values. Since the altitude is the main factor controlling the air temperature and there are very sparse stations in the region, this correction using lapse rate is very important.

**Results**

We took the 1961–1990 January mean air temperature as an example. To show the results, all the interpolated results were visualized as contour maps. In addition, air temperatures at the meteorological stations were also illustrated as gradient dots in the maps for direct visualization.

**INTERPOLATION RESULT OF INVERSE DISTANCE WEIGHT**

The result (Fig. 2) shows that the spatial distribution of meteorological stations can significantly affect the interpolation result. Colder temperature centers occur in the vicinity of several meteorological stations with low-temperature values, including Shiquanhe, Gerze, Madoi, Wudaoliang, Tutuhe, and Qilian Mountain. Air temperature in these regions is less than \(-10^\circ\)C. Warmer temperature centers occur in the vicinity of Lhasa, Xigaze, and Nyalam, with smaller areas. The largest warm-temperature center is to the south of Qamdo, with an air temperature that varied between \(-3^\circ\)C near Qamdo and \(6^\circ\)C at the southeast corner of the plateau. Because there is no meteorological station in the northwest part of the Qinghai-Tibet Plateau and air temperatures observed at the stations at northwest margin of the plateau (in the Tarim Basin) are relatively high, the air temperature interpolation values in the whole northwestern plateau varies between \(-10^\circ\)C and \(8^\circ\)C. Based on the very high elevation in the region, the results are unreasonable.

**INTERPOLATION RESULT OF ORDINARY KRIGING**

Figure 3 shows the experimental air temperature semivariogram and the linear model of regionalization (LMR) fitted. The major features of the variogram can be modeled as a combination of linear model and spherical model with the range of \(1.74 \times 10^5\) m (Equation 6). The sill value is about 7.7.

\[
\gamma(h) = 2.28 \times 10^{-5}h + 3.97 \text{ Sph} \left( \frac{h}{1.74 \times 10^5} \right)
\]

where \(h\) is the distance between data pairs.

In Figure 4 the interpolation result of ordinary kriging is illustrated. The spatial pattern displayed here has some changes from that of inverse distance weight. The low-value area in the northwest plateau increases significantly, and the interpolation results exhibit a latitudinal variation.

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**TABLE 1**

Lapse rates of different latitudinal and altitudinal zones in the Qinghai-Tibet Plateau (°C/100m).

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<tr>
<td>28°</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.54</td>
<td>0.52</td>
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<tr>
<td>30°</td>
<td>0.48</td>
<td>0.50</td>
<td>0.48</td>
<td>0.50</td>
<td>0.54</td>
<td>0.50</td>
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<tr>
<td>32°</td>
<td>0.54</td>
<td>0.52</td>
<td>0.54</td>
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<td>0.54</td>
<td>0.54</td>
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<tr>
<td>34°</td>
<td>0.46</td>
<td>0.44</td>
<td>0.46</td>
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<td>0.46</td>
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<tr>
<td>36°</td>
<td>0.48</td>
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<td>0.48</td>
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<td>0.48</td>
<td>0.48</td>
<td>0.47</td>
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<tr>
<td>average</td>
<td>0.50</td>
<td>0.49</td>
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</table>

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**FIGURE 2.** Interpolation result of inverse distance weight.
zonality. This implies that the kriging method, when observations are very sparse, can manifest some of the spatial pattern.

INTERPOLATION RESULT OF COKRIGING

The experimental air temperature semivariogram is the same as Equation 6, while the experimental cross-variogram and linear model of coregionalization (LMC) fitted are shown in Figure 5. The cross-variogram of air temperature and altitude is negative, suggesting that air temperature and altitude vary in opposite directions, i.e., air temperature decreases with increasing altitude. Hence, the cokriging should be able to obtain a better estimation than kriging does because it takes the altitude of meteorological stations as an additional variable.

The results of cokriging are similar to that of kriging in spatial pattern (Fig. 6), but the low-value area in the northwest plateau increases. From former analysis we know the elevation in the north and west plateau is higher, so incorporating the altitude variable improves the interpolation. However, owing to the relatively low altitude of the meteorological stations on the Qinghai-Tibet Plateau—and therefore limited “altitude” information contained in the co-variable—the interpolation results obtained are also not ideal.

INTERPOLATION RESULT OF THE COMBINED METHOD

After the mean January air temperature is corrected to 3000 m a.s.l., it is considered a spatially correlated variable without structural component. The experimental variogram of corrected air temperature is then calculated (Fig. 7). It has three major characteristics:

1. The starting point of the experimental variogram does not pass through the origin, suggesting that very close data pairs (within a grid scale) have poor spatial correlation. In the Qinghai-Tibet Plateau, the air temperature difference for small distances may be significant due to their great difference in altitude. Such variation in air temperature can be described by the nugget model.
2. The experimental variogram has a tendency to increase linearly.
3. The feature of the initial part of the variogram is shaped like a parabola, suggesting smooth spatial variation. When the distance is greater than $4.0 \times 10^5$ m, the spatial correlation tends to fade away. Such a variation can be described by Gaussian variogram model.

Therefore, the LMR fitted is modeled as a combination of nugget, linear, and Gaussian models (Equation 7):

$$\gamma(h) = 1.13g_0(h) + 1.94 \times 10^{-6}h + 0.859 \left[ 1 - \exp \left( \frac{-3h^2}{4.0 \times 10^3} \right) \right]$$  (7)

The calibrated air temperature is then kriged and added by the analysis increment. The interpolation result (Fig. 8) is substantially different compared to those from other methods. The greatest cold-temperature center occurs in the region north of 34°N and west of 93°E in the northwest plateau, with a mean January air temperature less than −16°C, and a minimum value of −25°C. Another low-temperature center is in the Qilian Mountains region; other regions such as Tutuhe and Shiquanhe are secondary level low-temperature centers with small areas. The distribution of low-temperature centers are affected not only by the station positions and observation values, but also greatly by very high altitude and the latitudinal zonality. The overlay analysis with DEM indicates that the altitudes of low-value grids are all higher than 5000 m, even reaching 6000 m or more.

The distribution of the warm-temperature center is similar to the results of other interpolation methods. It is located in the southeast part of the plateau with Qamdo as the center and extends westward along

FIGURE 3. Experimental variogram and LMR fitted of the 1961–1990 mean January air temperature in the Qinghai-Tibet Plateau (crosses express experimental variogram and solid line is the LMR fitted).

FIGURE 4. Interpolation result of ordinary kriging.

FIGURE 4. Interpolation result of ordinary kriging.
29°N (valley of the Yarlung Zangbo River) to Lhasa and Xigaze. The air temperature values of the warm-temperature center are lower than the interpolation results of other methods.

**Discussion**

In this study, it is very difficult to compare the interpolation results with the observations directly, particularly in the western part of the Qinghai-Tibet Plateau, because there are very sparse meteorological stations in the region. In addition, their elevations are far below than the mean elevations of the corresponding DEM grids (Table 2). Therefore, it is unreasonable to compare the interpolation results that represent the averaged values of the grids with the observation data that only represent the values in the stations.

Instead of direct comparison, we used two methods to evaluate the performance of different interpolators. The first was to compare the interpolation results with subjective analysis, which is very important and sometime the unique way to evaluate the interpolation result in a region that can be regarded as a data void or "hole" (Goovaerts, 1997). Particularly in this case, the mapping of air temperature is an interpolation and extrapolation problem, with the high-mountain extreme unsupported by data (for lack of stations). Thus geographic knowledge is required, and the usual set of estimation methods yields unsatisfactory results. The second evaluation method uses interpolation variances. Although as noted by some investigators (Goovaerts, 1997; Journel, 1986), variance is not an absolute measure of errors because it is not conditioned to the data values used, it still can be considered as a criterion for evaluating interpolation performance.

The spatial pattern of the surface air temperature distribution in the Qinghai-Tibet Plateau was established as the first step. Because air temperature usually complies with the vertical and latitudinal zonalities and the relief of Qinghai-Tibet Plateau is high in the west and low in the east, the air temperature distribution in the plateau should have a pattern of east-warm and west-cold as well as south-warm and north-cold. Based on the above analysis and previous works (Institute of Geography, CAS, 1990; National Meteorological Administration, 1979; The Scientific Investigation Group on the Qinghai-Tibet Plateau, CAS, 1984; Ye and Gao, 1979), the distribution pattern of the surface air temperature in the Qinghai-Tibet Plateau in January can be established as the following: (1) the cold temperature centers are in the Qiangtang Highland of northwest Qinghai-Tibet Plateau, the Qilian Mountains, the Shule-Nanshan region, and the narrow region between 90°–100°E and along 35°N; and (2) the high-temperature centers are located at the south margin of the Tarim Basin, south margin of the Qaidam Basin, and the regions to the south and east of Qamdo (Fig. 1).

**FIGURE 5.** Experimental cross-variogram and LMC fitted of air temperature and altitude (crosses express experimental cross-variogram and solid line is the LMC fitted).

**FIGURE 6.** Interpolation result of ordinary cokriging.

**FIGURE 7.** Experimental variogram and LMR fitted of the 1961–1990 mean January air temperature in the Qinghai-Tibet Plateau after being corrected for altitude (crosses express experimental variogram and solid line is the LMR fitted).
Compared with the pattern established, we can conclude that the problem of mapping air temperature in the Qinghai-Tibet Plateau cannot be resolved by a simple geometric interpolation method such as the inverse distance weight. This is because there is no meteorological station in the northwest plateau. The results in Figure 2 are obviously not in agreement with the actual situation. For ordinary kriging, the performance was not improved too much, but some spatial pattern was demonstrated. The cokriged map to a certain extent was an improvement of kriging interpolation results, but due to the limited altitude information included in the co-variable, the interpolation results were not in agreement with the actual situation as well. The combined method is the best interpolator in the comparative study. This can be proved by both the subjective analysis and many previous works. For example, our results showed that in January the air temperature in the Qiangtang Highland is less than -16°C, which is in very good agreement with the conclusions of The Scientific Investigation Group on the Qinghai-Tibet Plateau, CAS (1984). Moreover, although there are no meteorological stations in the northwest plateau, there are some short-term observations in this region. The measurements made by a field survey showed that at Tianshuihai (35°21'N, 79°33'E, 4900 m a.s.l.), Qiangtang Highland, the mean air temperatures in January and December 1966 were -21.9°C and -20.6°C, respectively, far lower than the air temperature of other regions on the plateau. The comparison of the four methods leads to the conclusion that for regions with sparse meteorological stations, such as the Qinghai-Tibet Plateau, stochastic interpolation methods must be combined with corrections, e.g., the correction of altitude effect, for estimating the spatial distribution of climatic variables.

Then we use variance for evaluation. The error variances of kriged and cokriged results have the following characteristics: (1) The variances of the west Qinghai-Tibet Plateau with sparse meteorological stations are far higher than those of the east plateau with relatively dense meteorological stations. (2) The highest variances occur in northwest plateau where no meteorological station exists. The error variances of the interpolation results from combined interpolation are characterized as evenly distributed. In addition, the mean and maximum variances of the combined method are 1.96 and 3.34, respectively, far below the corresponding values of cokriging’s 6.61 and 15.62. The combined method has smaller variance because a lot of the variability of air temperature was taken away by the correction, suggesting that the correction by using lapse rate is an essential way to reduce the errors. The variance analyses also proved that the sampling design is a very important factor affecting the interpolation accuracy, implying that some meteorological stations should be established in the farmost region of the Qinghai-Tibet Plateau for better understanding of climate on the world’s roof.

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