PRELIMINARY NUMERICAL STUDY OF TOPOGRAPHIC EFFECTS OF THE TIBETAN PLATEAU ON SURFACE DIRECT RADIATION*

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ABSTRACT

To improve the simulating ability of a model, this paper presents a scheme of calculating direct radiation at land surface with topography in the model. A numerical study is conducted for the topographic effects of the Tibetan Plateau on the direct radiation using NCEP terrain data. Results show that, after taking account into the topographic radiation effect, the regional average of the radiation over the Plateau obviously increases in the local early morning and late afternoon, but changes less around noon. The effect is stronger in winter than that in summer. And heterogeneous topography has also affected the distribution of the radiation in this area. A simple numerical experiment shows that considering the effect will lead ground temperature to increase on the slope having more sunshine, and vice versa.

Key words: the Tibetan Plateau, topographic effect, direct radiation, characteristics

I. INTRODUCTION

The Tibetan Plateau is often called as the roof of the world, and its existence has very important effects not only on its peripheral climatic environment but also on weather and climate change over China as well as the globe. For example, it is related with the formation of monsoon climate and weather change over Southeast Asia, the formation of the Gobi Desert and having its location towards higher latitudes. Therefore, more attentions from meteorologists all over the world have been paid to the study of the effects of the Plateau on global weather and climatic environmental change, especially from meteorological researchers of China. Direct solar radiation at ground surface is a very important component of energy budget at the surface, for it directly affects the status of the soil and air temperatures near ground surface. Currently, there are a lot of work on surface direct solar radiation (Weng 1997), but a little was done on the effects of Tibetan Plateau on the radiation using numerical models. Therefore it is of significance to numerically study the topographic effect on the direct radiation at ground surface.

On the other hand, with the development of meteorological science and technology,

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meteorological research method has been changed from qualitative description to quantitative calculation. Having the development of numerical models, meteorologists have focused their studies on land surface processes, because the land surface is the lowest boundary of a GCM and there energy, momentum and mass interchanges between air and land take place, with very complicated physical processes. At present, there are various kinds of parameterization schemes of land surface processes (Pitman et al. 1992; Dickinson et al. 1993; Sellers et al. 1996), but those schemes have not considered the effects of the heterogeneous distribution of meteorological parameters. The effects of complicated topography on direct radiation at ground surface as a very important aspect of heterogeneity have not been considered in most current parameterizations of land surface processes, neither. Terrain complexity is directly related with the heterogeneous distribution of ground variables (Giorgi 1997), and treating the heterogeneous distribution over grid point area as uniform one will certainly cause the discrepancy of calculated results from the reality. Under the condition with and without considering the topographic effect, what is the difference of their ground direct radiation and what is the effect of topography? We did not know it and should do some work in this regard.

The purpose of this study is to improve the application of vegetation model SSiB (Xue et al. 1991) in the research on Tibetan Plateau when coupling SSiB into the MM5. Because the Tibetan Plateau has a very high altitude and complicated topography, the directly coupling may improve the model simulating ability in this area. However, SSiB is one-dimensional model, not considering the effects of heterogeneous distribution of the meteorological elements at ground surface, which differs from the reality. Therefore, this article first presents the scheme to calculate the direct radiation at ground surface with topographic effect, and then uses NCEP terrain data to study the characteristics of effects of the Tibetan Plateau on the radiation.

II. COMPUTATION OF SURFACE DIRECT RADIATION USING GRID TERRAIN HEIGHT

1. *The Method of Computing Direct Radiation at Ground Surface*

Most parameterizations of land surface processes have not considered the topographic effects on solar radiation. It is well known that land shape affects the terrain absorption of solar radiation, such that the southern side of a mountain has more sunshine than the northern side. Therefore, because of the existence of mountains, the local microclimate is formed.

Weng et al. (1979) and Weng (1997) have made a lot of researches on mountainous microclimate. Assuming the gradient of a slope is α, and its azimuthal orientation is β (starting from due south, positive clockwise), taking S_m as the direct radiation at the surface perpendicular to sunlight, according to Weng et al. (1979), the direct radiation on a slanted surface can be modified as

$$S_{\alpha\beta} = S_m(U\sin\delta + V\cos\delta\cos\omega + W\cos\delta\sin\omega), \qquad (1)$$

where

$$\begin{cases} U = \sin\varphi\cos\alpha - \cos\varphi\sin\alpha\cos\beta, \\ V = \sin\varphi\cos\alpha\cos\beta + \cos\varphi\cos\alpha, \\ W = \sin\alpha - \sin\beta, \end{cases} \qquad (2)$$

and

$$U^2 + V^2 + W^2 = 1,$$

where φ is the latitude, δ the solar declination, and ω the solar hour angle. According to Eq. (2), U, V and W can be known from α, β and φ. Let $S_{\alpha\beta}=0$ in Eq. (1), the hour angle ω_s can be obtained at sunrise and sunset for any slope (because the radiation is just 0 at the time), i. e.

$$U\sin\delta + V\cos\delta\cos\omega + W\cos\delta\sin\omega = 0.$$

From the equation, we have

$$\omega_s = \arcsin\frac{-UW\mathrm{tg}\delta \pm V\sqrt{W^2 + V^2 - U^2\mathrm{tg}^2\delta}}{W^2 + V^2}, \tag{3}$$

where the positive and negative symbols before the second term of the numerator indicate the hour angles at sunset and sunrise respectively. Note that, the hour angle was inappropriately represented as anti-cosine in some papers (Weng et al. 1979). But one cosine value may correspond to two angles in the scope from $-90°$ to $90°$, thus we can only obtain the absolute value of the hour angle rather than the hour angle at sunrise or sunset for a slope.

From above-mentioned Eqs. (1) — (3), we can compute the potential total direct radiation at a slope. The radiation is related with the solar constant, the climatologic transmission coefficient, the hour angle at sunset (ending sunshine) and sunrise (starting sunshine) as well as the corrected term of average distance between the sun and the earth (Weng et al. 1979).

2. *Scheme for Calculating the Direct Radiation at Ground Surface in Models*

Above-mentioned equations still can not be directly implemented in models, and we should know how to compute the gradient and orientation. Assuming any terrain height is the function of x and y, i. e. $z=z(x, y)$, it can be written in the form of differentiation as

$$\Delta z = \frac{\partial z}{\partial x}\Delta x + \frac{\partial z}{\partial y}\Delta y. \tag{4}$$

From the above expression, the plane equation for a slope can be written as

$$\frac{\partial z}{\partial x}x + \frac{\partial z}{\partial y}y - z = C, \tag{5}$$

where C is any constant. Since the equation for a horizontal surface is $z = D$ (any constant), and a slope angle can only be acute. Assuming that the positive directions of x-axis and y-axis are taken as the eastward and northward respectively, according to the calculation of angle between two planes, we have

$$\alpha = \arctan A, \tag{6}$$

where

$$A = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}.$$

From Eq. (5) and the plane equation $z=D$, we can determine the intersected line between a mountain slope and horizontal surface, thus the formula to calculate the orientation of a mountain slope can be deduced as

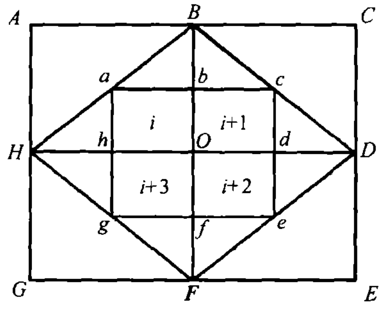

Fig. 1. Setting for calculating the slope gradient and orientation in models.

$$\beta = \begin{cases} \beta_a, & \partial z/\partial x > 0 \\ \pi + \beta_a, & \partial z/\partial x \leqslant 0 \end{cases} \tag{7}$$

where

$$\beta_a = \arccos\left(\frac{\partial z}{\partial y}\Big/A\right).$$

As shown in the above equations, when the partial derivatives of east-west and south-north are known, the gradient and orientation of a slope can be solved. Having the equations of calculating slope gradient and orientation, now let us decide how to implement the calculation of surface direct radiation at grids of models. Since grids in models are discrete, so connecting three grid points that are close to each other can determine a plane, shown in Fig. 1. In the figure, the capital letters O, A, B, C, D, F, G and H represent the centers of model grid points. And the area surrounded by the corresponding small letters a, b, c, d, e, f, g and h represent a grid cell area, consisting of four squares i, $i+1$, $i+2$ and $i+3$. The squares are located on the planes HBO, BDO, DFO and FHO respectively, whose gradients and orientations can be calculated from grid terrain heights. Thus the gradient and orientation of each square can also be determined. Therefore direct radiation and its daily total amount at ground surface can be calculated for each model grid.

III. TOPOGRAPHIC EFFECTS OF THE TIBETAN PLATEAU ON SURFACE DIRECT RADIATION

1. *Data and Analyzing Method*

This study chooses the $10' \times 10'$ terrain data of the National Centers for Environmental Prediction(NCEP), USA, and interpolates it into the data of 20 km $\times$ 20 km using the preprocessing program of the MM5. The grid number in the experiment area is taken as 97×166, locations of the four vertexes are (23.70°N, 73.97°E), (24.52°N, 105.53°E), (40.32°N, 68.81°E) and (41.44°N, 109.49°E), as shown in Fig. 2.

In the figure, isolines of terrain height in the southwestern side and some part of the northern side are denser, indicating greater gradient there. The slope gradient is obviously smaller on the top of the Plateau than on the southwestern and northern sides. The land peripheral to the southwestern slope is quite smooth.

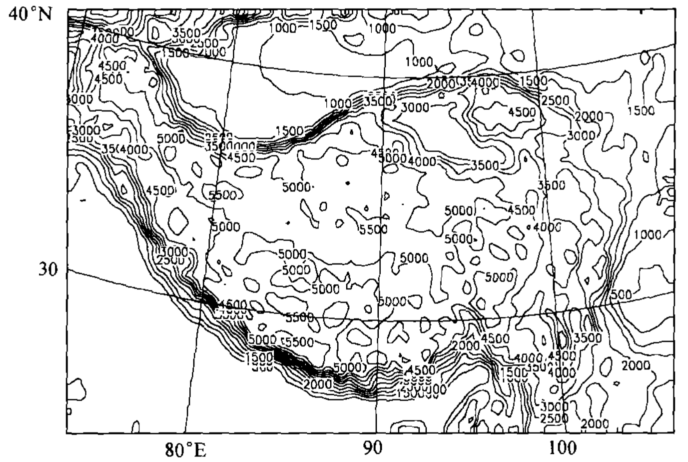

Fig. 2. Distribution of terrain height for the Tibetan Plateau (in m).

To analyze topographic effects, we investigate the increasing ratio (C) of the direct radiation at slope to that at horizontal level, i. e.

$$C = \frac{A - B}{B}, \tag{8}$$

where A is the direct radiation or its daily total amount with topographic effect, B the corresponding result without the topographic effect that is also the result calculated in most of current models.

Analysis will be preformed on the topographic effect from temporal and spatial aspects. Temporally, we study the area-averaged value over the Plateau. For convenience, when analyzing the hourly change of area-averaged direct radiation and distribution of daily total direct radiation, we only choose the summer, winter solstices, and spring /autumn equinox (solar declination is taken as 23. 5°, −23. 5° and 0° respectively) for our study.

2. Temporal Change of Increasing Ratio of Area-Averaged Direct Radiation

Figure 3 demonstrates the day-to-day change of increasing ratio of the area-averaged daily total direct radiation over the Tibetan Plateau within a year. The x-axis of the figure represents the percentage of increased or decreased value of the area-averaged daily total direct radiation at slope compared to horizontal level over the Tibetan Plateau area, and the y-axis represents the number of days, starting from January 1, being 82 in spring equinox. Figure 4 gives out the hourly change of increasing ratio of area-averaged direct radiation at summer, winter solstices, and spring/autumn equinox. In the figure, the cross, circle and dark-dotted points correspond to summer, winter solstices, and spring/ autumn equinox respectively. The mark of x-axis represents Beijing Time and that of y-axis denotes the increasing ratio.

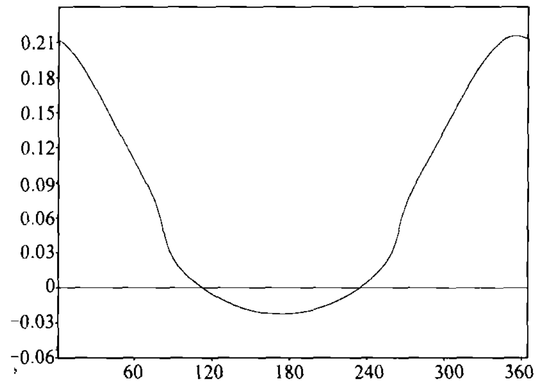

Fig. 3. Day-to-day change of increasing ratio of the area-averaged daily total direct radiation (x-axis: d, y-axis: %).

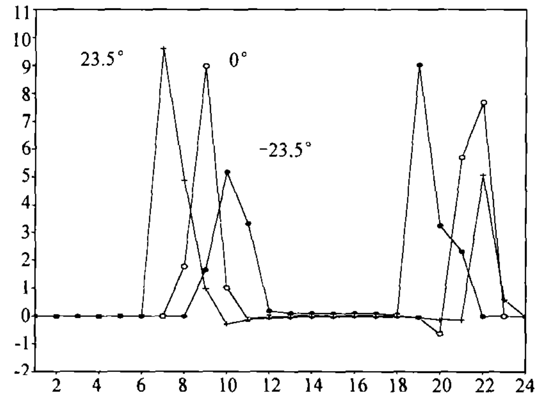

Fig. 4. Hourly change of increasing ratio of the area-averaged direct radiation (x-axis: Beijing Time, y-axis: %).

As shown in Fig. 3, considering topographic effect, the area-averaged daily total direct radiation over the Tibetan Plateau in winter increases in comparison with that without slope; however, the difference between the two cases is less in summer, sometimes being negative. This phenomenon probably results from that the solar zenith is lower in winter, the gradient of southern slope of the Tibetan Plateau is greater, and the location of the sun is towards the south during daytime. All the above factors make the southern slope of the Plateau have more sunshine; but in summer, the location of the sun moves more towards the north, the northern slope gradient of the Plateau is smaller, thus sunlight spreads over the Plateau much like over a horizontal surface.

As shown in Fig. 4, whenever in summer, winter solstices, and spring/autumn equinox, the direct radiation over a slope obviously increases in comparison with that over a horizontal surface in local early morning and late afternoon over the Plateau area, but the change is very small around noon. This also may result from the topography, because the solar zenith is lower in early morning and late afternoon, a slope will receive more sunshine than a horizontal surface. However, around noon, the solar zenith is high, there are less differences in receiving direct radiation between a slope and a horizontal surface.

3. *Spatial Distribution of Daily Total Amount of Direct Radiation*

Figure 5 demonstrates the distributions of increasing ratios of direct radiation considering the topographic effect.

As shown in the figure, after considering the topographic effects, in winter solstice the increase of C mainly appears in the southwestern side of the Plateau (Himalayan southwestern side), the southwestern side of the Tarim Basin, etc. But the decrease of C mainly appears in the southeastern slope of the Tarim Basin, the Sichuan Basin and the southeast of the Plateau. The magnitude of C variation over the Plateau is relatively small, almost being zero in the place peripheral to the southwestern slope of the Plateau, which is closely and obviously related with the topography. In spring/autumn equinox, the pattern of C distribution resembles that in winter solstice, but obviously has smaller

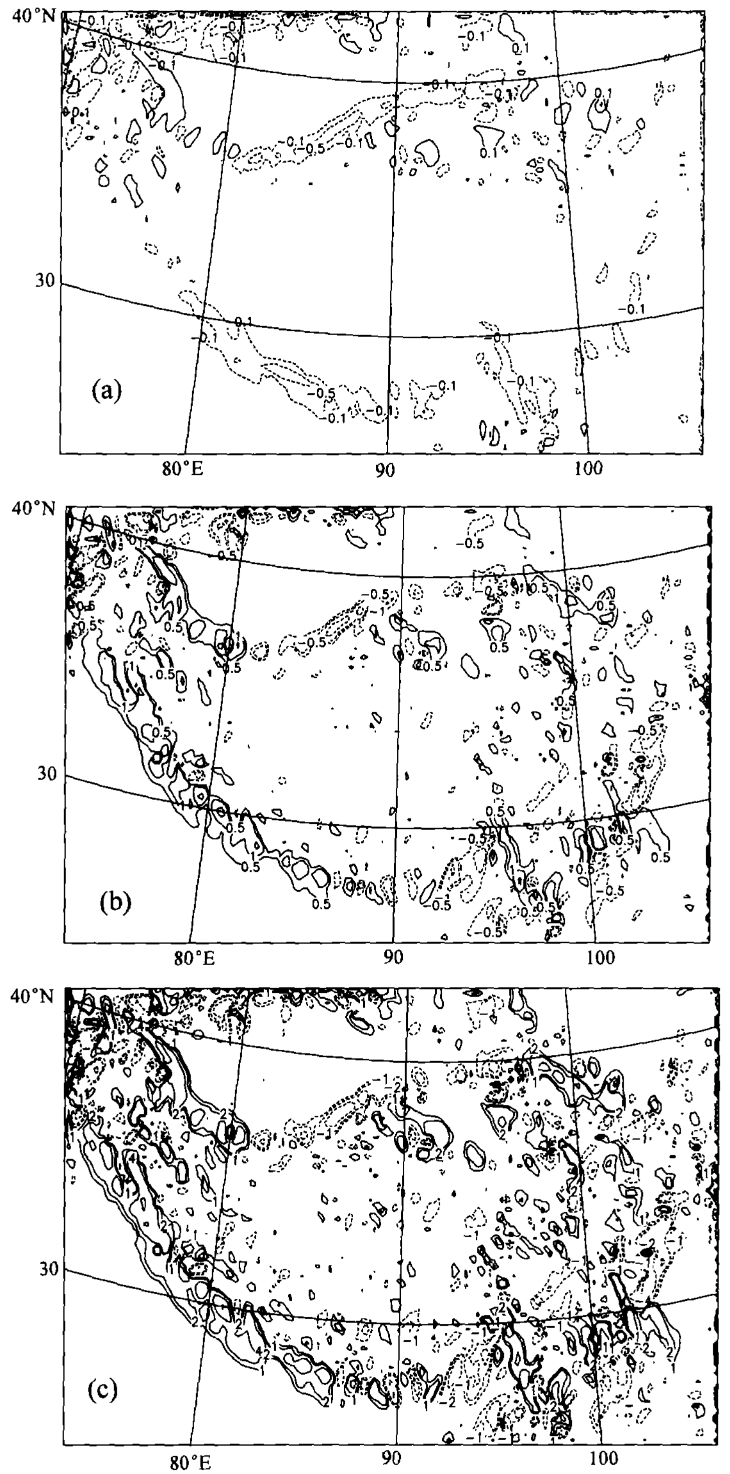

Fig. 5. Distribution of increasing ratio of daily total direct radiation over the Tibetan Plateau: (a) 23.5° (summer solstice), (b) 0° (spring/autumn equinox), (c) −23.5° (winter solstice). Solid lines indicate positive values and dashed negative.

variation magnitude. In summer solstice C variation becomes much smaller, still negative in the southwestern slope of the Tarim Basin. But C changes from positive to negative over most southern slope of the Plateau, indicating that the total radiation becomes less because of topography, and may result from the topographic blocking of sunshine. This kind of distribution is almost in agreement with the observed (Weng 1997).

Generally speaking, with the northward movement of the sun, the effect of the Plateau on the radiation becomes less, and vice versa. As shown in Table 1, under the resolution of 20 km × 20 km, the maximum increase of the daily total direct radiation at ground surface is about 14.6%, the maximum decrease is about 8.8% and the average increase is about 2.2‰ in winter solstice. For spring/autumn equinox the maximum increase is about 4.3%, maximum decrease is about 3.1%, and the average increase is about 0.5‰, which are less than the former case. As for the radiation change in summer solstice, the maxima of increase and decrease are about 0.8% and 3.0% respectively, and average decrease is about 0.2‰. Therefore, the topographic effect of the Tibetan Plateau on the daily total direct radiation at ground surface is greater in winter than in summer.

Table 1. Topographic Effects on Daily Total Direct Radiation at Ground Surface under Different Model Resolutions

Resolution	δ (°)	Maximum (%)	Minimum (%)	Average (‰)
	23.5	(41.44°N, 109.49°E) 0.82	(42.19°N, 79.91°E) −3.02	−0.22
20 km × 20 km	0.0	(41.44°N, 109.49°E) 4.28	(33.86°N, 107.49°E) −3.09	0.50
	−23.5	(41.44°N, 109.49°E) 14.61	(41.08°N, 109.38°E) −8.77	2.16
	23.5	(39.12°N, 75.42°E) 0.31	(38.07°N, 86.36°E) −0.43	−0.10
60 km × 60 km	0.0	(32.54°N, 76.38°E) 1.78	(38.07°N, 86.36°E) −1.52	0.37
	−23.5	(32.54°N, 76.38°E) 5.69	(41.28°N, 78.59°E) −4.42	1.43

4. *In Comparison with Observed Data*

A lot of work on radiation observation and study has been carried out (Weng et al. 1979; Weng 1997). Weng (1997) gave out the flux density distributions of seasonal and yearly averages of solar direct radiation over China in the book "Radiation Climate over China". As known from the observed results, the direct radiation in the southwest of the Tibetan Plateau has high values in winter, summer and yearly averages. Low values of radiation are found in the Tarim Basin and the Sichuan Basin, where the direct radiation in the place near the windward slope of the Hengduan Mountains is obviously greater in winter than in summer. The calculated results of this paper are basically in agreement with the observations. Because the spatial distribution of direct solar radiation was traditionally obtained from the data observed by very small number of isolated observation stations, the spatial distribution of direct radiation is too rough, but we can estimate the detailed spatial distribution of direct radiation change using land height data (NCEP, 20 km × 20 km). Although the status of direct solar radiation is related with many other factors such as air quality, we can still obtain the results almost in agreement with the observation, when estimating the topographic effects on direct solar radiation using terrain data. This indicates that topography has a strong influence on the distribution of direct solar radiation. This fact is encouraging, because inclusion of this kind of calculation in models will improve the calculation of the direct solar radiation at ground surface.

IV. PRELIMINARY ANALYSIS OF HETEROGENEOUS TOPOGRAPHIC EFFECT ON RADIATION

From the above analysis we can note that the effects of the Tibetan Plateau on the direct radiation at ground surface are apparent, especially in winter, the topographic effect is greater. Here, we will further analyze the effects of topographic heterogeneity on the direct radiation. In other words, we will analyze what is the difference of the simulated results due to different resolutions of numerical models. For calculation, the original model resolution of 20 km$\times$20 km is changed into that of 60 km$\times$60 km by averaging the land heights of smaller grids within larger grids, thus we have the experiment area with grid number of 32 $\times$ 55, the locations of its four vertexes are (23.91°N, 74.11°E), (24.72°N, 105.37°E), (40.20°N, 69.11°E) and (41.30°N, 109.19°E). The coverage of this experiment is equivalent to that in the above section.

To analyze the difference caused by smoothing the terrain height, we calculated the height difference between the results before and after averaging (figure omitted). During calculating height difference, the grid numbers of both cases have a matrix 97$\times$166. After averaging, the height of each grid in the matrix is the average height of original smaller grid. That is, each grid in the new matrix 32$\times$55 has 9 original smaller grids which have the same height. As known from the distribution of the terrain height difference, the change of the difference is greater in the edge of the Plateau and smaller for the other areas. This indicates that, after the height averaging, the change in terrain height distribution is greater at the edge of the Plateau, and the slope gradient becomes less.

Table 1 denotes the topographic effects on the daily total direct radiation under different model resolutions over the Plateau. From Table 1 it can be seen that, after averaging, the change of area-averaged C becomes smaller in comparison with the calculated results in the above section. The absolute values of the maximum and minimum all also become smaller together with their locations changed. Meanwhile we should note that area-averaged value is one order less than the absolute value of the maximum and minimum.

Figure 6 denotes the difference between the increasing ratios. As shown in the figure, after averaging, the increase magnitude of daily total direct radiation in winter becomes less. And the decrease magnitude of daily total radiation in summer also obviously becomes less, indicating that terrain heterogeneity has something to do with change magnitude of daily total direct radiation at ground surface.

To analyze the difference of direct radiation change between the results from grid terrain height averaging and those calculated in the previous section, we calculated their differences of daily total direct radiation in summer, winter solstices, and spring/autumn equinox, as well as their difference of the area-averaged time series (figures omitted). From the results, we can see that the difference magnitude of daily total direct radiation is

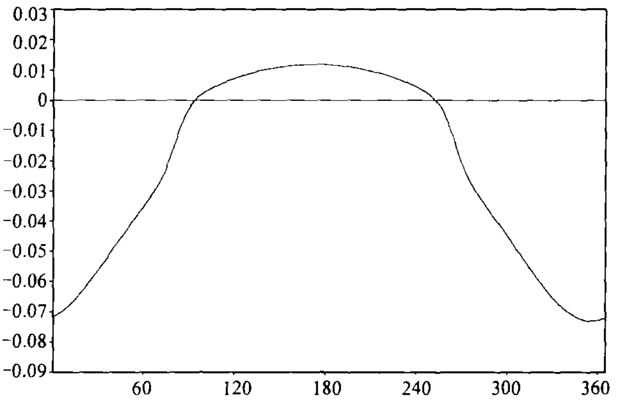

Fig. 6. Difference between the increasing ratios of daily total direct radiation after and before grid terrain height averaging (x-axis: d, y-axis: %).

greater in winter solstice than in spring/autumn equinox, and the smallest appears in summer solstice. This indicates that, after smoothing, the terrain heterogeneity still affects greatly the daily total radiation in winter solstice.

From the analysis above, one can note that, when smoothing the terrain height, the topographic effect on the direct radiation is weakened. In other words, terrain heterogeneous distribution has a close relationship with the topographic effect on the direct radiation at ground surface. That is, the more complicated the terrain heterogeneity, the stronger the topographic effect on the direct radiation.

V. EXPERIMENT OF CLIMATIC CHANGE DUE TO TOPOGRAPHIC EFFECTS ON RADIATION

To demonstrate the climatic effects resulting from topographic effects on the direct radiation at ground surface, we coupled the scheme SSiB into the MM5, and performed integration under different conditions, i.e., conducting sensitivity experiments with and without the topographic effect. The coupling of SSiB into the MM5 is of two-way approach, the resolution of the model is 60 km × 60 km, and the experimental area is chosen at the Tibetan Plateau, shown in Fig. 2. The time step of integration is 90 seconds and the period is from 00 UTC 1 to 00 UTC 10, January 1995. Initial and background fields of the integration are the NCEP data of the same period. Figure 7 gives out the distribution of ground temperature differences in 10-day integration period average, between with and without consideration of the topographic effects on the direct radiation. For simplicity, the distributions of other elements are omitted.

As shown in the figure, after considering the topographic effect the locations of ground temperature increase and decrease are almost in agreement with those of the direct radiation. One can note that, averaged ground temperature increases over the regions of the southwestern side of the Tibetan Plateau (Himalayan southwestern side), the southern slope of the Qilian Mountains, etc., which result from the increase of absorption of the direct radiation over the regions. However, the averaged ground temperature obviously decreases at the northern slope of the Tibetan Plateau and near Bangladesh, resulting from the topographic blocking of sunshine. The variations of ground temperature

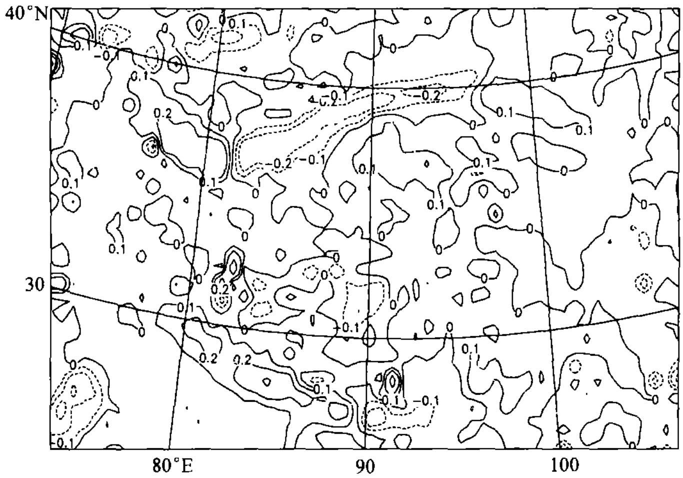

Fig. 7. Difference of ground temperatures between results with and without the topographic effect on direct radiation (in ℃).

for the other areas is also related with topographic characteristics, or result from the environmental influence around them. From the magnitude of ground temperature change, after considering the topographic effect, the difference of the averaged ground temperature may reach about 1℃, depending on the scheme of land surface processes. Higher model resolution may make this kind of difference greater.

As known from the results, because of the difference of slope gradient and orientation between different places, the absorption of direct solar radiation is different, which will directly lead to the difference of local ground temperatures. In turn, the local climate change affects its peripheral environment through energy and momentum exchange between land surface and atmosphere.

VI. CONCLUSIONS

After considering the topographic effect on the solar radiation, we can clearly note that, the existence of the Tibetan Plateau has changed the spatial distribution of the direct solar radiation at ground surface over this region. And the radiation at ground surface will be changed as follows:

(1) The area-averaged direct radiation at ground surface over the Plateau obviously increment at locally early morning and late afternoon, but changes less around noon.

(2) The area-averaged daily total direct radiation increases in winter, but the increment is less in summer and even reduced.

(3) Spatially, the local difference of daily total direct radiation is greater in winter than that in summer.

(4) The daily total direct radiation obviously increases in most part of southern side of the Tibetan Plateau in winter, whereas the radiation decreases in less part of the southern side in summer.

(5) With the increase of the complexity of terrain heterogeneity, the topographic effect on the direct radiation at ground surface also increases. Spatially, the maximum and minimum magnitudes of the radiation may become great.

(6) Topographic heterogeneity will act as an amplifier of positive feedback, making the area with greater direct radiation have even much greater direct radiation, and vice versa.

(7) Generally, the increasing ratio of the area-averaged daily total direct radiation over the Plateau is much less than the maximum or minimum of the increasing ratio at local sites, indicating that the topography of the Tibetan Plateau plays a role in redistributing direct radiation over the area.

From the above analysis, one can note that the topography affects the distribution of direct radiation at ground surface, and the simulated results are basically in agreement with the observed. The scheme presented in this paper is very simple and can be easily implemented in numerical models. According to the results, the topographic effect is mainly through changing the solar altitude angle, which is not only the important factor for solar energy budget but also related to the status of snow surface reflectance (Dickinson et al. 1993). From this point, the topography of the Tibetan Plateau plays a very important role in redistributing local solar energy in the area, and the viewpoint is in agreement with the results of this study (the indirect effect of topography on snow surface reflectance is not studied in this paper). Solar energy is very important to the change of meteorological elements, therefore inclusion of the topographic effect on the solar altitude angle at ground surface will help to improve the numerical simulation of local climatic changes of meteorological variables. As known from the experimental results, considering the effect will increase the ground temperature on the slope having more sunshine, and vice versa.

In summary, when calculating surface direct radiation in a model, considering the topographic effect will improve its result or simulating ability. We should further study this aspect in future work.

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