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ANNUAL VARIATIONS OF TEMPERATURE ON FOUR URBAN UNDERLYING SURFACES AND FITTING ANALYSIS

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Abstract: Based on the observed 2-year temperature data for four kinds of typical urban underlying surfaces, including asphalt, cement, bare land and grass land, the annual variations and influencing factors of land surface temperature are analyzed. Then fitting equations for surface temperature are established. It is shown that the annual variation of daily average, maximum and minimum temperature and daily temperature range on the four urban underlying surfaces is consistent with the change in air temperature. The difference of temperature on different underlying surfaces in the summer half year (May to October) is much more evident than that in the winter half year (December to the following April). The daily average and maximum temperatures of asphalt, cement, bare land and grass land are higher than air temperature due to the atmospheric heating in the daytime, with that of asphalt being the highest, followed in turn by cement, bare land and grass land. Moreover, the daily average, maximum and minimum temperature on the four urban underlying surfaces are strongly impacted by total cloud amount, daily average relative humidity and sunshine hours. The land surface can be cooled (warmed) by increased total cloud amount (relative humidity). The changes in temperature on bare land and grass land are influenced by both the total cloud amount and the daily average relative humidity. The temperature parameters of the four land surfaces are significantly correlated with daily average, maximum and minimum temperature, sunshine hours, daily average relative humidity and total cloud amount, respectively. The analysis also indicates that the range of fitting parameter of a linear regression equation between the surface temperature of the four kinds of typical land surface and the air temperature is from 0.809 to 0.971, passing the *F*-test with a confidence level of 0.99.

Key words: fitting analysis; urban underlying surface; land surface temperature

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1 INTRODUCTION

The environmental problem of urban heat island has been an effect emphasized by many scholars since Howard[1] found it in the early 19th century. Urbanization speed is accelerated in recent years due to rapid economic development, significantly changing land use/land cover. In addition, reduced arable and green land and increased artificial buildings are changing the original urban landscape, replacing the natural vegetation with all kinds of impervious surfaces, such as asphalt, cement and concrete. Not only do these land surfaces absorb heat in the daytime and release heat at night, they also have good thermal conductivities and heat capacities, which are the primary reasons for the effect of urban heat island[1-3] and have a negative effect on urban environment[4]. Thus insights are required into the temporal and spatial characteristics of temperatures on typical urban underlying surfaces and related simulations.

Urban climate is affected by the land-air system over the urban underlying surface. Therefore, the relationship among surface temperatures on different urban underlying surfaces, air temperature and heat island attracted much attention from many scholars. By studying the impact of changes in land use and cover on ambient temperature over Takamatsu of Japan, Atsuko[5] pointed out that the main reasons are

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the growth of non-permeable underlying surface area. And the non-permeable underlying surface of Beijing was proportional to the surface temperature[6]. Based on the remote sensing data, Streutker[7] and Roth[8] studied the relationship between the surface temperature and the spatial distribution of several coastal cities of North America and indicated that the land use is related to the thermal characteristics of inner urban areas during the day but it is not much related to the heat island intensity during the night. Simultaneously, it was clearly shown that the surface temperature is significantly correlated with four indexes, namely NDVI (normalized difference vegetation index), MNDWI (modified normalized difference water index), NDBI (normalized difference built-up index) and NDBaI (normalized difference barren index). And there are significant differences among the temperatures on different kinds of land use or land cover in the previous studies[9, 10]. The interaction between air temperature and urban underlying surface are revealed by the studies above. However, the accurate temporal and spatial distributions of surface temperature on the different underlying surfaces are difficult to obtain because of low sampling frequencies from the object of interest and low resolutions of satellites. On the other hand, the albedo of objects on the ground is sensitive to the wind, clouds and other factors, which could amplify the error of observed temperature on the underlying surface of land in the study. Some preceding researchers used the surface observations to analyze and forecast the temperature on different kinds of typical underlying surfaces[11-15] without clear temporal distribution and influence factors. In the current study, based on the observed 2-year temperature data of the typical urban underlying surfaces of asphalt, cement, bare land and grass land, we analyzed the annual variations and influence factors of daily average, maximum and minimum temperature for these land surfaces and then established fitting equations of surface temperature. Furthermore, a linear statistical model based on a variety of meteorological elements will be built to provide technical support for retrieval of urban microclimate and to provide basis for comparison and validation of remote-sensing data.

2 DATA AND METHODS

2.1 *Data*

The temperature observation site is located at the Agro Meteorological Experimental Station of Guangdong Province. A stretch of 5-cm tall perennial grass (Taiwan Manila) surrounded by open place covers the observation site. The observation blocks of the four kinds of underlying surfaces are all 2.5 m^2 with the grass land managed in the same way as the observation field itself. Following the specifications of meteorological observation[16], thermometers were placed on the four different underlying surfaces from May 1 of 2004 to April 30 of 2006 to measure the maximum and minimum temperature. The reference data, including air temperature, sunshine hours, total cloud amount, and daily average relative humidity, is collected from an observation station at Nanhai, 1.5 kilometres from the observation site.

2.2 *Analysis methods*

The data is processed and plotted with the 2003 version of Microsoft Excel. The temperatures on different underlying surfaces are compared in multiple times with Least Significance Difference (LSD, with test statistics and observed significance levels) in Statistical Product and Service Solutions (SPSS) version 11.5. Analysis is then conducted for correlation of the surface temperature with air temperature, total cloud amount, daily mean relative humidity and sunshine hours, respectively. In the end, a linear fitting equation for underlying surface temperature and meteorological factors is achieved by stepwise regression analysis.

3 RESULTS AND ANALYSIS

3.1 *Annual variation of temperature on the four urban underlying surfaces*

3.1.1 DAILY AVERAGE TEMPERATURE

The annual variations of daily average temperatures on the four urban underlying surfaces are consistent with the change in air temperature. The results show a single peak with the maximum in July and the minimum in January (Figure 1a). The daily average temperatures on the four underlying surfaces are all higher than the air temperature. This phenomenon in the summer-half of the year is much more obvious than in the winter-half. In the summer-half of the year, the daily average temperature of asphalt is the highest (38.7℃), followed by that of cement (35.7℃), bare land and grass land in descending order. The difference of temperature between bare land and grass land, however, is not significant. The average temperature on the four underlying surfaces is higher than air temperature in the summer-half of the year, with the values of 10.5℃, 7.5℃, 6.2℃ and 5.9℃, respectively. In the winter-half of the year, the daily average temperature of asphalt is also the highest (24.7℃), followed by cement, bare land and grass land with insignificant differences between the three. The daily average temperature of asphalt, cement, bare land and grass is 6.2℃, 4.9℃, 4.6℃ and 4.3℃ higher than air temperature (Table 1), respectively.

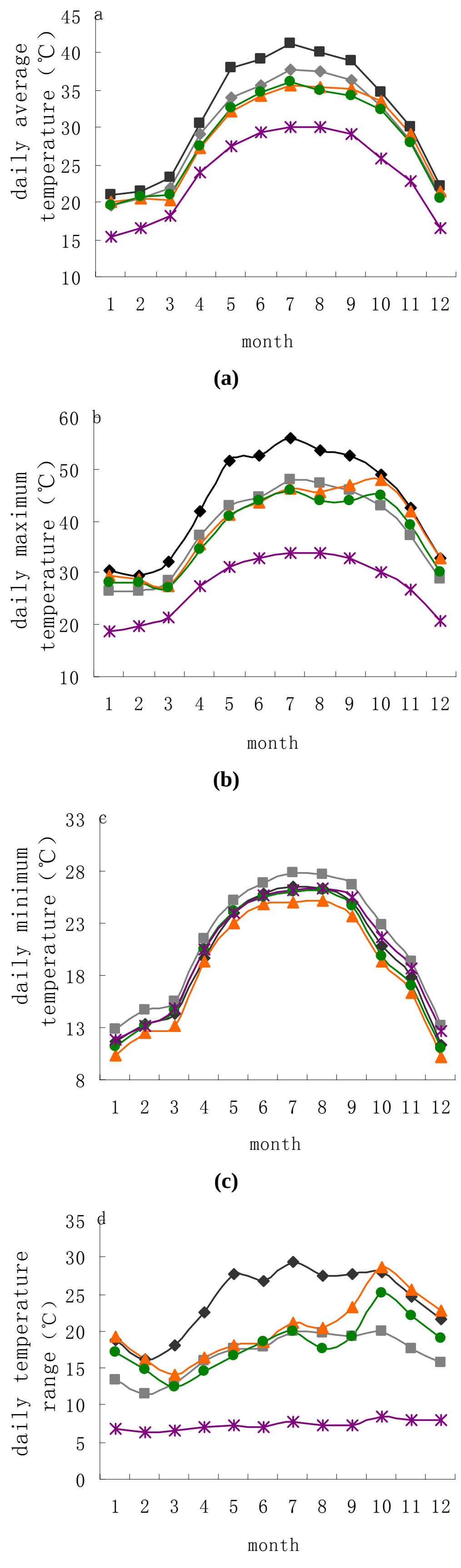

Figure 1. Daily average temperature (a), daily maximum temperature (b), daily minimum temperature (c) and daily temperature range (d) on the four kinds of urban underlying surfaces.

3.1.2 Daily maximum temperature

The annual variations of daily maximum temperatures on the four urban underlying surfaces are consistent with the changes in the daily maximum air temperature as well. The extreme temperatures of asphalt and cement are coincided with air temperature, accompanied by the highest and lowest values appearing in July and January, respectively. Meanwhile, the extreme values of bare land and grass land occur two months later (Figure 1b). Daily maximum temperatures on the four underlying surfaces are significantly higher than the daily maximum air temperature, especially in the summer-half of the year. In the summer-half of the year, the daily maximum temperature of asphalt is highest (34.9℃), followed by that of cement, bare land and grass land, respectively. The daily maximum temperature of asphalt, cement, bare land and grass are 12.5℃, 8.2℃, 10.2℃ and 8.8℃ higher than the air temperature, respectively (Table 1).

Note that the daily maximum temperatures on bare land and grass land are higher than that on the cement in the winter-half of the year, but the situation is reversed in the summer-half. A possible reason is that the relatively low humidity could decrease the heat capacity of bare land and grass land, leading to the increased temperature. At the same time, it is correlated with relative cloud amount which results in the enhanced radiation cooling of cement.

3.1.3 Daily minimum temperature

The annual variations of daily minimum temperatures on the four urban underlying surfaces are also consistent with the changes in the daily minimum air temperature. These annual variations of the four urban underlying surfaces exhibit a single peak with the highest and lowest in July and January, respectively (Figure 1c). In the summer-half of the year, the daily minimum temperature of cement is the highest (26.6℃), followed by that of asphalt，bare land and grass land, respectively. The minimum temperature of cement is 1.3℃ higher than air temperature, while that of asphalt, bare land and grass land is 0.2℃, 0.5℃, and 1.4℃ less than the air temperature, respectively. In the winter-half of the year, the daily minimum temperature of cement is also the highest (16.1℃), followed by that of asphalt and bare land, and grass land, respectively. Meanwhile, the minimum temperature of cement is 0.8℃ higher than air temperature, while that of asphalt, grass land and bare land is 0.6, 0.8, and 1.7℃ less than it, respectively (Table 1).

Table 1. Comparisons of the average surface temperatures between the four kinds of urban underlying surfaces and the air temperature in summer/winter-half of the year (℃).

Summer-half of the year (From May to October)					
	asphalt	cement	bare land	grass land	air temperature
daily average temperature	38.7a	35.7b	34.4c	34.1c	28.2d
daily maximum temperature	52.6a	45.3b	45.2b	43.9c	32.4d
daily minimum temperature	24.7b	26.2a	23.5d	24.4c	24.9b
daily change	27.9a	19.1c	21.7b	19.6c	7.5d
Winter-half of the year (From December to April)					
	asphalt	cement	bare land	grass land	air temperature
daily average temperature	24.7a	23.4b	23.1b	22.8b	18.5c
daily maximum temperature	34.9a	30.6c	32.6b	31.2c	22.4d
daily minimum temperature	14.7bc	16.1a	13.6d	14.5c	15.3b
daily change	20.3a	14.6d	19.1b	16.7c	7.2e

Note: The LSD method is used to make the comparison. The magnitude of the numerals decreases in the order of the letters a, b, c, and d, and the use of the same letter within a row indicates insignificant difference ($P > 0.05$) among the numerals concerned.

3.1.4 Daily temperature range

Daily temperature ranges of the four kinds of underlying surfaces are all more evident than that of air temperature, and they are more significant in the summer-half of the year than that in the winter-half. At the same time, the daily range of air temperature shows little fluctuation all the year round. Temperature variations of bare land and grass land are similar, with the highest in July and the lowest in February. The annual variation of bare land is consistent with that of grass land, reaching the maximum in October. The peak and valley of daily temperature range for the two underlying surfaces are 1 month later than that of asphalt but 3 months later than that of cement. In the summer-half of the year, the daily range of asphalt temperature is largest (27.9℃), while that of the grass land takes the second place, followed by those of grass land and cement (there is no significant difference between grass and cement). The daily range of temperature for asphalt, bare land, grass land and cement is 20.4℃, 14.2℃, 12.1℃, 11.6℃ above that of air temperature, respectively. In the winter-half of the year, moreover, the daily range of asphalt temperature is the largest (20.3℃) as well, bare land takes the second place, and grass land and cement (there is no significant difference between grass and cement) are the smallest. Besides, the daily range of temperature over asphalt, bare land, grass land and cement is 13.1℃, 11.9℃, 9.5 ℃, 7.4℃ above that of the air temperature, respectively (Table 1).

In a word, the daily average temperatures of the four kinds of underlying surfaces are higher in the summer-half of the year than that in the winter-half. Note that the asphalt and cement exhibit similar thermal absorption and dissipation characteristics, but the daily range of asphalt temperature is much more obvious than that of the other three kinds of underlying surfaces. The reasons may be as follows. (1) With deeper color and smaller albedo, asphalt can absorb more energy under the same condition. (2) The specific heat of asphalt is smaller than that of cement, but equal to that of bare land. (3) The thermal radiation and dissipation are relatively stronger during the night, causing the daily minimum temperature to be lower than that of cement. Though both cement and asphalt are impervious underlying surfaces, both the color and albedo of cement are relatively lighter and larger, making it absorb less solar radiation. Furthermore, the specific thermal capacity of asphalt is relatively large, thereby its daily average and maximum temperature are lower but daily minimum temperature is higher than that of asphalt. As impervious underlying surfaces, both bare land and grass land are easily influenced by soil humidity and their temperature characteristics tend to be identical. But as the grass land is covered by sward, its good heat preservation favors less daily change in temperature compared with that of bare land.

3.2 *Correlation between the temperature on different surfaces and meteorological factors*

Except for the intrinsic physical properties the cloud amount, sunshine hours and relative humidity can also influence the temperatures on different underlying surfaces. The correlation analysis (Table 2) shows that the sunshine hours are in significant positive correlation with the daily average, maximum, and minimum temperature.

Cloud amount is in significant negative correlation with the daily maximum temperature, but positively correlated with the daily minimum temperature. It implies that clouds prevent the temperature from rising up by stemming solar radiation in the day but slowdown its decreasing trend via increasing downward atmospheric radiation at night. Due to comprehensive influence, cloud amount is in significant negative correlation with daily average temperature, appearing as a hypothermal effect on the land surface.

Table 2. Correlation coefficients between the four kinds of underlying surfaces and meteorological factors (*r*).

		T(*a*)	*Ra*	*ND*	*RH*
daily average temperature	*T*(*A*)	0.967**	0.467**	–0.222**	0.053
	T(*C*)	0.978**	0.426**	–0.190**	0.085*
	T(*B*)	0.970**	0.421**	–0.204**	0.082*
	T(*G*)	0.978**	0.351**	–0.115**	0.165**
daily maximum temperature	$T(A)_{max}$	0.910**	0.602**	–0.343**	–0.080*
	$T(C)_{max}$	0.934**	0.573**	–0.324**	–0.063
	$T(B)_{max}$	0.847**	0.621**	–0.452**	–0.208**
	$T(G)_{max}$	0.864**	0.555**	–0.355**	–0.111**
daily minimum temperature	$T(A)_{min}$	0.982**	0.143**	0.077*	0.320**
	$T(C)_{min}$	0.982**	0.182**	0.031	0.285**
	$T(B)_{min}$	0.975**	0.105**	0.117**	0.369**
	$T(G)_{min}$	0.968**	0.105**	0.117**	0.372**

Note: ** is the significance level of 0.01 and * that of 0.05. T(A), T(C), T(B) and T(G) stand for the temperatures for asphalt, cement, bare land and grass land, respectively. For the subscripts, max is the daily maximum temperature and min is the daily minimum temperature. T(ɑ) is the air temperature (℃), *Rɑ* the hours of sunshine, *RH* the daily mean relative humidity (%), and *ND* the cloud amount. The size of the sample is 730.

Daily average relative humidity is positively correlated with the daily maximum temperature of the four kinds of surfaces but negatively correlated with the daily minimum temperature. The result demonstrates that although high water vapor content is not conducive to the rising surface temperature by reducing solar radiation in the daylight, it could increase the surface temperature by enhancing downward atmospheric radiation. Relative humidity is positively correlated with daily average temperature, which is contrary to the cloud amount. The relationship between maximum and minimum temperature on the permeable underlying surfaces (bare land and grass land) is closer than that on the impermeable underlying surfaces (asphalt and cement). It is revealed that the permeable underlying surfaces are easily influenced by cloud amount and relative humidity.

3.3 *Fitting equations of temperature on different underlying surfaces*

Based on conventional observations, fitting equations of surface temperature can help conduct urban environmental evaluation, disaster monitoring service, etc. The fitting equations (Table 3) of temperature on different underlying surfaces, determined with several meteorological factors, are established by stepwise regression analysis. The results indicate that the influence of sunshine hours, cloud amount, and daily average relative humidity on the temperature on the four kinds of underlying surfaces can sometimes be insignificant (below the confidence level *P*=0.01).

4 DISCUSSION AND CONCLUSIONS

The land surface temperature will increase by absorbing solar shortwave radiation and decrease by releasing sensible heating and longwave radiation. Different kinds of underlying surfaces exhibit distinct characteristics and produce different temperature changes. The higher (lower) surface temperature on the underlying surfaces can increase (decrease) the air temperature. Results demonstrate that the daily average and maximum temperature on the four kinds of underlying surfaces are higher than that of air temperature. Furthermore, they are higher in the summer-half of the year than that in the winter-half. It is shown that typical underlying surfaces can heat up the air with asphalt having the strongest heating effect of all, followed in turn by cement, bare land and grass land. Therefore, the urban underlying surface influences the regional climate by land-air interaction. In China, most of the materials used in building urban roads and buildings are asphalt and cement. The albedo of these impervious underlying surfaces is relatively low with small heat capacities, which do contribute to urban heat environment[17, 18]. This will amplify the differences of surface temperature between urban and rural areas and aggravate the effect of urban heat island[19-21].

(1) The monthly variations of daily average, maximum and minimum and daily range of surface temperature on the four urban underlying surfaces are consistent with the changes in air temperature. The difference of temperature is much more prominent in the summer-half of the year (from May to October) than in the winter-half (from December to April). The daily average and maximum temperature of asphalt, cement, bare land and grass land are higher than air temperature due to the atmospheric heating in the daytime, and the heating effect is the most with asphalt, followed by cement, bare land and grass land, respectively. The daily ranges of temperature in the four kinds of typical urban underlying surfaces are all higher than the air temperature all the year round, with that of asphalt the highest in the summer-half of the year and bare land the highest in the winter-half.

Table 3. Fitting equations for underlying surface temperature and air temperature.

		Linear **regression** equation	R^2	*P*
Summer-half of the year	average temperature	$T(A)=1.231T(a)+0.406Ra-5.130RH+0.087ND+0.145$	0.858	0.000
		$T(C)=1.214T(a)+0.208Ra-4.574RH+0.615$	0.955	0.000
		$T(B)=1.106T(a)-7.348RH-0.128ND+5.009$	0.820	0.000
		$T(G)=0.940T(a)+0.115Ra+3.169$	0.823	0.000
	maximum temperature	$T(A)max=1.755T(a)max+1.251Ra+0.391ND-12.882$	0.745	0.000
		$T(C)max=1.572T(a)max+0.684Ra-8.109RH+0.250\mathrm{ND}-4.850$	0.799	0.000
		$T(B)max=1.420T(a)max+0.061Ra-29.527RH-0.292ND+22.276$	0.671	0.000
		$T(G)max=1.101T(a)max+0.449Ra-12.247RH+14.966$	0.492	0.000
	minimum temperature	$T(A)min=1.019\mathrm{T(a)}min+0.133ND-1.493$	0.889	0.000
		$T(C)min=0.984T(a)min+1.707$	0.850	0.000
		$T(B)min=0.922T(a)mim+5.045RH+0.106ND-3.788$	0.899	0.000
		$T(G)min=0.976T(a)min+6.903RH+0.064ND-5.354$	0.851	0.000
Winter-half of the year	average temperature	$T(A)=1.091T(a)+0.321Ra-3.801RH+0.124ND+2.715$	0.955	0.000
		$T(C)=1.044T(a)+0.197Ra-3.249RH+0.109ND+2.972$	0.955	0.000
		$T(B)=1.013T(a)+0.261Ra-2.106RH+0.139ND+0.820$	0.936	0.000
		$T(G)=0.883T(a)+0.114Ra-1.240RH+0.154ND+3.338$	0.931	0.000
	maximum temperature	$T(A)max=1.528T(a)max+0.957Ra-12.363RH+0.261ND+4.793$	0.852	0.000
		$T(C)max=1.320T(a)max+0.568Ra-9.808RH+0.225ND+4.715$	0.889	0.000
		$T(B)max=1.401T(a)max+0.667Ra-13.312RH+8.763$	0.834	0.000
		$T(G)max=1.279T(a)max+0.384Ra-11.407RH+9.415$	0.770	0.000
	minimum temperature	$T(A)min=0.949T(a)min-0.129Ra+0.126ND-0.415$	0.948	0.000
		$T(C)min=0.976T(a)min+0.140ND+0.257$	0.939	0.000
		$T(B)min=0.935T(a)min+2.246RH+0.238ND-3.922$	0.939	0.000
		$T(G)min=0,894T(a)min+2.306RH+0.227ND-2.382$	0.923	0.000

(2) The relationship between meteorological factors, such as cloud amount, daily average relative humidity, sunshine hours and the temperatures on the four kinds of underlying surfaces are all significant. Generally, the surface temperature will be decreased by the clouds but increased by the relative humidity. Permeable underlying surfaces are easily affected by both the cloud amount and the daily average relative humidity, which are meteorological factors related with water vapor.

(3) Regression fitting equations about the temperature parameters of the four kinds of underlying surfaces, including daily average, maximum and minimum temperature, sunshine hours, daily relative humidity and cloud amount, are established. And the temperatures of asphalt, cement, bare land and grass land can be obtained according to the equations. Thus the efficiency of meteorological service can be improved.

In this paper, the temporal distribution of temperature for the underlying surfaces of asphalt, cement, bare land and grass land are analyzed. Spatial distribution is not discussed. Therefore, it will be examined in future based on the database from 86 weather stations of Guangdong.

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