ISSN 1024-8560, Atmospheric and Oceanic Optics, 2015, Vol. 28, No. 4, pp. 312–317. © Pleiades Publishing, Ltd., 2015.
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Radiation Balance of Underlying Surface in Tomsk during 2004–2005

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Received January 23, 2015

Abstract—Radiation balance and its components are determined for Tomsk during 2004–2005. The radiation balance for Tomsk is shown to be positive for the most part of the year, and has negative values from November to January. The maxima are observed in June and equal 176 W/m^2 in 2004 and 167 W/m^2 in 2005. The minima are observed in December, with magnitudes of –26 W/ m^2 in 2004 and –41 W/ m^2 in 2005.

Keywords: city, radiation balance, effective radiation, total radiation, albedo

DOI: 10.1134/S1024856015040065

INTRODUCTION

The present-day city differs from its surroundings by the presence of a large number of buildings and structures, which can serve as additional heat suppliers to atmospheric air, thus raising the air temperature over urban territory. This phenomenon was called the "urban heat island" [1]. The temperature difference between the city center and outskirts may reach 12°C, depending on many factors [2]. The key factors responsible for changes in the thermal balance of the urban underlying surface, leading to heat island formation, include the direct heat emissions due to human economic activity, as well as changes in surface albedo and radiation balance due to an additional absorption of solar radiation by anthropogenic pollutants (gases and aerosol) [3].

The radiation balance of the underlying surface is the main component of the thermal balance. Taking into account human economic activity, the thermal balance equation for the underlying surface, which reflects the energy conservation law in the case of interaction of solar, atmospheric, and terrestrial radiation, can be written as [4]:

$$R + Q_F = Q_S + Q_H + Q_E + Q_T, \qquad (1)$$

where R is the radiation balance of the underlying surface; Q_F is the anthropogenic heat flux, Q_S is the heat flux between the underlying surface and underlying layers, Q_H is the turbulent heat flux between the underlying surface and the atmosphere, Q_E and Q_T are heat fluxes associated with water phase transformations, Q_E is the heat flux associated with evaporation and condensation, and Q_T is the heat flux associated with ice melting and water freezing.

The radiation balance, represented as the difference between incoming and outgoing radiation, may take either positive or negative values. When the difference between incoming and outgoing radiation is nonzero, heat fluxes to the atmosphere and soil may arise. Correspondingly, change in the microclimate and urban underlying surface type, altering the radiation balance, substantially influences urban heat fluxes.

Tomsk is located at midlatitudes (56° N) and, as such, has a pronounced continental climate and underlying surface typical for Russian cities. In the last 10–15 years, the city has markedly increased in area, accompanied by construction of many new buildings, as well as by substantial vehicle traffic intensification. Under these conditions, it seems urgent to understand the radiation balance of the city and its effect on the net thermal balance.

The radiation balance of the underlying surface R, defined as the difference between absorbed solar radiation and effective radiation of the underlying surface [5], can be directly measured with an actinometric radiation balance gauge, although it is useless under certain meteorological conditions and, as such, is difficult to use for long-term stationary measurements [6].

1. METHOD FOR CALCULATING THE RADIATION BALANCE COMPONENTS

The radiation balance of the underlying surface is calculated using the following formula [1, 6]:

$$R = Q(1 - A) - B_n^*, \qquad (2)$$

where $Q = I + i$ is the downward solar radiation, I and i are the direct and atmosphere-scattered solar radia-

Annually average values of meteorological variables during 2004 and 2005 and their 11-year (1995–2005) averages

Period	t, °C	Rh, %	V, m/s	P, mm Hg	Q, W/m^2	s, g/kg
2004	2.16	74.63	2.12	747.58	129.02	4.33
2005	2.45	74.27	2.06	749.74	125.76	4.46
1995–2005	2.36	78.89	2.62	748.33	141.89	4.88

tion; A is the albedo of the underlying surface; and B_n^* is the effective radiation of the underlying surface.

It is noteworthy that the flux of downward shortwave solar radiation Q is measured with the help of pyranometers. The effective radiation of the underlying surface B_n^* is usually determined by applying approaches on the basis of measurements of the temperature of the air and underlying surface, water vapor pressure, and clouds [1].

The radiation balance in Tomsk was calculated using measured data available from the following sources. Values of total solar radiation were those from TOR station at the V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences [7, 8], which monitors atmospheric parameters every hour. The surface albedo was calculated on the basis of monthly measurements on board AN-30 Optik-E flying laboratory [9–11], designed to measure the pollutant amount in air and at the underlying surface. The meteorological parameters, i.e., air and soil temperature, air humidity, and total cloud fraction, were provided by the Tomsk Center for Hydrometeorology and Environmental Monitoring, a branch of the Federal State Budgetary Institution “Western Siberian Administration for Hydrometeorology and Environmental Monitoring” [12].

The radiation balance was studied for 2004 and 2005, the years with quite typical meteorological characteristics for the climate of Tomsk. Figure 1 shows the annual behavior of meteorological parameters in 2004–2005, as well as their 11-year (from 1995 to 2005) averages. The annual average values of meteorological parameters are presented in the table. We will show below that deviations of these parameters from their average values are manifested in changes of radiation balance components (2).

1.1. Downward Shortwave Radiation

In a classical case, the annual behavior of the total solar radiation is described by bell-shaped curve with a June maximum at midlatitudes (when sun elevation is maximal) and a December minimum. The dotted line with crosses in Fig. 2 shows values of the possible total radiation Q_0 for the latitude 55° [13]. Possible total radiation is considered to be the total radiation that could be incident at a given geographic point under the conditions of clear sky, location-specific atmospheric transparency, and typical surface albedo.

In fact, the total solar radiation depends strongly not only on sun elevation, but also on cloud amount and atmospheric transparency conditions, explaining why annual Q behavior deviates somewhat from classical representations. Estimates of these dependencies for Tomsk are presented in works [14, 15], and those for the territory of the Western Siberia are presented in [16].

As can be seen from Fig. 2, the annual behavior of the total solar radiation in Tomsk follows the classical bell-shaped curve. It is noteworthy that Q maxima are observed in June of both years and equal 297 W/m^2 in 2004 and 264 W/m^2 in 2005. Minimum is recorded in December and equals 17 W/m^2 in 2004 and 19 W/m^2 in 2005.

1.2. Albedo of Urban Underlying Surface

The surface albedo was calculated on the basis of measurements of solar radiation with the help of pyranometers on board the airborne laboratory [17]. Figure 3 shows the annual behavior of albedo of urban underlying surface for this period of time. It can be seen that A values are minimal in the snow-free period and equal 0.04–0.16. The wintertime albedo increases to 0.25–0.56, which corresponds to albedo of polluted snow according to the data of Budyko [18].

1.3. Effective Radiation of Urban Underlying Surface

The effective radiation of underlying surface B_n^* is determined by surface temperature and type, total cloud amount, as well as by atmospheric emissivity, which depends on the water vapor content. During clear-sky weather, the effective surface radiation represents the difference between intrinsic surface emission B_0 and surface-absorbed part of the atmospheric counter-radiation B_A [1]:

$$B^* = B_0 - \delta B_A, \tag{3}$$

where δ is the relative coefficient of absorption of longwave radiation by the underlying surface, which in this paper is assumed to be 0.98 in winter and 0.97 in summer [1].

The radiation flux of the underlying surface B_0 was determined according to the formula [1]:

$$B_0 = \delta\sigma T_0^4, \tag{4}$$

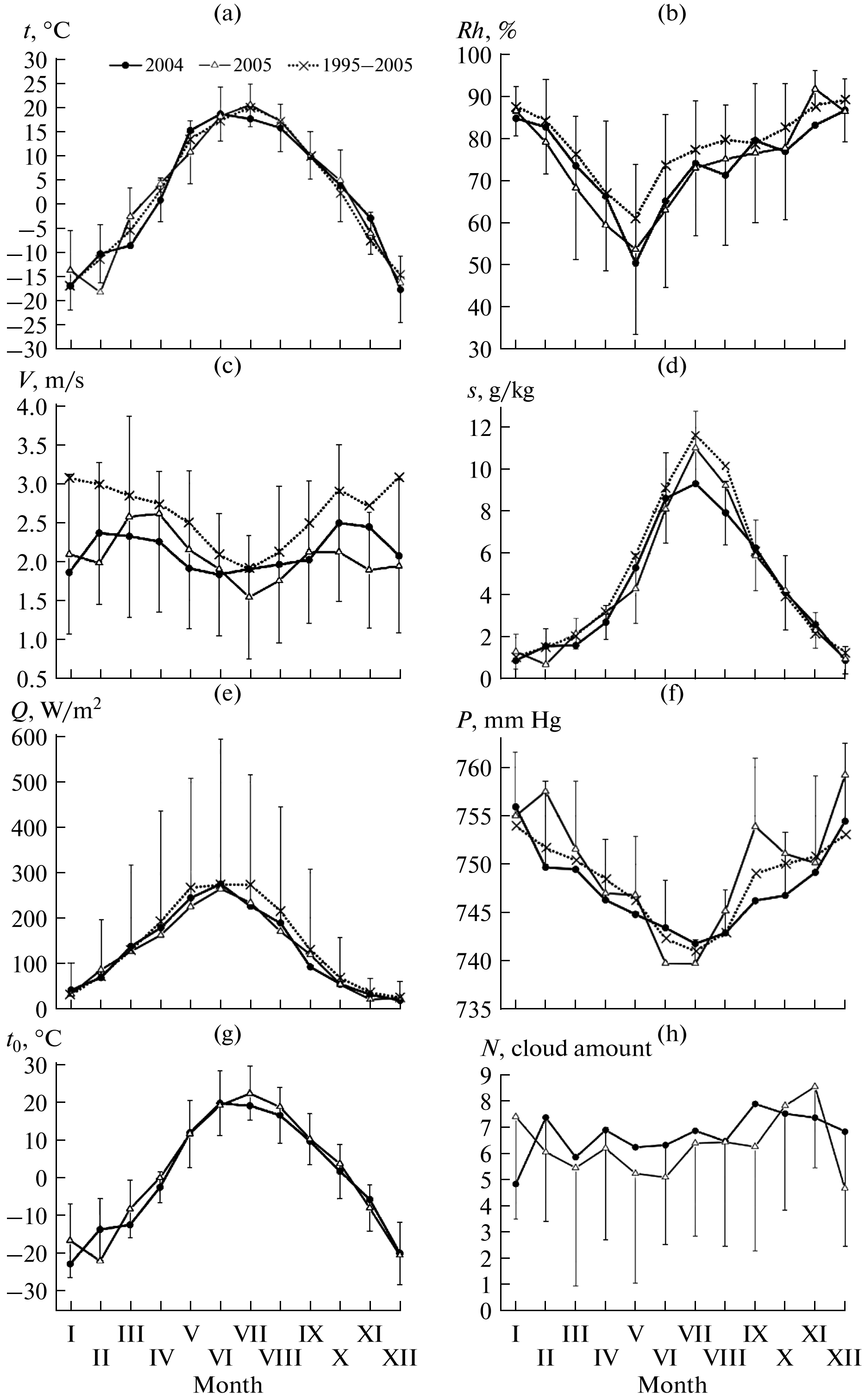

Fig. 1. Annual variations in meteorological parameters in Tomsk during 2004 and 2005 and their 11-year (1995–2005) averages: (a) air temperature; (b) relative air humidity; (c) wind speed; (d) specific air humidity; (e) total solar radiation; (f) atmospheric pressure; (g) soil surface temperature; and (h) total cloud amount.

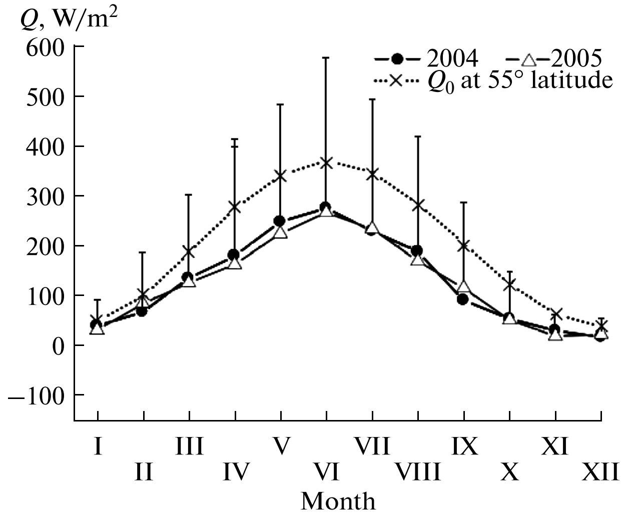

Fig. 2. Annual behavior of the total solar radiation in Tomsk during 2004 and 2005 and its maximally possible value at 55° latitude.

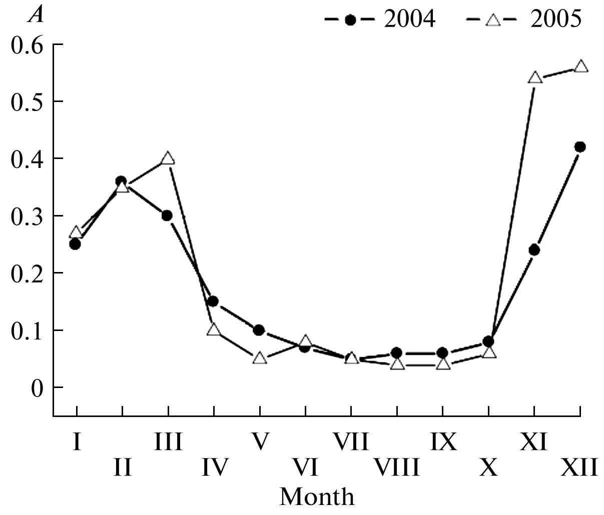

Fig. 3. Annual behavior of albedo of urban underlying surface.

where T_0 is the absolute temperature of the underlying surface; and $\sigma = 5.6696 \times 10^{-8}$ W/(m^2 K^4) is the Stefan–Boltzmann constant.

The Brunts's formula for clear-sky case [1], which was used to calculate the flux of atmospheric counter-radiation B_A, has the following form:

$$B_A = \sigma T^4(a_1 + b_1\sqrt{e}). \tag{5}$$

Here, T is the air temperature in K; the factor in parentheses, $(a_1 + b_1\sqrt{e})$, characterizes the emissivity of the atmosphere and depends on the water vapor content, $a_1 = 0.526$ and $b_1 = 0.065$ are the empirical coefficients; and e is the partial pressure of water vapor in hPa.

The atmospheric counter-radiation and, correspondingly, the effective radiation of the Earth's surface are known to be influenced strongly not only by the water vapor content, but also by the cloud amount and height [1]. The effective radiation of the underlying surface accounting for clouds, B_n^*, was calculated according to the formula

$$B_n^* = B^*[1 - cn], \tag{6}$$

where c is the mean value of empirical coefficient, equaling 0.77 for the cold half-year and 0.70 for the warm half-year; $n = N/10$ is the total cloud amount in fractions of unity (N is the total cloud amount in cloud fractions).

Figure 4 shows the annual behavior of effective radiation of the underlying surface. It can be seen that B_n^* values are maximal (minimal) in the warm (cold) period of the year. The flux of effective radiation at these latitudes usually peaks in June (Fig. 4, annual behavior of effective radiation of underlying surface in 2004).

The 2005 peak shifted toward May, primarily because the air temperature in May, 2005, was much lower than in 2004; while soil surface temperature was almost the same in these periods of time (see Figs. 1a and 1g). It should be noted that, according to (6), the variations in the monthly average B_n^* values are determined by cloud variations (see Fig. 1h). For instance, a second maximum occurred in September, 2005, because of the small cloud fraction: the total cloud amount in September, 2005, was 2 cloud fractions lower than that in September, 2004.

It can be noted that the calculated effective radiation of the underlying surface agrees well with results

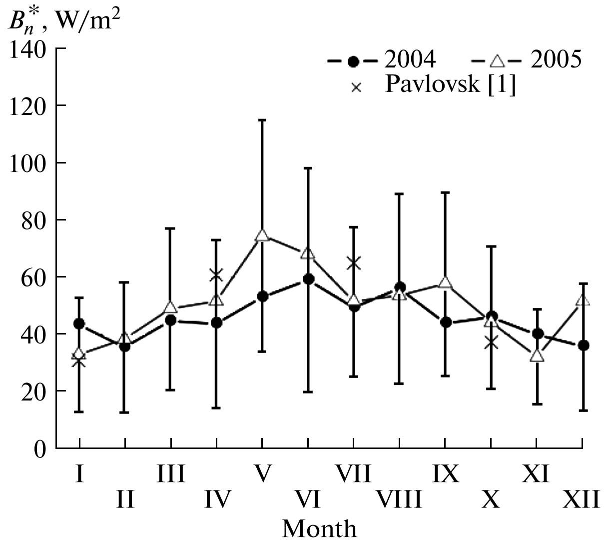

Fig. 4. Annual behavior of effective radiation of the underlying surface.

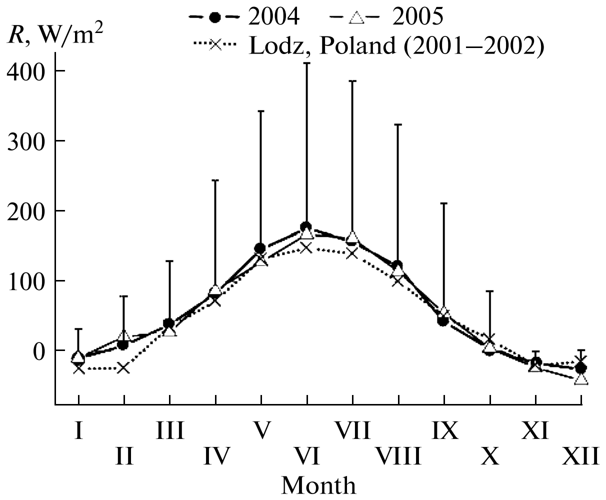

Fig. 5. Annual behavior of the radiation balance of the underlying surface in Tomsk and Lodz.

obtained by Matveev for Pavlovsk [1]. The lower (higher) values of effective radiation during the cold (warm) half-year in Pavlovsk can be explained by a more humid climate and more cloudy weather than in Tomsk.

2. RESULTS AND DISCUSSION

Figure 5 compares the annual behavior of the radiation balance of the urban underlying surface in Tomsk with that in Lodz, characteristics of which are closest to Tomsk out of those available in the literature [19].

It can be seen that the radiation balance R is positive during most of the year, and is negative in November, December, and January. Maxima are observed during June and equal 176 W/m^2 in 2004 and 167 W/m^2 in 2005, somewhat larger in magnitude than in Lodz. The R value was minimal in December, when the intrinsic radiation of the Earth's surface exceeds the incoming shortwave radiation due to low air temperatures and short daytime period. The minima were –26 W/m^2 in 2004 and –41 W/m^2 in 2005.

The annual behavior of the radiation balance of the underlying surface in Tomsk during 2004 is almost echoed in 2005. The largest interannual R differences are observed in May, primarily because of the marked air temperature difference between the years, which had been 5°C in May (see Fig. 1a). It should be noted that radiation balances of Tomsk and Lodz also do not differ significantly.

Figure 6 shows the diurnal behavior of the radiation balance of the underlying surface in Tomsk. It can be seen that R values are maximum at summer afternoon hours when peak values of the radiation balance reached 780 W/m^2 in both cities. At the same time, R assumes negative values at nighttime hours throughout the year. In the figure it can also be seen that a certain R increase at daytime hours in 2005 as compared to 2004 is compensated for by an R decrease at nighttime hours.

CONCLUSIONS

Study of the key component of thermal balance, i.e., the radiation balance of underlying surface in Tomsk during 2004–2005, showed that the annual behavior of this characteristic in Tomsk follows a smoothed bell-shaped curve with an amplitude of

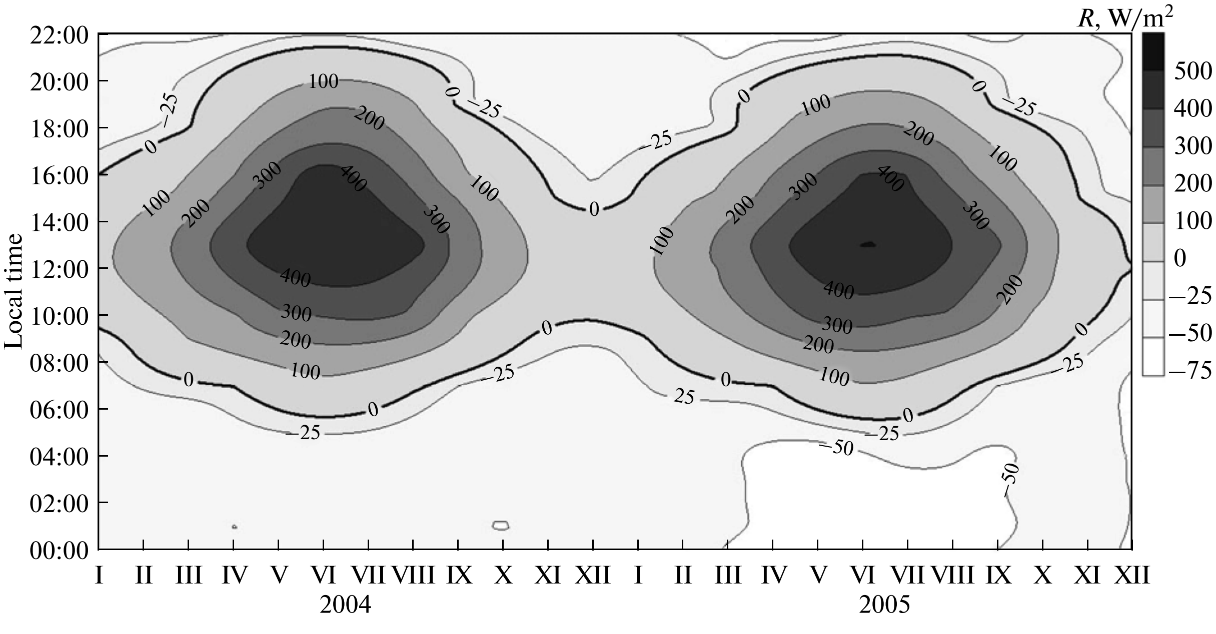

Fig. 6. Monthly average diurnal behavior of radiation balance of underlying surface in Tomsk.

about 200 W/m^2. The interannual deviation of monthly average values of the radiation balance may reach 15 W/m^2.

The radiation balance components have the following characteristics.

The maxima of the annual behavior of the total solar radiation Q in Tomsk are observed in June and equal 297 W/m^2 in 2004 and 264 W/m^2 in 2005. The minima take place in December and equal 17 W/m^2 in 2004 and 19 W/m^2 in 2005.

The minimal albedos are recorded in the snow-free period and equal 0.04–0.16. The albedo increases to 0.25–0.56 during winter.

In the annual behavior of the effective radiation of underlying surface, the B_n^* values are maximal (minimal) in the warm (cold) period of the year.

ACKNOWLEDGMENTS

This work was supported by the Presidium of Russian Academy of Sciences (Program no. 4); Department of Earth Sciences, Russian Academy of sciences (Program no. 5); Siberian Branch, Russian Academy of Sciences (Interdisciplinary Integration Project nos. 35, 70, and 131), Russian Foundation for Basic Research (grant nos. 14-05-00526 and 14-05-00590); Ministry of Education and Science (State contract no. 14.604.21.0100, identification no. RFMTFIBBB210290; and State contract no. 14.613.21.0013; identification no. RFMEFI61314X0013).

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Translated by O. Bazhenov