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Detailed Spatial Modeling of Temperature in Moscow

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Abstract—A computer complex is described developed for the detailed temperature forecasting in large megalopolises. It consists of the global and microclimatic models implementing the modeling of the thermal regime within Moscow. To increase the modeling quality, an improved technique is proposed of computation of temperature characteristics within the urban canyon. A spatial resolution of output modeling data reaches 500 m. A comparison with the station data demonstrates that the accuracy of air temperature simulation in Moscow and in its nearest vicinities is quite satisfactory.

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1. INTRODUCTION

Modeling is a recognized tool of analysis and forecast of the climate. However, an important shortcoming of climate models restricting significantly the range of problems which can be solved using them is their low spatial resolution (the size of one cell of the atmosphere general circulation models (AGCM) amounts to tens of kilometers) that does not enable to use directly their data for the diagnosis of climatic differences under conditions of the complex underlying surface. The resolution of mesoscale models is considerably higher (kilometers), however, it is not sufficient, for example, for the microclimatic regime description. The urbanized territories are the typical examples of such mosaic structure: it is created by the complex configuration of streets, industrial zones, rivers, ponds, and woodland park areas [6, 16, 18].

One of the approaches to the climate forecast issue at the scales of hundreds of meters is the microscopization (or downscaling) algorithm, i.e., the algorithm of the conversion of model data of low resolution to the fine grid realized in one way or another. The present paper deals with the development of such algorithm and its practical implementation within the large megalopolis (by the example of Moscow). The authors consider that it is reasonable to solve the problem at the horizontal resolution of about 500 m. On the one hand, it ensures a good information detail. On the other hand, it is not required yet to consider the certain buildings, yards, and streets as analysis objects at this scale. Such approaches are feasible (see [9, 10, 15]), however, the practical realization is complicated by a number of unsolved problems. First, this is the absence of reliable theoretical approaches to the explicit description of turbulent motions at the scales of the order of meters [6, 9]. Second, an unachievable level of informational support is needed from the point of view of parameters and initial data needed for modeling. Third, the problem is extremely complicated that results, in particular, in the serious increase in the time of computations. Thus, the useful effect from the scale enlargement is hardly feasible.

In the present paper, the model is developed being able to simulate the processes of heat exchange under conditions of the urban landscape similar to the real ones. After the description of the model complex structure (section 2), the approaches to the description of heat exchange processes in various types of urban landscape and the heat exchange between them are given in section 3. In section 4, the technique of temperature field modeling within Moscow is considered and the results are represented in section 5.

2. MODEL COMLEX DESCRIPTION

The structure of the model complex is the following. The climatic regime is simulated within the frameworks of the atmosphere general circulation model or regional model. The data belonging to the corresponding grid point come to the microclimatic model in which the AGCM signal modification occurs, i.e, the recalculation for the cells of the fine grid. This technique was repeatedly used before when carrying out the detailing procedure for different problems [2–5, 8]. In the present paper, the size of microclimatic

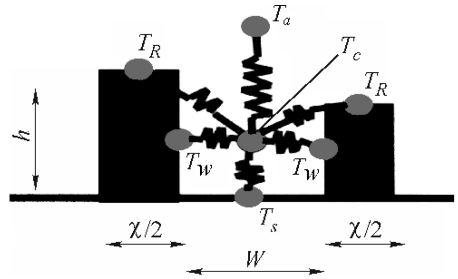

Fig. 1. Canyon characteristics and the heat transport scheme between its different blocks. The designations are given in the text.

Morphometric and physical characteristics of two canyon types

Cell type	City building	
	standard	dense and high-rise
Height h, m	30	60
Street width W, m	20	10
Building width χ, m	10	10
Albedo of the street, walls, and roofs (α_s, α_w, α_R)	0.1	0.1
Heat capacity of streets, walls, and roofs (C_s, C_w, C_R), J/(m^3 K)	2010000	2010000
Roughness parameter, m	0.5	0.5
Dimensionless parameter		
$\eta = h/(W + \chi)$	0.7	3.0
$\xi = \chi/(\chi + W)$	0.5	0.3

cells is 500 × 500 m. The time scale of output data is one day. On the one hand, the use of average daily values provides the user with rather important information, on the other hand, it enables to avoid the complex description of the daily dynamics of urban boundary layer [6].

The analysis of the surface structure features taking account of the data of Moscow Committee on Architecture and Town Building enabled to mark out six types of underlying surface: asphalt surfaces (large squares and airport airfields); urban parks, meadows, forest tracts, agricultural fields; water surfaces (the Moskva River and reservoirs); industrial zones (garage areas, waste plots of land, and dumps); areas with the standard building; areas with dense and high-rise building.

3. DESCRIPTION OF HEAT EXCHANGE PROCESSES IN VARIOUS TYPES OF URBAN LANDSCAPE

The variety of urban active layer features can be described using the urban canyon conception (so-called TEB scheme [16]). This is a simplified geometrical figure of the street in profile having two sides (house walls) and the bottom (the street itself). Practically in all models of urban boundary layer [12, 13, 17], the urban canyon is one of the types of underlying surface and in some investigations, the whole city is considered in the simplified way as the single canyon oriented in the certain direction. For the cities having a complex structure, a simplified scheme of heat balance computation which does not depend on the spatial orientation of the canyon was proposed in [13]. For Moscow, this approach seems to be promising. The scheme of such canyon with the enumeration of structural characteristics is presented in Fig. 1, and the parameters are given in the table.

Let us give the designations of the principal parameters and variables used in the paper:

Temperature of the		
air at the lower σ-level of the model, K	–	T_a
surface of the Earth or street, K	–	T_s
air at 2-m level, K	–	T_c
house wall surface in the canyon, K	–	T_w
roof surface, K	–	T_R
Heat flux near the surface, W/m^2		
sensible	–	H_s
latent	–	LE_s
Total solar radiation flux, W/m^2		
to the surface	–	Q_s
to the vertical surface of the wall	–	Q_w
to the roof surface	–	Q_R
Back atmospheric radiation flux, W/m^2	–	E
Anthropogenic heat flux, W/m^2	–	Q
Wind speed module	–	$\lvert u_a \rvert$
Air density, kg/m^3	–	ρ
Air resistance coefficient (it is different for different parts of the surface layer)	–	C
Stefan–Boltzmann constant, W/(m K^4)	–	σ
Specific heat of vaporization of water	–	L
Number of seconds in the day, s	–	τ
Specific heat of air at constant pressure, J/(kg K)	–	c_p

The authors of the present paper having kept the term *canyon* which became traditional modified the traditional scheme [12] having included into consideration the additional heat fluxes from roofs in the horizontal direction (Fig. 1).

The main problem is to determine the air temperature within the canyon, between the houses at 2-m level (T_c). This variable is convenient, in particular, due to the fact that the results of computations can be verified by means of the comparison (where possible) with traditionally measured air temperature at meteorological stations. To compute T_c, an auxiliary temperature of roofs, surface (street), and walls of the buildings should be determined. For noncanyon cell types (see table), the scheme of temperature computation is simpler, the heat exchange in the vertical direction only is taken into account here (see [1]). The physical characteristics of noncanyon cells are the following:

Cell type	Asphalt	Park	Water	Industrial zone
Albedo	0.1	0.25	0.1	0.1
Heat capacity of the surface, J/(m^3 K)	2010000	700000	1816200	2000000
Roughness parameter, m	0.00002	0.3	0.0001	0.1
Presence of moisture flux from the surface	No	Yes	Yes	No

To describe the surface (street) temperature, the heat balance equation is used represented by the difference time scheme:

$$T_s^{k+1} = T_s^k + \frac{\tau}{C_s}\{Q_s(1-\alpha_s) + (\widetilde{E} - \sigma T_s^4) - H_s - LE_s\}^{k+1}. \tag{1}$$

Sensible and latent heat fluxes are described by the expressions (see [3])

$$H_s = -c_p\rho\lvert u_a\rvert C(T_s - T_a) = h_s(T_s - T_a), \tag{2}$$

$$LE_s \approx e_s(T_s - T_a). \tag{3}$$

As is known, the resistance coefficient depends in the complex manner on the surface properties and atmospheric stratification. In the present paper, when computing, the supposition was accepted that the atmospheric stratification is neutral at the daily mean scale of averaging. Within the city, the variable C may vary by more than an order depending on the surface type.

In formula (1), let us expand the Taylor function (T_s^4) and write the obtained expression in the special form taking account of the fact that the temperatures T_s, T_c, and T_a are similar to each other: $T_s^4 \approx T_a^4 +$

$+ 4T_a^3(T_s - T_c)$. As a result, the expression to determine the temporal variations of street surface temperature on the $(k + 1)$th time step is derived from (1):

$$T_s^{k+1} = T_c^{k+1} + \frac{T_s^k - T_c^{k+1} + \dfrac{\tau}{C_s}[Q_s(1-\alpha_s) + \widetilde{E} - \sigma T_a^4]}{1 + \dfrac{\tau}{C_s}[r + h_s + e_s]}, \quad (4)$$

where $r = 4\sigma T_a^3$. It is supposed that Q_s, $\widetilde{E}$, T_a, and $|\vec{u}|$ are available from the AGCM data.

In a similar way, the expression for the roof surface temperature is obtained where the heat losses for evaporation are not taken into account and other parameters are used (another albedo, etc.). The expression of the same type is obtained for the wall temperature in the urban canyon, however, for the simplification, we will neglect here all types of the heat exchange besides the one carried out by sensible heat fluxes. To simplify the form of Eq. (4) and equations being analogous to it, let us introduce the designations used below:

$$\frac{1}{1 + \dfrac{\tau}{C_R}[h_R + 1]} \equiv l, \quad \frac{1}{1 + \dfrac{\tau}{C_s}[h_s + e_s + r]} \equiv p, \quad \frac{1}{1 + \dfrac{\tau}{C_w}[h_w]} \equiv n, \quad (5)$$

$$B_w \equiv nT_w^k + n\frac{\tau}{C_w}Q_w(1-\alpha_w), \quad (6)$$

$$B_s = pT_s^k + p\frac{\tau}{C_s}[Q_s(1-\alpha_s) + \widetilde{E} - \sigma T_a^4], \quad (7)$$

$$B_R = lT_R^k + l\frac{\tau}{C_R}[Q_R(1-\alpha_R) + \widetilde{E} - \sigma T_a^4]. \quad (8)$$

Let us write the heat balance equation of air layer between the houses. It is natural to consider its heat content variations to be small as compared with its analogous values for the walls, roofs, and surface. It is also logical to consider that the heat exchange is defined practically by the turbulent exchange processes only. Then, taking account of morphometric characteristics of the canyon, we obtain for any time moment

$$(1-\xi)(h_s + e_s)(T_s - T_c) + 2\eta h_w(T_w - T_c) + Q + \xi h_R(T_R - T_c) - (1-\xi)(h_a + e_a)(T_c - T_a) = 0. \quad (9)$$

And, correspondingly,

$$T_c = \frac{(1-\xi)(h_s + e_s)T_s + 2\eta h_w T_w + \xi h_R T_R + (1-\xi)(h_a + e_a) + Q}{(1-\xi)(h_s + e_s) + 2\eta h_w + \xi h_R + (1-\xi)(h_a + e_a)}. \quad (10)$$

Let us designate the denominator by ψ and in the numerator, the factors before the temperature values by a, b, and c, respectively. Let us designate two last summands as B_c.

Let us pass from Eqs. (4), (10), et al. to the system of four equations with four unknown quantities:

$$\begin{cases} \psi T_c - aT_s - bT_w - cT_R = B_c, \\ (p-1)T_c + T_s = B_s, \\ (n-1)T_c + T_w = B_w, \\ (l-1)T_c + T_R = B_R. \end{cases} \quad (11)$$

When the model cell is not of the canyon type, the scheme is appreciably simplified. In this case,

$$T_c = \frac{(h_a + e_a)T_a + (h_s + e_s)B_s + Q}{(h_s + e_s + h_a + e_a) + (h_s + e_s)(p-1)}. \quad (12)$$

To compute the thermal regime, it is necessary to have an algorithm of computation of resistance coefficient and wind speed module included into formulas for heat fluxes. These variables can be computed on the basis of Monin–Obukhov theory using the information at the AGCM σ-level being nearest to the surface. In the present paper oriented to the average daily values, to solve this problem, a neutral stratification approximation was used with the specified roughness parameter and displacement layer.

The above algorithm enables to compute the temperature at each microclimatic cell. The horizontal heat exchange is of great importance as well. As it was mentioned in Introduction, it is almost impossible to solve such problem by means of the modeling of air motions being similar to the real ones under conditions of complex city building. Therefore, the simplest way was chosen. The wind regime of the city is considered to be chaotic. Evidently, this is the supposition close to reality; at least, at the used division of the territory, there are no reasons to consider the air movement along and across the streets. To describe the heat exchange in this case, it is possible to use the flat diffusion model with constant temperature values specified at the boundaries of the area (Dirichlet condition) which are assumed to be equal to the values obtained for the AGCM grid cell. These computations were realized in the form of the application of the filter corresponding to this difference scheme to the obtained temperature field.

4. TECHNIQUE OF NUMERICAL EXPERIMENTS WITH THE CURRENT CLIMATE

As it was demonstrated in the previous section, the data on the air temperature and humidity, wind speed and total solar radiation flux at the upper level of microclimatic model are needed to compute the temperature fields within Moscow region. According to the authors' conception, this level coincides with the lower AGCM σ-level.

The numerical experiments were concentrated on the simulation of average climatic conditions of July for Moscow. The simulation of winter conditions is a different problem since the needed description of snow cover can be correct only if the snow removal efficiency is taken into account.

The input data needed for the microclimatic model were obtained using the global T42L15 model, the version of the operational model of the Hydrometcenter of Russia modified for carrying out climatic experiments. As well as in [4], the numerical experiments were organized in the manner enabling to obtain the ensemble of realizations. It was carried out in the following way. Each experiment with slightly differing initial conditions started on April 15 (from the data set for the concrete year) and the integration continued till August 1. The data for July only were kept for the analysis, i.e., first 76 days of each experiment during which the model adaptation to boundary conditions took place were rejected. The date of the start of numerical experiment was chosen for two reasons. First, 2.5-month integration enables the model to reach the regime of the dependence on the current boundary conditions of summer period. Second, by the middle of April, the seasonal snow cover almost melts in the most part of the Northern Hemisphere. Thus, an important source of modeling errors vanishes. Thirty such experiments were carried out in all. The statistical analysis (based on the use of the median criterion [7]) enabled to reveal that all numerical samples belong to one statistical totality. It enables to consider that the results of ensemble averaging characterize the model climate. The comparison of model temperatures averaged in such way (for the model area including Moscow) with climatic data for July (observational data at stations surrounding Moscow) demonstrated a good coincidence of the results (differences both in average values and standard deviations amounted to less than 0.5°C).

5. RESULTS

The detailing of the T42L15 AGCM data was carried out for the area of the size of 30×30 km including Moscow and the nearest vicinities. This territory was divided into 3600 elementary microclimatic cells which were referred to the certain type with specified properties. For each cell, the recalculation was carried out of the T42L15 AGCM temperature being single for the whole region (for each day of model July in 30 realizations, 930 days in all) to the value of T_c.

The main result of carried out experiments is that the simulated thermal regime of Moscow summer conditions is close to the real one. It is confirmed by the comparison of the model data with the measurement data from Moscow meteorological stations (Fig. 2). The discrepancy does not exceed tenths of degree; it indicates the correct choice of the modeling methodology and principal set of characteristics of underlying surface. Of course, the choice of parameters during the work was carried out in the way that enables to reach the best coincidence with the data of observational network. However, it was not the formal fitting of free parameters to ensure the error minimization. The choice was carried out for the variables having a clear physical sense and was conducted within the permissible limits only determined by the information error.

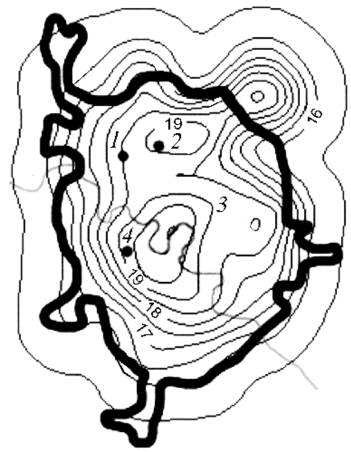

Fig. 2. The results of current Moscow climate modeling and the comparison with the measurement data at four Moscow meteorological stations (averaged for 1960–2000). (*1*) Russian State Agrarian University (18.2°C); (*2*) All-Russian Exhibition Center (18.5°C); (*3*) Balchug (19.5°C); (*4*) Moscow State University (18.4°C).

The model simulates realistically the contrast (3–4°C) between completely asphalted center of the city and the nearest vicinities of Moscow. The warmth centers confirmed by the real observations (at Balchug meteorological station) were clearly revealed in the center of Moscow. It should be noted that, according to the sense of the problem, these are the differences in average climatic values and in some situations, the anomalies can be expressed more sharply [3]. Average daily temperature gradients between different intracity areas do not exceed 1–2.5°C that corresponds to the data from other towns [11, 16].

6. CONCLUSIONS

The microclimatic model intended for the detailed modeling of air temperature within Moscow is described. The model simulates the realistic picture of spatial inhomogeneity of monthly mean temperature values for July under conditions of the present-day climate that enables to consider this technique satisfactory and to use it when solving the similar problems for other urban agglomerations and time samples.

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