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Application of a Weather Research and Forecasting model to study the urban heat island in Tomsk

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Abstract. The results of application of a Weather Research and Forecasting model (version 4.2) to study the heat island phenomenon in the city of Tomsk are considered. The results of numerical calculations were compared with measurements obtained using the instruments of Joint Use Center (JUC) Atmosphere and Tomsk Bogashevo Airport. On some days, the temperature difference between the city and the suburbs was shown to reach 1-3 °C.

1. Introduction

An urban heat island (UHI) is an increase in the air temperature in a city compared to the surrounding area. This phenomenon has long been established. The main indicator of UHI intensity is the temperature difference between the city and the surrounding areas. The manifestation of UHI depends on several factors: on the scale of the city, climatic conditions, season of the year, time of day. In large cities of the world, the temperature difference can 10-15 °C [1]. UHI affects the temperature and humidity structure and dynamics of the surface air layer, and, as a result, the quality of atmospheric air in the city. One of the reasons for the formation of UHI in large cities in Europe and the United States is the presence of a large number of dark surfaces (buildings, asphalt or concrete roads, etc.), high-rise buildings that provide multiple reflection and absorption of sunlight and block the wind that is cooling the city [2-4]. In the city of Tomsk, located in Western Siberia on the river bank, the main role in the formation of UHI is played by anthropogenic heat sources [5].

To simulate the heat island effect, the mesoscale Weather Research & Forecasting (WRF) [6] model can be (and is) used, which is one of the most universal and modern systems for modeling the atmosphere It is a free software product that is widely and successfully used for meteorological forecasting in scientific centers and meteorological services in various countries. The WRF model continues to evolve continuously, drawing on the experience of its application around the world, including for the study of UHI.

This research aims to use a WRF model [6] to study the heat island phenomenon for the conditions of the city of Tomsk.

2. Mathematical model

The dynamic ARW core (Advanced Research WRF) is based on non-hydrostatic Reynolds equations [6]. The ARW equations are formulated using the vertical coordinates of the hydrostatic pressure following the terrain relief denoted η and defined as:

$$\eta = \frac{p_h - p_{ht}}{\mu}, where\ \mu = p_{hs} - p_{ht},$$

where p_h is the hydrostatic component of pressure, and p_{hs} and p_{ht} refer to the values along the surface and upper boundaries, respectively. η changes from 1 on the surface to 0 on the upper boundary of the model region.

Since $\mu(x, y)$ represents the mass per unit area in a column in the model area at a point (x, y), the corresponding variables are defined as follows:

$$\vec{V} = \mu\vec{v} = (U, V, W), \Omega = \mu\dot{\eta}, \Theta = \mu\theta,$$

where $\vec{v} = (u, v, \omega)$ is the velocity vector in two horizontal and vertical directions, respectively, $\omega = \dot{\eta}$ is the "vertical" velocity, and θ is the potential air temperature. The defining ARW equations also include nonconservative variables $\phi = gz$ – geopotential, p – pressure, and $\alpha = \frac{1}{\rho}$ – inverse density.

Using the above variables, the Reynolds equations can be written as:

$$\partial_t U + (\nabla \cdot \vec{V}u) - \partial_x(p\phi_\eta) + \partial_\eta(p\phi_x) = F_U, \tag{1}$$

$$\partial_t V + (\nabla \cdot \vec{V}\upsilon) - \partial_y(p\phi_\eta) + \partial_\eta(p\phi_y) = F_V, \tag{2}$$

$$\partial_t W + (\nabla \cdot \vec{V}\omega) - g(\partial_\eta p - \mu) = F_W, \tag{3}$$

$$\partial_t \Theta + (\nabla \cdot \vec{V}\theta) = F_\Theta, \tag{4}$$

$$\partial_t \mu + (\nabla \cdot \vec{V}) = 0, \tag{5}$$

$$\partial_t \phi + \mu^{-1}[(\vec{V} \cdot \nabla\phi) - gW] = 0 \tag{6}$$

along with the diagnostic ratio for the inverse density:

$$\partial_\eta \phi = -\alpha\mu \tag{7}$$

and the equation of state:

$$p = p_0(R_d\theta/p_0\alpha)^\gamma. \tag{8}$$

In (1)-(8), the indices x, y and η denote the differentiation, $\nabla \cdot \vec{V}a = \partial_x(Ua) + \partial_y(Va) + \partial_\eta(\Omega a)$, and $\vec{V} \cdot \nabla a = U\partial_x a + V\partial_y a + \Omega\partial_\eta a$, where a represents the generalized variable, $\gamma = \frac{c_p}{c_v} = 1,4$ – the ratio of heat capacities for dry air, R_d – the gas constant for dry air, p_0 is the reference pressure (usually 10^5 Pa). The right-hand terms F_U, F_V, F_W and F_Θ are the source terms from model physics, turbulent mixing, spherical projections, and the rotation of the Earth [7].

The Global Forecast System (GFS) of the National Center for Environmental Prediction (NCEP) can be used as a "leading" model for obtaining initial data and boundary data for the forecast period [6].

3. Terms of using the WRF model
Based on the NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive (ds084.1) reanalysis data using the programs of the WRF (WPS) preprocessing system, files with the values of the initial and boundary meteorological characteristics and geodetic parameters on the mesh covering the study area were generated.

The dimensions of the simulation area are 450x450 km (the coordinates of the area center, 56.5° N, 85° E, coincide with the city center) with two nested subdomains with the dimensions of 150x150 and 50x50 km. The grid spacing for the regions is 9, 3, and 1 km, respectively. In the vertical direction, 51 levels were considered. The lower predicted level was at an altitude of 22 m.

When conducting the calculations, 5 sets of parameterizations of subgrid meteorological processes were used. The set of parameterizations took the following processes into account: microphysics of moisture, long-wave radiation, short-wave radiation, surface layer, land surface, planetary boundary layer, and urban surface [6].

To verify the correctness of the model calculations, the measurement data obtained from the instruments installed in the 3 observation points indicated in figure 1 were used together with the distributions of land use categories.

Point 1. "IAO", located on the laboratory building roof of the IAO SB RAS (the eastern outskirts of the city of Tomsk, Akademgorodok). The item is assigned the position "city" ("urbanized territory" – ultrasonic weather station (UWS) "IAO").

Point 2. The Territory of the Basic Experimental Complex ("BEC") IAO SB RAS. The nearest suburb of Tomsk (to the east-north-east). Natural landscape (a large clearing surrounded by woodlands) with several one-story buildings.

Point 3. Bogashevo Airport ("AIRPORT"), a suburb located 18 km southeast of the city center. Natural landscape with several office and residential buildings.
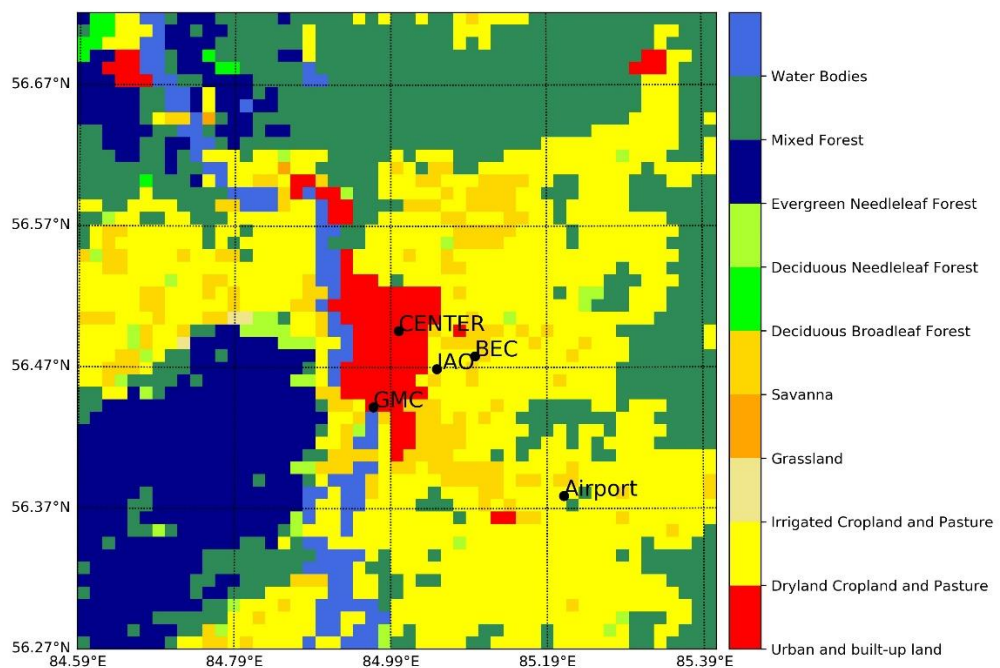

Figure 1. Map of the distribution of land use categories for the 50x50 km area.

In [7], to evaluate the effectiveness of calculations based on the model it is recommended to use the following statistical indicators:
Fractional Bias:

$$FB = \frac{(\bar{O} - \bar{P})}{0.5(\bar{O} + \bar{P})}, \bar{O} = \frac{1}{N}\sum_{i=1}^{N} O_i, \bar{P} = \frac{1}{N}\sum_{i=1}^{N} P_i, \tag{9}$$

Normal Mean Square Error:

$$NMSE = \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i P_i)}, \tag{10}$$

FAC2 index:

$$FAC2 = \frac{1}{N}\sum_{i=1}^{N} f_i, \quad f_i = \begin{cases} 1, for\ 0.5 \le \dfrac{P_i}{O_i} \le 2.0, \\ 0, else, \end{cases} \tag{11}$$

Coefficient hit rate:

$$q = \frac{1}{N}\sum_{i=1}^{N} L_i, \quad L_i = \begin{cases} 1, for\ \left|\dfrac{P_i - O_i}{O_i}\right| \le 0.25, \\ 0, else, \end{cases} \tag{12}$$

Correlation coefficient:

$$R = \frac{\sum_{i=1}^{N}[(O_i - \bar{O})(P_i - \bar{P})]}{[\sum_{i=1}^{N}(O_i - \bar{O})^2]^{1/2}[\sum_{i=1}^{N}(P_i - \bar{P})^2]^{1/2}}, \tag{13}$$

where P_i – forecast, O_i – observation, and the line at the top ($\bar{P}$) symbolise averaging over the data set, N – the number of points at which the data was compared.

The ideal model should have q and $FAC2 = 1.0$, and FB and $NMSE = 0.0$. In order for the computational model to be of satisfactory quality, the values of the statistical parameters described above should take the following values: $|FB| < 0.3$; $NMSE < 4$; $FAC2 \ge 0.5$; $q \ge 0.66$; $R > 0.5$.

4. Results

The calculations were made for nine winter (November-February) and seven summer (June-August) dates of 2015 recommended by meteorologists to study the heat island in Tomsk. The most striking cases of the heat island phenomenon were recorded in the summer period, on July 18, 22, and August 18. These days were characterized by clear hot weather with a calm, mainly east wind. The surface air temperature varied from 11 to 27 degrees Celsius.

Figure 2 shows the differences calculated by the WRF model of the surface air temperature between the center of Tomsk and Bogashevo Airport during the day and night for the selected summer dates. Figure 3 shows that a difference of more than 1 °C persisted throughout the day and night on July 18. At night (from 0 to 6 h), the maximum difference of 3 °C, when the temperature in the city was higher than that outside the city, was reached at 3 h, and in the evening (from 17 to 23 h), the maximum difference of 3 °C was at 22 h. On July 22, the difference of more than 1 °C persisted throughout the day and night. At night (from 0 to 6 h), the maximum difference of 2.5 °C was observed at 3 h, and in the evening (from 17 to 23 h), the maximum difference of 2.4 °C was at 20 h. On August 18, the maximum difference of 2.5 °C was recorded at 20 h.
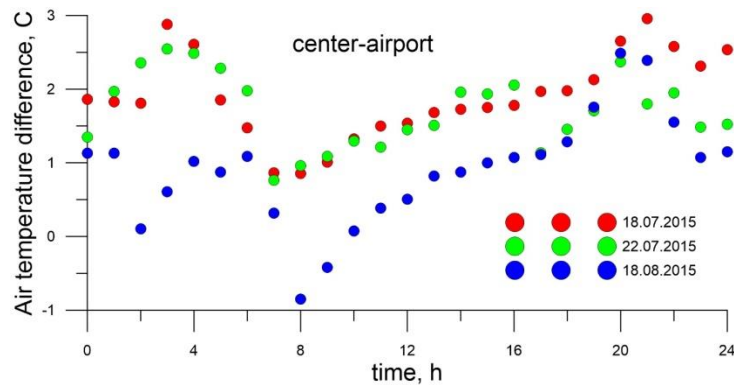
Figure 2. The difference in air temperature between the center of Tomsk and Bogashevo Airport.

In winter, the WRF model does not make a satisfactory forecast of the heat island. This can be seen, for example, in figure 3 (solid lines – model calculations; points and triangles – observations).
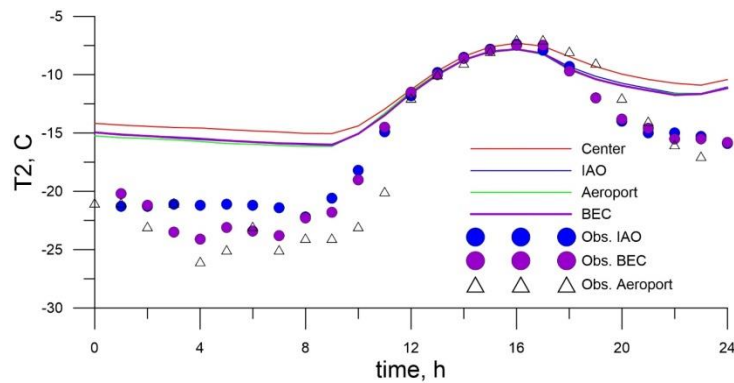

Figure 3. An example of an unsuccessful forecast of the heat island on February 21, 2015.

According to the observations, it is clear that from 2 to 11 h, the observations showed the heat island, but the WRF model did not predict it. Therefore, in the further use of the WRF model, special attention should be paid to the adequate representation of the distribution of land use categories for the study area, as well as to the correct choice and refinement of the parameterizations of heat and moisture exchange in the near-surface layer, covered with a significant layer of snow, and in the adjacent surface air layer.

Below are tables with estimates of the precision of the calculations (using formulas (9)-(13) based on the WRF model for summer dates.

Table 1. Indicators of the precision of the calculations of the surface air temperature for 18.07.2015.

Point	FB	NMSE	FAC2	q	R
Airport	0.049	0.004	1.0	1.0	0.989
BEC	0.022	0.005	1.0	1.0	0.948
IAO	0.047	0.003	1.0	1.0	0.98

Table 2. Indicators of the precision of the calculations of the surface air temperature for 22.07.2015.

Point	FB	NMSE	FAC2	q	R
Airport	0.037	0.004	1.0	1.0	0.983

| BEC | 0.044 | 0.005 | 1.0 | 1.0 | 0.967 |
| IAO | 0.055 | 0.006 | 1.0 | 1.0 | 0.974 |

Table 3. Indicators of the precision of the calculations of the surface air temperature for 18.08.2015.

Point	FB	NMSE	FAC2	q	R
Airport	-0.043	0.003	1.0	1.0	0.986
BEC	-	-	-	-	-
IAO	-0.029	0.003	1.0	1.0	0.99

Tables 1-3 show that on summer dates, satisfactory calculation results of the surface air temperature using the WRF model were obtained.

5. Conclusion

Thus, the surface air temperature was calculated using the WRF model (version 4.2) for the dates recommended by meteorologists.

To evaluate the precision of the calculations using the WRF model, the statistical parameters: Fractional Bias (FB), Normal Mean Square Error (NMSE), FAC2 index, Coefficient hit rate (q), and Correlation coefficient (R) were used.

It was found that the model makes accurate forecasts of the heat island in the summer period, and the forecasts are unsatisfactory in winter. This may be due to the fact that success in mesoscale modeling depends on the quality of the calculations of the "leading" GFS model and the accuracy of displaying urban land-use categories.

Acknowledgements

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