Application of the numerical model TSUNM3 to study the urban heat island and the intensity of precipitation over the Siberian city of Tomsk

AV Starchenko$^{1,2}$, L I Kizhner$^1$, S L Odintsov$^{2,1}$, E A Danilkin$^{1,2}$ and A A Bart$^1$

$^1$National Research Tomsk State University, Tomsk, 634050, Russia
$^2$V.E. Zuev Institute of Atmospheric Optics, Tomsk, 634055, Russia

E-mail: starch@math.tsu.ru

Abstract. The relevance of the study is associated with the development and validation of the TSUNM3 model for numerical local weather prediction. The results of its application over a limited territory of the Siberian region are presented. A study of the characteristics of an urban "heat island" and the analysis of the reliability of forecasting precipitation have been carried out. The calculation results are compared with observations of the atmospheric boundary layer parameters obtained with meteorological instruments of the Joint Use Center "Atmosphere" at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences.

1. Introduction

Nowadays, numerical models of high spatial resolution (with a horizontal resolution from several hundred meters to several kilometers) for short- and ultra-short-term weather forecasting and research, are being developed and improved, which make it possible to predict local mesoscale atmospheric phenomena for different regions of the globe [1].

In many countries, the most widespread model is the Weather Research and Forecasting (WRF) mesoscale model [2], which is widely used to solve many practical problems in the numerical study of weather and air quality. For the territory of the Russian Federation the COSMO-Ru model [3], created by international cooperation between the countries of Europe and Russia, is one of the main regional models currently used at the Hydrometeorological Center of Russia for forecasting weather elements. For the European territory of the Russian Federation, versions of the COSMO model with a grid step from 1.1 to 13.2 km have been implemented, and for the Siberian region, the COSMO-Ru14-Sib technology is used, where numerical forecasts are carried out along with forecasts using the ICON model in the German Meteorological Service. The recent COSMO model version reasonably reproduces “urban heat island” effect in high-resolution simulations for selected European cities, namely Turin, Naples and Moscow [4].

The aim of this work is to simulate numerically the atmospheric boundary layer parameters over a particular territory of the Siberian region as a result of the application of the mesoscale meteorological model TSUNM3 (Tomsk State University Nonhydrostatic Mesoscale Meteorology Model) [5], and to make a comparative analysis of the calculation results with observational data reached using the meteorological instruments of "Atmosphere".
2. TSUNM3 numerical model

The basic equations of the TSUNM3 atmospheric boundary layer model are the Reynolds-averaged Navier–Stokes equations [6] in the coordinate system associated with the Earth’s surface, using the following assumptions:

1. Mesoscale density variations are quasistationary. The Boussinesq approximation is used to represent the buoyancy force in the vertical velocity equation.
2. Molecular diffusion is assumed to be negligible in relation to turbulent exchange.
3. Phase transitions of moisture in the atmospheric boundary layer, short- and long-wave radiation heat transfer with an explicit representation in the atmosphere are taken into account.

The mathematical model of TSUNM3 includes the following equations:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho v)}{\partial x} + \frac{\partial (\rho w)}{\partial z} = 0
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \rho f v + \frac{\partial}{\partial y} \left( K_h \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_h \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial u}{\partial z} \right)
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} - \rho f u + \frac{\partial}{\partial x} \left( K_h \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_h \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial v}{\partial z} \right)
\]

\[
\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} - \rho g + \frac{\partial}{\partial x} \left( K_h \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial w}{\partial z} \right)
\]

\[
\rho \left( \frac{\partial \theta}{\partial t} + u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + w \frac{\partial \theta}{\partial z} \right) = \frac{\partial}{\partial x} \left( K_h \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_h \frac{\partial \theta}{\partial z} \right) + \frac{\theta}{c_p T} \left( Q_{\text{rad}} - \rho L_v \Phi \right)
\]

\[
p = \rho RT, \quad R = R_0 \left[ \frac{1 - q_v}{M_{\text{air}}} + \frac{q_v}{M_{H_2O}} \right]
\]

Here \( t \) is time, \( u, v, w \) are the longitudinal, transverse and vertical components of the averaged wind velocity vector in the direction of the Cartesian coordinates \( x, y, z \), respectively, \( \rho \) is the density, \( f \) is the Coriolis parameter, \( K_h \) is the horizontal diffusion coefficient, \( K_z \) is the momentum vertical diffusion coefficient, \( g \) is the gravity acceleration, \( p \) is the pressure, \( T \) is the absolute temperature, \( \theta \) is the potential temperature, \( \theta = T(p_0/p)^{k_c}, \) \( c_p \) is the heat capacity of air at constant pressure, \( p_0 = 101300 \, \text{N/m}^2, \) \( R_o \) is the universal gas constant, \( Q_{\text{rad}} \) is the heating (cooling) of the atmosphere due to long- and short-wave radiation heat fluxes propagating in a humid atmosphere, \( \rho L_v \Phi \) is the temperature change due to moisture phase transitions in the atmosphere, \( K_z^\text{v} \) is the vertical diffusion coefficient of heat and moisture, \( L_v \) is the heat of vaporization, \( M_{\text{air}} \) is the molar air mass, \( M_{H_2O} \) is the molar mass of water vapor, and \( q_v \) is the specific density of water vapor in the atmosphere.

To simulate the processes of phase transformations of water moisture in the atmosphere, we use the 6-class scheme of microphysics of moisture WSM6 [7], developed by Korean scientists Hong and Lim for the well-known mesoscale meteorological model WRF [2]. It considers six states of atmospheric moisture (water vapor, cloud water, rain water, ice particles, snow, graupel (hail)). The transport equation is used for each of the moisture state parameters in the atmosphere. For each transport equation, along with advective transport, various parameterizations of physical processes are included that lead to a change in the phase state of the considered forms of moisture state.

The basic equations of the WSM6 scheme are as follows:
\begin{eqnarray}
\rho \left( \frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + w \frac{\partial q}{\partial z} \right) + \frac{\partial (\rho V_j)}{\partial z} = \frac{\partial}{\partial x} \left( K_n \frac{\partial q_j}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_n \frac{\partial q_j}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_n \frac{\partial q_j}{\partial z} \right) + \rho \Phi_j \quad (7)
\end{eqnarray}

\begin{flushright}
j = V, C, R, S, I, G
\end{flushright}

Here \( q_V, q_C, q_R, q_S, q_I, q_G \) are mass concentrations of water vapor (Vapor), cloud moisture (Cloud), rainfall moisture (Rain), snow (Snow), ice crystals (Ice) and graupel (Graupel) in the atmosphere. \( V_j \) is the deposition rate of component \( j \) \((V_j = V_R = 0)\) [7]. For non-gaseous components, diffusion processes are not taken into account.

The source terms of the equations \( \Phi_j \) for \( j \) class are a mathematical notation for the parametrization of the atmospheric moisture transitions from one state to another. Some of the transitions are carried out at a positive air temperature, and some at a negative air temperature. The WSM6 scheme [7] considers such processes as capture of some components by others (accretion), melting of ice crystals, snow, graupel, evaporation/condensation of rain drops or cloud moisture, deposition/sublimation of graupel or snow, cloud-to-rain (ice crystals-to-snow or snow-to-graupel) autoconversion, evaporation/melting of snow, rain drop freezing with the formation of graupel, etc.

To complete the system of equations (1)-(7), a turbulence model, which consists of an equation for kinetic energy [8], and algebraic relations for determining the coefficients of turbulent diffusion are used:

\begin{equation}
\frac{\partial \rho k}{\partial t} + \rho u \frac{\partial \rho k}{\partial x} + \rho v \frac{\partial \rho k}{\partial y} + \rho w \frac{\partial \rho k}{\partial z} = \frac{\partial}{\partial x} \left( \rho \sigma_k \sqrt{k} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho \sigma_k \sqrt{k} \frac{\partial k}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho \sigma_k \sqrt{k} \frac{\partial k}{\partial z} \right) + P + B - \frac{\rho C_{\mu} k^{3/2}}{l} \quad (8)
\end{equation}

Here \( k \) is the kinetic energy of turbulent pulsations; \( l \) is the integral scale of turbulence; \( \sigma_k = 1.2 \) is the numerical coefficient; the term \( C_{\mu} k^{3/2}/l \) is responsible for the viscous dissipation of turbulence energy \((C_{\mu} = 0.189)\), and the \( P \) and \( B \) terms express the generation of turbulence due to shear stresses and the action of the buoyancy force:

\begin{align*}
P &= K^w \left[ 2 \left( \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right) + \left( \frac{\partial w}{\partial z} \right)^2 + \left( \frac{\partial u \partial v}{\partial y \partial x} + \frac{\partial v \partial w}{\partial z \partial y} + \frac{\partial w \partial u}{\partial z \partial x} \right)^2 + \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 \right] \\
B &= -K^h \frac{\partial}{\partial \theta} \left( \frac{\partial \theta}{\partial z} - \gamma_0 \right)
\end{align*}

where \( \gamma_0 = 0.00065 \text{ K/m} \).

The coefficients of vertical diffusion of the momentum and heat are calculated as [9]:

\begin{align*}
K^w &= \rho c^m \sqrt{kl} \quad K^h = \rho c^h \sqrt{kl}
\end{align*}

The horizontal diffusion coefficient is estimated using the Smagorinsky formula [10]:

\begin{align*}
K^h &= \alpha_{Sm} (\Delta x \Delta y) \left\{ \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right\}^{1/2}
\end{align*}

where \( \alpha_{Sm} \) is the coefficient depending on the choice of horizontal grid steps \( \Delta x \) and \( \Delta y \).

The TSUNM3 mesoscale model predicts the components of wind velocity, temperature and humidity in the boundary layer of the atmosphere at 50 vertical levels (up to \( H = 10000 \text{ m} \)) for an area of 200×200 km and enclosed in it 50×50 km (grid step 1 km with the center in the city of Tomsk) for 24 hours. The initialization of the model is carried out on the basis of the results of a numerical
forecast using the operational SL-AV global model [11] of the Hydrometeorological Center of the Russian Federation.

The boundary conditions for equations (1)-(7) have the following form:

\[ z = H: \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = \frac{\partial q}{\partial z} = \frac{\partial k}{\partial z} = 0, \quad w = 0, \quad \frac{\partial \theta}{\partial z} = \gamma_0 \quad (9) \]

\[ x = 0, x = L_x: \begin{cases} \frac{\partial \phi}{\partial t} + c_\phi \frac{\partial \phi}{\partial x} = \frac{\partial \phi_0}{\partial t} + c_b \frac{\partial \phi_0}{\partial x} + c_\phi \frac{\partial \phi_0}{\partial y}, \quad \phi = u, v, \theta, q_c \\ \frac{\partial w}{\partial x} = 0, \frac{\partial q_c}{\partial x} = 0, \frac{\partial k}{\partial x} = 0 \end{cases} \quad y = 0, y = L_y: \begin{cases} \frac{\partial \phi}{\partial t} + c_\phi \frac{\partial \phi}{\partial y} = \frac{\partial \phi_0}{\partial t} + c_b \frac{\partial \phi_0}{\partial y} + c_\phi \frac{\partial \phi_0}{\partial x}, \quad \phi = u, v, \theta, q_c \\ \frac{\partial w}{\partial y} = 0, \frac{\partial q_c}{\partial y} = 0, \frac{\partial k}{\partial y} = 0 \end{cases} \quad (10) \]

The index \(( \cdot )_0\) corresponds to the dynamic and thermodynamic parameters of the synoptic scale, \(c_\phi\) is the phase velocity. Boundary conditions of the form (10) are often called “radiation” type conditions [12]. The phase velocity \(c_\phi\) is calculated numerically from the spatial and temporal trends within the grid region near its boundaries.

Near the underlying surface, the conditions are set to correspond to the basic relations of the Monin-Obukhov similarity theory [13, 14].

When determining the temperature of the Earth's surface \(\theta_g\), the heat flux through the surface is used, due to radiation heating (cooling) and turbulent fluxes of heat and moisture on the surface; the change in temperature and moisture content of the lower soil layers is also taken into account (depth \(\approx 2\)m, the simulation period is several days).

The ISBA (Interaction Soil Biosphere Atmosphere) parameterization scheme developed by Noilhan and Planton [15] is used to simulate the processes of heat and moisture exchange between the lower level of the atmosphere, vegetation, and soil. This scheme takes into account changes in the thermal regime of the soil, moisture content in the soil, precipitation accumulating on vegetation, and aerodynamic transport processes in the surface layer of the atmosphere. The scheme uses a soil heat and moisture recovery model and an evaporation model.

When the effect of cloudiness is taken into account, Stephens’ assumption is used [16], according to which it is assumed that clear and cloudy areas of the sky can separately contribute to the total radiation balance. The short- and long-wave components of radiation are modified by cloudy areas according to empirical relationships that determine the degree of transmission and scattering of radiation depending on the content of condensed moisture in the atmosphere [17, 18].

When modeling the magnitude of anthropogenic heat flux from the surface of an urban area (land use category “urban development”), information from [19] was used. In [19], the most universal profile of changes in the normalized value of anthropogenic heat flow during the day is recommended, which is also used in the WRF modeling system [2]. As the maximum values of anthropogenic heat flow for the city of Tomsk (a city with a population of 0.5 million inhabitants from a region with a sharply continental climate), according to the recommendation [19], 25 W/m\(^2\) was chosen for the warm period of the year (from May 1 to October 1) and 90 W/m\(^2\) – for cold.

3. Numerical method
Before solving the system of equations by the method of grids, the coordinate transformation for this system was used:

\[ \xi = x, \quad \eta = y, \quad \sigma = H \frac{z - h(x, y)}{H - h(x, y)} \quad (11) \]
The approximation of the above-constructed differential problem with the performed transformation (11) is carried out on the basis of the finite volume method. For discretization, a grid that is uniform along the horizontal directions is used with a refinement of the grid planes when approaching the Earth’s surface. The values of the velocity components are determined at the edges of the finite volumes, and the scalar characteristics are determined at their centers. The approximation of the convective terms of the transport equations is performed using the monotonized linear upstream MLU Van Leer scheme [20]. For discretization in time, the explicit Adams-Bashforth method and the implicit Crank-Nicolson method of the second order of approximation are used:

\[
\Phi_{n}^{t+1} = \Phi_{n}^{t} + \Delta t \left( \frac{3}{2} L_{h} \left( \Phi_{n}^{t} \right) - \frac{1}{2} L_{h} \left( \Phi_{n}^{t-1} \right) \right) + \Delta t \left( \frac{1}{2} \Lambda_{h} \left( \Phi_{n+1}^{t} \right) + \frac{1}{2} \Lambda_{h} \left( \Phi_{n-1}^{t} \right) \right) + \Delta t \left( \frac{3}{2} S_{h} \left( \Phi_{n}^{t} \right) - \frac{1}{2} S_{h} \left( \Phi_{n}^{t-1} \right) \right)
\]

Here \( L_{h} \) is the finite-difference analogue of the convective-diffusion operator in equations (2)-(5), (7), (8) with the exception of vertical diffusion along the \( Oz \) axis, \( \Lambda_{h} \) is the difference analogue of the differential operator of vertical diffusion, \( S(\Phi) \) are the source terms of equations (2)-(5), (7), (8). Note that the chosen approximation method for convective-diffusion equations makes it possible to use a tridiagonal matrix algorithm along vertical grid lines in their numerical solution.

In the hydrodynamic part of the model, a predictor-corrector method was used to match the velocity and pressure fields. According to this method the explicit-implicit scheme (12) for the equations of motion (2)-(4) was performed the function of a predictor for the velocity components. The correction to the velocity field for the purpose of satisfying the grid analogue of the continuity equation (1) was carried out on the basis of the iterative solution of the discrete Poisson’s equation for the correction to the non-hydrostatic part of the pressure \( p_{n}^{t} = p_{h}^{t+1} - p_{h}^{t} \). In this paper, to solve the difference equation for the pressure correction \( p_{n}^{t} \), the linear Seidel method with red-black ordering of the computational grid nodes [21] is used. The parallel implementation of such a method shows the independence of the convergence rate of the iterative process on the number of used processor elements during calculations. It is important that such an implementation of the algorithm on a multiprocessor computer system wholly preserves the property of a sequential algorithm and scales well to any reasonable number of computational nodes.

**Figure 1.** Distribution of land-use categories (red for urban, green for forest, gray for low vegetation, blue for water) and surface elevations above sea level for the study area. The yellow circles mark the positions of observation points IAO, BEC and Aeroport.
4. Results and discussion
The developed mesoscale model was applied to the study of meteorological conditions over the city of Tomsk (85.0°E 56.5°N, center of the city) and Bogashevo airport (Aeroport, 85.21°E, 56.38°N) (Figure 1).

The results of calculations using the TSUNM3 model [5] were compared with measurements obtained using meteorological instruments (ultrasonic meteorological stations «Meteo-2», temperature profiler MTP-5, sodar «Volna-4M») of the Joint Use Center "Atmosphere" IAO SB RAS for various seasonal conditions [22]. Ultrasonic meteorological stations "Meteo-2" are installed at points IAO and BEC, and the temperature profiler MTP-5 at point IAO. Point IAO is located on the eastern border of the city, and point BEC is located to the east, in a suburban area surrounded by forest plantations. The airport is located 12 km southeast of the city (Figure 1).

The ability of the TSUNM3 model to predict precipitation in the Siberian region was estimated for several selected case studies in the period of 2016–2018 (11.07.2016, 24.11.2016, 27.06.2016, 5.08.2017, 6.08.2017, 25.01.2017, 29.12.2017, 2.05.2017, 8.05.2017, 21.05.2018), when intense precipitation was observed on the territory of Bogashevo airport and which was recorded by standard meteorological observations [23].

Figure 2. The predicted values of precipitation accumulated over 1 hour on November 25, 2016 and May 8, 2018 in the vicinity of the airport.

Figure 2 shows the precipitation calculated using the TSUNM3 model in the area of Bogashevo airport from November 25, 2016 and May 8, 2018. The figure shows that the first date (25.11.2016) is characterized by snowfall. Observations at the airport [23] indicate continuous snowfall during the day with an increase during the time intervals: 7:00-9:30, 17:00-18:30 (local time). In the second date (8.05.2018) until 10:30 meteorologists recorded snowfall [23], then until 17:00 only liquid precipitation was observed. After 17:00, light snow and rain were recorded. In general, the TSUNM3 model satisfactorily predicted the observed pattern of precipitation changes during the day for each selected period.

Table 1. Characteristics of the quality of precipitation forecast based on precipitation.

| №  | Characteristics                      | Rain forecast | Snow forecast | Overall precipitation forecast |
|----|--------------------------------------|---------------|---------------|--------------------------------|
| 1  | General accuracy $U$                 | 77            | 68            | 74                            |
| 2  | Accuracy of the forecast of precipitation events $U_\nu$ | 34            | 68            | 57                            |
| 3  | Forewarning of precipitation events $P_\nu$ | 59            | 98            | 87                            |
| 4  | Accuracy of the forecast of events without precipitation $U_\zeta$ | 92            | –             | 91                            |
| 5  | Forewarning of events without precipitation $P_\zeta$ | 80            | –             | 67                            |
| 6  | The Pearcy-Obukhov criterion $T$     | 39            | –             | 54                            |

The results of assessing the quality of the numerical forecast of precipitation based on precipitation for the selected case studies in the period 2016–2018, are given in Table 1. The last column represents
the characteristics for all precipitation events (rain, snow). The quality of numerical precipitation forecasts is established by their presence or absence and the amount of precipitation by comparing the calculated data on precipitation with actual observations. Assessing the precipitation forecast in fact, the following characteristics are calculated: the general accuracy $U$, the accuracy of the forecast of precipitation events $U_+$ and without precipitation events $U_-$, forewarning of precipitation events $P_+$ and without precipitation events $P_-$ (all values are calculated as %) and also the Pearcy-Obukhov quality criterion $T$. To obtain these characteristics, a contingency table is constructed showing the relationship between the number of forecast cases and the fact of precipitation. Assessing the quality of the precipitation forecast based on the fact of precipitation, hourly forecasts and actual precipitation data were used for the dates considered above.

Table 1 concludes the following:

- general accuracy for all types of precipitation according to the TSUNM3 model is 74%;
- for all precipitation, characteristics 1, 2, 4 and 6 correspond to the quality of modern mesoscale models;
- the forewarning of precipitation is higher, and the absence of precipitation is slightly lower than for the known models;
- general accuracy for rain is slightly higher than accuracy for snow;
- the TSUNM3 model better predicts the absence of rain, and its presence is better predicted from snow, which is possibly related to the peculiarities of the samples;
- the model accurately predicts the phase state of precipitation: there was rain given as snow only in one case in the forecast;
- out of 6 cases of hail, the model did not predict it.

Figure 3. Numerical and experimental values of surface temperature, wind velocity and direction for March 1, 2020 (left) and September 8, 2018 (right).
As for the estimation of the model for forecasting the amount of precipitation, due to the lack of actual hourly data on its amount, it is impossible to obtain numerical characteristics. However, it could be preliminarily stated that the model predicts "rain" and "heavy rain" for the corresponding hour in the amount of precipitation from 0.2 to 1.0 mm. In the case of snowfall based on "snow", the calculations by the TSUNM3 model give the amount of precipitation up to 1 mm/h, in the case of "heavy snow" precipitation, the model forecasts from 1 to 5 mm/h.

Also, the TSUNM3 numerical weather forecast model considered in this work was applied to study the "urban heat island" phenomenon in the city of Tomsk. Figure 3 below shows the results of calculations and observations for two selected dates: March 1, 2020 and September 8, 2018. The results of the numerical calculations are compared with the experimental data.

Figure 3 shows the hourly experimental and numerical results of calculations of the surface wind velocity, and wind direction and temperature for the selected day. The first date refers to the cold season, when the earth's surface is completely covered with a uniform layer of dry crumbly snow and the river is under a meter layer of ice. The meteorological situation in the area under consideration on March 1, 2020 was characterized by weak wind and cloudy weather conditions. The temperature during the night hours dropped to \(-10^\circ\text{C}\) to \(-12^\circ\text{C}\). During the daytime, positive values of air temperature were observed. Figure 3 shows that due to the prevailing quiet, cloudless dry weather, both calculations and observations (during most of the day) show a weak southeast wind, which changes slightly in velocity and direction during the day. Note that the wind velocity and direction also change insignificantly for the IAO and BEC points located in the city and outside the city.

As follows from the results of calculations and measurements, the lowest air temperature values near the surface on March 1, 2020 are observed at night. This fact occurred due to the cooling of the underlying snow surface in calm, clear weather. The increase in air temperature near the earth's surface during the day is associated with solar radiation. In this case, the "urban heat island" effect is observed - the values of the surface air temperature are lower outside the city than in the city. The temperature difference reaches, as follows from calculations and observations, several degrees. Due to the prevailing eastern transport, albeit weak, the area of higher urban temperatures shifts slightly to the west.

![Figure 3](image1)

**Figure 3.** Colored surface temperature maps (scale to the right in °C) and surface wind vector field calculated using the TSUNM3 model at 04:00 on March 1, 2020 and 04:00 on September 8, 2018, in the center of Tomsk. Area size in km.

The second date, September 8, 2018, is typical for the warm season. During this period, the thermal regime of the surface air was warmed significantly by the nearby Tom River, about 1 km wide, in the
city area. Therefore, the effect of a small anthropogenic heat flux is insignificant. In this case, the air temperature at the BEC point was predicted accurately, but in the IAO it turned out to be underestimated by about 2 °; the “urban heat island” did not appear in the calculations. In a warmer area along the river bed, according to calculations, convergence of air flows is observed.

Figure 4, to confirm the findings mentioned above, shows the isolines of the surface air temperature and the wind field calculated by the TSUNM3 model for 4 hours on March 1, 2020 and September 8, 2018. The figure shows that at night during the cold period of the year the "urban heat island" meteorological phenomenon manifests itself much more strongly, although a significant increase in temperature does not have a significant effect on the horizontal velocity of the surface wind.

5. Conclusion
The paper considers the mathematical formulation and numerical weather prediction in the Siberian region using the developed high-resolution mesoscale meteorological model TSUNM3. This model, as the "leading" global weather forecast model, provides calculations to the operational weather forecast model SL-AV of the Hydrometeorological Center.

The results of numerical forecasting of the meteorological parameters: temperature, wind velocity and direction, precipitation in different seasons are presented. The model was applied for pre-selected case studies characterized by intense precipitation in the form of rain, snow or graupel in the Tomsk region, as well as the experimentally established effect of an urban heat island.

The results were as follows. In general, the improved TSUNM3 model adequately simulates the time of precipitation and the intensity of precipitation, however, in some cases, the start and end times do not always coincide with observations, and the difference between predictions and observations can reach several hours. The phase state of precipitation is reliably displayed. More than 70% of precipitation cases are confirmed by numerical calculations. The model predicts the temperature and humidity characteristics satisfactorily. The quality of the precipitation forecast model is comparable to modern mesoscale models [3].

The capabilities of the model are shown to predict the state of the atmosphere over the city, including the “heat island” and its characteristics (intensity and horizontal dimensions, lifetime, air circulation).

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