Global meteorological forecast data and instrumental measurement application for simulation of mesoscale atmospheric boundary layer processes

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ABSTRACT

The accuracy of the results of numerical modeling of local atmospheric processes, in particular those in the ground layer, to a great extend depends on the input data characterizing the initial state of meteorological parameters within the area of research or their variation at the boundary. The paper considers a mesoscale model of atmospheric ground layer where medium-range weather prediction data calculated with the help of the global SL-AV model of the Hydrometcenter of the RF are applied as the initial and boundary conditions. Besides, the results of measurements carried out in the Institute of Monitoring of Climatic and Ecological Systems, SB RAS (IMCES) with the help of meteorological stations and temperature profiler are used for quality improvement.

Keywords: mesoscale meteorological model, data assimilation, nudging

1. INTRODUCTION

The advantage of the use of dynamic relations for the analysis of atmospheric problems instead of just a spatial-temporal gridding was acknowledged long ago. Charney with the co-authors [1] in his pioneer work in 1969 proposed to combine current and previous observation data in the explicit dynamic atmospheric model in such a way as for the model prognostic equations to provide for the temporary continuity and dynamic interaction between different fields of atmospheric values. This concept afterwards came to be known as the FDDA – four-dimensional data assimilation. Although most of FDDA- applications were initially performed for the global scale an avid interest to the use of FDDA in mesoscale models both with the dynamic initialization and as an analytic or research instrument is the logic expansion of this conceptual relation between the methods of the targeted analysis [2].

Different ways of data insertion into atmospheric dynamic models of various complexity have been elaborated for the last 40 years. They vary from a simple continuous direct substitution of model variable values in the next time interval in the closest research point to the more complicated partial substitution in the space and time. One of the up-to-date approaches of data assimilation - variation method [3] -applies the full dynamic model as a strong constraint in the four dimensional variation scheme. This approach significantly makes the model fit the data distributed within the terminal time domain. Literature shows that [2] if we ignore forecast errors over the time interval covering the observations this approach defines the optimal three dimensional initial state of the investigated atmospheric region whereby corresponding model development better falls on the observations over a complete period of modeling. A complete four dimensional data assimilation is a result thereof. In spite of the complexity of this approach and immense requirements to the computational resources the functioning implementations of the variation method have been proving to provide for the best result over a number of years already.

In general, all modern methods of data assimilation can be subdivided into three types [4]. The first type of methods is based on the variation principles of the search for the minimum of some functional (problem statement is proposed in [3]) describing the deviation of the model solution and measured data in some preset metrics as functions of initial and boundary conditions. This type is called "variation method" of assimilation problem solution. It rests upon the adjoint equation perturbation theory developed by academician G. Marchuk for the discrete models of atmosphere and ocean dynamics [5]. The theory is successfully applied in practice though requiring significant computational resources as well as the establishment and maintenance of the conjugate model for its implementation. Lately, another method, i.e. dynamic-stochastic approach based on the use of the Kalman filter algorithm has been intensively introduced into the data assimilation practice [6]. The physical significance of this approach involves the definition of the relation between the known (observed) and unknown state of the atmosphere in time and space which are assigned through the

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expectation function and covariance functions in the linear approximation. This approach is much easier to implement than the variation one. This method can be properly applied only for the linear systems [7]. One of the main advantages of the Kalman filter for the definition of the analysis fields as compared to the variation data assimilation algorithm lies in the fact that this method allows for the obvious consideration of the forecast error covariances and does not impose constraints upon the time interval wherein the previous observation data are assimilated. Another advantage of the Kalman algorithm is its recurrent nature which efficiently emerges during real-time operations as well as the possibility of a priori estimate of the accuracy of the results obtained by the means of the algorithm itself [4].

The third type of the four dimensional data assimilation is the continuous (repeated) dynamic assimilation where special forcing terms are added to the model transfer equations in order to drive the current state of model variables towards observations. This technique is efficiently used in the United Kingdom Meteorological Office both for the global and regional data assimilation. Small value forcing terms constantly adjust meteorological model numerical fields which stay in the approximated equilibrium in each time step.

Nudging or Newtonian relaxation [2,8] is primarily used for weather modeling on the global scale, although it has already been applied in the models for bounded areas. The results of its application demonstrate flexibility of this approach: data for Newtonian relaxation can be of different types (measured and calculated) obtained from the analysis on the grid for the assimilation into the model or inserted as separate observations. Grid analysis of assimilated observations can be obtained from the successive correction, variation method or statistical optimal interpolation with various weight coefficients being applied. In 1986 Lorenz [9] demonstrated that the successive correction, optimal interpolation and variation approaches are fundamentally related to the idealized analysis and, therefore, each of them is related to the others. In practice nudging or Newtonian interpolation is the successive correction approach which uses numerical model for the insertion into the analysis of the temporal measurement for observations.

Initially nudging was designed for the initialization of dynamic atmospheric models that was used before the forecast period in order to create well balanced initial conditions for the model to perform numerical prediction. As opposed to this application of Newtonian relaxation where the interest to the assimilated state lies predominantly at the end of the preforecast period the given paper studies the accuracy of modeling for the bounded area within the time interval wherein nudging is used.

The paper studies the applicability of Newtonian relaxation in the mesoscale numerical model used as a means for the generation of improved sets of obtained numerical meteorological data applicable for the diagnostic studies of the atmosphere boundary layer over a limited urban territory with the purpose to assess air quality.

2. SHORT DESCRIPTION OF MESOSCALE MODEL TSU-NM3

The three dimensional in primitive variables mesoscale meteorological model developed in TSU is designed for the modeling of atmospheric processes in the planetary boundary layer with the horizontal resolution up to several kilometers. The model is described in [10]. Some of the main characteristics and options of the model used for air quality assessment over large urban areas are as follows:

- Non-hydrostatic quasicompressible approximation for motion equations;
- Coordinate system with following surface topography;
- Nested computational domains (inner domain with dimension of 50x50 km with the horizontal grid increment of 1 km is located within the domain of 200x200 km with the horizontal grid increment of 4 km) with one-way interaction;
- lateral boundary conditions of "radiative" type (for the components of horizontal velocity, temperature and humidity) considering spatial and temporal trends of dependant variables generated by a larger scale model;
- prediction model for the soil temperature based upon the heat-transfer equation and diagnostic correlation for humidity of the upper soil layer;
- surface heat flows calculated on the basis of the Monin-Obukhov's similarity theory;
- short-wave and long-wave radiation considering cloud layer effects;
- warm rain microphysics proposed by Kessler;
- turbulent structure of the atmospheric boundary layer is modeled on the basis of the prediction equation for the turbulent energy and algebraic relations for the scale of turbulence and turbulent diffusion;

• initialization of the model is carried out based on the results of numerical prediction as per the global operational model SL-AV of the Hydrometcenter of the Russian Federation[11], the results of observations carried out with the help of the temperature profiler MTP -5 and automatic meteorological station WXR520[12].

3. INITIAL AND BOUNDARY CONDITIONS

All atmospheric models used for the analysis and prediction of meteorological conditions over a limited territory require input data to be set for the initial conditions and lateral boundary conditions. For the mesoscale model updated within the framework of this project we applied global weather forecast data supplied for the investigated region with the help of the operational model SL-AV of the Hydrometcenter of the Russian Federation [11]. SL-AV forecast is performed twice a day and we obtain an access through the Internet to the server of the Hydrometcenter of the Russian Federation to download forecast results for the local area of interest. Forecast results are provided with a 6-hour interval for the 48-hour period. 3D fields of horizontal components of wind, absolute temperature, relative humidity are available on the grid with the increment of about 60 km and at 12 vertical levels. Besides, prognostic values of the wind velocity components at the level of 10m, temperature and humidity at the altitude of 2m from the ground surface are used in order to obtain the fields of the main meteorological parameters on the mesoscale model grid. Apart from the calculated values, measured values of meteorological parameters preliminary averaged for each hour of observations are considered when developing initial profiles of meteorological values for the mesoscale model. Absolute temperature profiles supplied by the temperature profiler MTP-5 located at the observation point are taken into account. Temperature values are measured at 31 levels - altitudes of 0,10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000m from the upper part of the profiler. Besides, automatic weather station results averaged for each hour of observations carried out at the same geographic location where the temperature profiler MTP-5 is placed are considered for mesomodel initialization. The interpolation of the numerical prediction and observation results over a 3D mesoscale meteorological model grid is performed with the help of the weight coefficients whose values depend on the distance between the reference point of the global weather forecast model SL-AV or observation point and the grid node:

$$\Phi_{i,j,k} = \sum_{m=1}^{N} \Phi_m \frac{\sqrt{(x_m-x_i)^2+(y_m-y_j)^2+(z_m-z_k)^2}}{\sum_{m=1}^{N}\sqrt{(x_m-x_i)^2+(y_m-y_j)^2+(z_m-z_k)^2}}. \quad (1)$$

Where (x_i,y_j,z_k) is the location of the mesoscale model grid node; (x_m,y_m,z_m) is the location of the observation point or of the point where values are found with the help of the global SL-AV model [11]; Φ_m is the input calculated or measured value; N is the quantity of calculated and measured values. Such an approach is also used for the assessment of meteorological parameter variation trend close to the lateral boundaries of the mesomodel computational domain; however, in this case only the data of the 48-hour numerical forecast as per the global SL-AV model are used. The obtained analysis fields for meteorological values are used later for the setting of the boundary conditions of the "radiation" type:

$$\frac{\partial\Phi}{\partial t} + C_\Phi \frac{\partial\Phi}{\partial n} = \frac{\partial\Phi^0}{\partial t} + C_\Phi \frac{\partial\Phi^0}{\partial n}, \quad (2)$$

where C_Φ is the phase velocity calculated from the trend of the variation of the function Φ near the boundary; n is the external normal to the boundary of the area; Φ^0 is the calculated results of the forecast as per the global SL-AV model of the Hydrometcenter interpolated on the mesomodel grid.

3.1 Boundary conditions at the low boundary

For correct prediction of the sensitive (advective) and latent heat flows at the boundary of the "soil-atmosphere" interface with the help of the mesoscale model the non-steady-state 1D thermal conductivity equation is used in this work. The equation allows to calculate the instantaneous temperature profile in the soil up to the depth of 2 m on the uniform 30-layer grid for each node of the mesoscale model horizontal grid. Location of the horizontal grid node is determinant for the calculation of efficient thermal-physical properties of the soil upper layer which depends on the percent share of the land-use categories considered in the work: agricultural land, little vegetation, leaf forest, mixed forest, coniferous wood, city, water reservoir. Unfortunately, only average monthly data on the measured temperature of the soil at the depth of 1,6 and 2,4 m for the studied area are available to us. The data are used for the initialization of the soil model, which significantly reduces the quality of predicted or diagnostic values of meteoparameters calculated based on the mesoscale meteorological model. The following simple relation is used to define the absolute humidity of the air near the surface layer: $q_{surf}=\Psi q_{sat}(z_1)+(1-\Psi)q_1$, where $0\leq\Psi\leq1$ is the parameter of the underlying terrain humidity whose value depends on the land-use category ($\Psi=0$ for desert and $\Psi=1$ for water surface), $q_{sat}(z_1)$, q_1 is the humidity of the saturated steam and absolute air humidity at the first computational level of the vertical grid of the mesoscale model. Thermal-physical parameters of the land-use category are defined according to the values for the 24 land-use categories adopted in the US geological service [12].

Substitution of the current model of the heat and moisture exchange in the upper layer of soil for the parameterization scheme ISBA (Interaction Soil Biosphere Atmosphere) [13] applied in the global SL-AV model is expected in the future to enhance mesoscale model initialization quality.

4. DATA ASSIMILATION

Since small scale meteorological phenomena cannot be explicitly solved with the help of the global SL-AV model (horizontal grid increment ~ 60 km), or observational network of the Hydrometcenter of the RF, there can be examples where initial conditions for the applied mesoscale meteorological model inadequately represent the local wind field over the research area. The four-dimensional data assimilation (FDDA) and its approaches provide for the technique of the insertion of meteorological observation results (including high resolution data obtained from meteorological stations or from the instruments of the remote sensing of the atmospheric boundary layer vertical structure) or of the numerical weather forecast results supplied by the atmospheric model of a larger scale within a more extended time period. FDDA technologies are widely used in recent times not only for the initial conditions quality improvement for the mesoscale weather forecast models but also for the development of high quality 4D fields of weather elements which can be applied as the input data for the mesoscale air quality assessment models. Some of these FDDA techniques were developed for the insertion of the local observation data into the atmosphere model forecast. Newtonian relaxation (nudging) is among these techniques. Model variables gradually approach observations (or prediction calculations) supplemented by forcing terms in the transfer model equations in this technique. In spite of its lower accuracy as compared to such more up-to-date means as the Kalman-Bucy filter or variation method Newtonian relaxation is more efficient due to its simplicity of use and less requirements to the computational resources which are extremely important in the applications promptly assessing the state or providing a short-time forecast of air quality in cities. The results of previous studies [2,8] demonstrated that initial conditions improvement and short-time forecast can be performed with the help of this approach.

Therefore, the mesoscale meteorological model being developed in TSU was modified with the insertion of Newtonian relaxation in the way that meteorological observations (or numerical modeling results with a larger scale model) could be assimilated continuously during numerical mesoscale model prediction for a certain time period. In the present work as per the considered approach the forcing term of the following form is added to the forecast equations for horizontal velocity components, potential temperature and absolute humidity:

$$\rho * G * W_{xyz}(x,y,z) * W_t(t) * (\Phi_0 - \Phi). \qquad (3)$$

Where ρ is the air density, kg/m^3; G is the relaxation coefficient, 1/c; $W_{xyz}(x,y,z)$ is the spatial weight function; $W_t(t)$ is the time weight function; Φ_0 is the observed or calculated as per the atmospheric model of a larger scale values for the given moment interpolated onto the mesoscale model grid; Φ is the calculated values of the forecast variable at a separate moment. Typical values for $G=10^{-4}$-10^{-3}. Forcing term (3) gradually attracts or nudges model calculation results to the observed values. Spatial weight function $W_{xyz}(x,y,z)$ varies from 0, when the grid node is located far enough from the observation point, to 1, when the grid node coincides with the observation location. Spatial weight function reduces by the coefficient e^{-1} at the distance of 10km from the observation point [8]. Besides, the spatial weight reduces by the coefficient e^{-1} at the distance of 30m above or under the observation point [8]. In such a case if the observations are carried out at the point (x_0,y_0,z_0) weight functions pattern will be as follows:

$$W_{xyz}(x,y,z) = W_{xy}(x,y) * W_z(z),\ W_{xy}(x,y) = exp\left(-\frac{r(x,y)}{10000}\right),$$
$$r(x,y) = \sqrt{(x-x_0)^2 + (y-y_0)^2},\ W_z(z) = exp\left(-\frac{abs(z-z_0)}{30.0}\right). \qquad (4)$$

Since observations are performed within the time intervals which are significantly larger than the time step of the mesoscale model $W_t(t)$ is set up so as to consider relative contribution of the two consecutive observations which bound current model time [2,8]:

$$W_t(t) = \begin{cases} 1, & |t - t_0| < 0{,}5\tau \\ \dfrac{\tau - |t - t_0|}{0{,}5\tau}, & 0{,}5\tau < |t - t_0| < \tau \\ 0, & |t - t_0| > \tau. \end{cases} \quad (5)$$

Where t is the model time; t_0 is the observation time; τ is the semi-period of the time interval during which observations will influence the solution obtained with the help of the numerical model.

5. RESULTS

The approach of the calculation and observation data assimilation by the mesoscale model developed in TSU with the help of Newtonian relaxation was applied for some particular weather simulation cases around Tomsk (56,5^o north latitude and 85^o east longitude) for October 10-11, 2012 and October 10-11, 2015. For this very time period the project team had weather forecast data available for Tomsk region based on the global SL-AV model received from the site of the Hydrometcenter of the RF, observation data of the meteorological instruments, i.e. temperature profiler MTP-5 and automatic meteorological station WXT520 installed at Tomsk airport – Bogashevo (56,38^o;85,21^o) on October 10-11, 2012 and on the site of the Institute of Monitoring of Climatic and Ecological Systems (IMCES) SB RAS (56,48^o;85,06^o) on October 10-11, 2015. The results of the measurements of surface wind velocity, temperature and humidity performed at the meteorological stations of the Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Science (56,48^o;85,05^o) were applied to control the efficiency and adequacy of the observation and calculation assimilation[14].

The measuring system MTP-5 [15] allows to reflect the thermal structure of the lower 1000-meter layer of the atmosphere and to obtain its temporal dynamics with the increment along the vertical coordinate of 10-50m and frequency of 5 min. Temperature measuring range is from – 50 to +50 C. The meteorological temperature profiler MTP-5 is additionally supplemented by the automatic meteorological station WXT520. It automatically measures ground atmospheric pressure, temperature, relative humidity, wind direction and velocity, rain precipitations and hail.

The following cases were considered when performing computations with 4D assimilation of calculated and observed meteorological values with the help of Newtonian interpolation:

1. Weather forecast data obtained from the global SL-AV model were assimilated within the whole simulation period. Besides, they were used when setting up the initial and boundary conditions at the lateral boundaries of the area.

2. In addition to the conditions of the first case observation data obtained with the help of instruments MTP-5 and WXT520 were assimilated during simulation on October 10.

3. Only during the simulation of the meteorological conditions on October 10, numerical weather forecast and observation results were assimilated. The same data were used when setting up the initial conditions. Boundary conditions at the lateral boundaries of the local modeling area were obtained with the use of numerical weather forecast results.

4. Only global numerical SL-AV prediction results were assimilated within the first half of the simulation period – October 10. The same data were applied to set up the initial and boundary conditions at the lateral boundaries.

Figure 1 represents the results of calculations performed with the mesoscale meteorological model for the aforesaid first and second cases for October 11, 2012. Data measured with the TOR-station of the Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Science [14] and Tomsk South meteorological station (56,5^o;85,0^o) were applied for the forecast quality control.

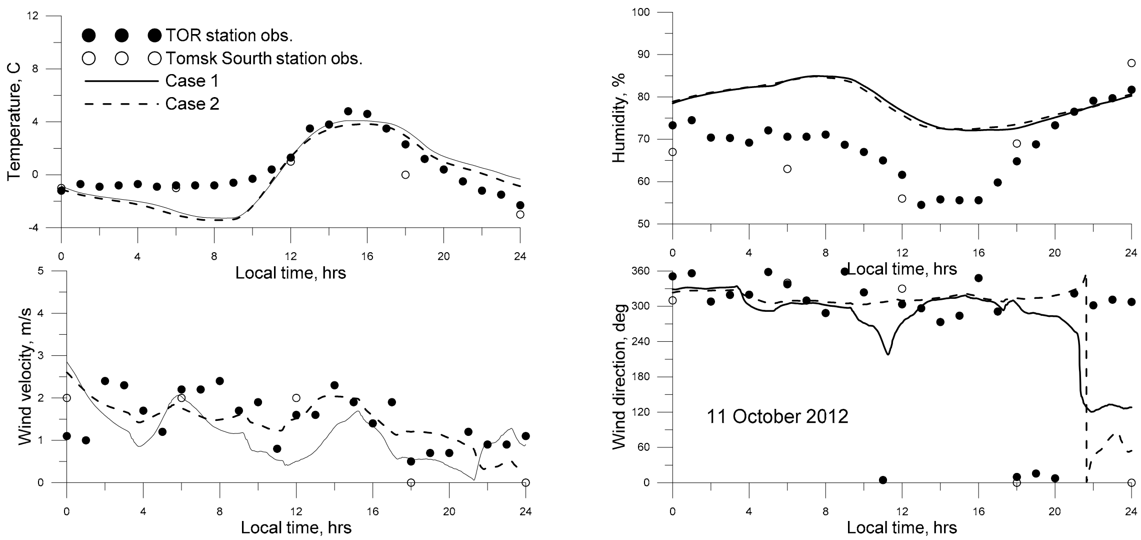

Figure 1 Calculated and measured values of the surface temperature, relative humidity, wind direction and force on October 11, 2012.

On October 10–11, 2012, the weather was cloudy without precipitations. At night and in the first half of the day, low level clouds were observed with the gradual transition after 3.00 p.m. to the upper level; and after 6.00 p.m. the weather was clear. Air temperature varied from -2 ºC at night to 3 ºC during the day, atmospheric pressure slightly increased from 758 at the beginning of the day to 760 mm at the end of the day. Wind velocity during the day varied from 3 to 5 m/s, wind direction was north-western with a gradual transition to the western one with velocity reduction in the second half of the day. Similar weather was observed at the aeronautical meteorological station of Tomsk airport.

Calculation and observation comparison results show that the best matching, at least in terms of wind force and direction, is provided by the second case when all available data are assimilated. It also should be noted that when forcing term is excluded with the assimilation of the global SL-AV weather forecast results on October 11, 2012 (the third and fourth cases) numerical stability of the mesoscale meteorological model relying on the explicit-implicit difference scheme slightly decreases, which leads to the necessity to reduce the time step of the numerical integration of the finite-difference equation system. Besides, the surface meteorological parameter forecast quality goes downward significantly.

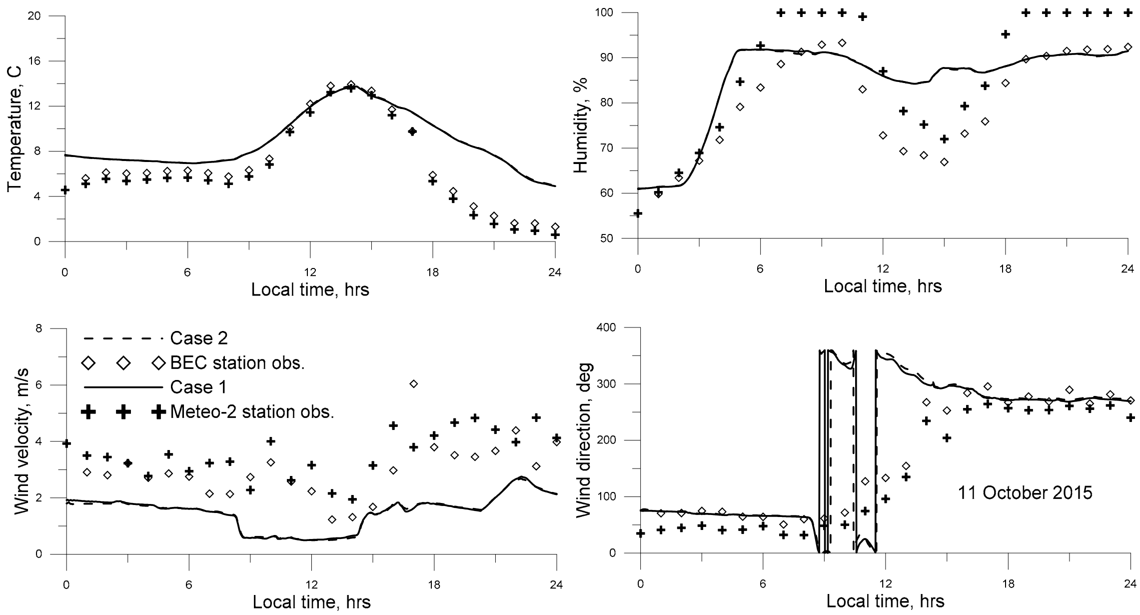

Figure 2 Calculated and measured values of the surface temperature, relative humidity, wind direction and force on October 11, 2015.

Figure 2 represents calculated and measured values of the surface wind velocity, temperature and air humidity for October 11, 2015. Apart from the period of comparative analysis, this case also defers by the fact that the data for assimilation were taken from the meteorological instruments MTP-5 and WXT520 installed on the site of the Institute of Monitoring of Climatic and Ecological System, SB RAS. Similar to the previous case, it was found that if numerical forecast results are not assimilated on the second day of simulation the congruity between the model-calculated values and measured values of the wind force and direction is significantly worse. However, the coherence of the mesoscale model-calculated results and measurements at the meteorological stations of the Institute of Atmospheric Optics, SB RAS is good enough both for the first and second cases. It should be noted that the influence of additional engagement for the assimilation of the data of MTP-5 and WXT520 in the considered case is less visible. It is likely to be connected with the wind direction on October 11, 2015 "staying away" from the point where the observation and calculation data were compared.

Some more extensive network of various (ground-based and remote observations) meteorological instruments over the area of numerical studies could probably save the situation. But, unfortunately, only observations of some ground-based meteorological stations can be added currently to the considered instruments (MTP-5 and WXT520) for Tomsk district in a best case scenario. However, the obtained results allow to affirm that observation data insertion even at a separate point together with the assimilation of the numerical global model prediction improves the predictability of the mesoscale model for a local limited area.

6. CONCLUSIONS

The mesoscale meteorological model being developed in TSU has been improved with the assimilation of available data of real-time measurements (automatic meteorological station WXT520 and temperature profiler MTP-5) and numerical weather forecast results (global SL-AV model of the Hydrometcenter). Newtonian relaxation is used for the four-dimensional data assimilation. The calculations performed demonstrate the perspectiveness of the considered method of assimilation of external data of measurements and of the weather forecast for Siberian conditions due to its simplicity, low requirements to computational resources, increasing accuracy of a short-time weather forecast for a limited area.

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