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Development of the High-resolution Operational System for Numerical Prediction of Weather and Severe Weather Events for the Moscow Region

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Abstract—The study presents the new system for operational short-range numerical weather prediction with the grid spacing of 1 km for the Moscow region that considers the features of urbanized surface and is based on the COSMO-Ru1M model configuration. This system is implemented in the Hydrometcenter of Russia. The results of the trial testing of the optimum model configuration for the Moscow region using observations from the dense network of weather stations and MTP-5 temperature profilers are presented. High prediction capabilities of the new forecasting system are demonstrated. The approaches to the minimization of the time of calculations for the technology chain implemented at the Roshydromet supercomputer are described. A case study of modeling with the grid spacing of 500 m versus 1000 m for summer convective weather events in the Moscow region has been analyzed.

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1. INTRODUCTION

The improvement of any weather prediction system is a complex process that includes not only the solution to scientific, technological, and operational problems but also joined activities. Activities on the development of the high-resolution (the grid spacing is 1 km) system for short-range numerical weather prediction (NWP) have been carried out at the Hydrometcenter of Russia since 2018 to improve the system for the forecasting of weather events, especially of severe ones, for Moscow. The work considers the urban development based on the Roadmap prepared by Roshydromet jointly with the Government of Moscow. The use of the high-resolution NWP technology, data from the new high-density observation network including automatic weather stations (AWS) and DMRL weather radars implied by the Roadmap is extremely important for a considerable increase in the accuracy of short-range weather forecasts and in the reliability of severe weather warnings.

The activities implied in the framework of the Roadmap are fully consistent with modern global tendencies of progressive meteorological development. The authors of [14] considered the concept of World Meteorological Organization (WMO) and substantiate a need in relevant studies for implementing integrated city services related to weather, climate, and the environment. These studies are aimed at developing complex urban meteorological, ecological, and climatic services that assist city services in case of strong winds and heavy showers, air pollution, abnormal heat waves, etc. The creation of the united city database for uniting monitoring services and all weather observation networks and high-resolution weather forecasting will perhaps be required for multi-hazard early warnings to provide the meteorological safety of big cities and to optimize the work of urban organizations.

The studies in this direction have been carried out all over the world. Let us note some results that are important in the context of the strategy for the development of operational technologies.

For example, the authors of [15] use the WRF operational model (the grid spacing is 1 km) utilized in the Institute of Urban Meteorology (IUM, China Meteorological Administration) and its comparison with the great number of AWS measurements to analyze the effects of algorithms for the parameterization of atmospheric processes and urban environment on the forecast for three close megacities: Beijing, Tangjin, and Tangshan. It is shown that even the most successful urban scheme of the boundary layer leads to errors in surface air temperature of about 2 C and, hence, in forecasting the conditions that determine convective or inversion processes. In some cases, the introduction of the parametric description of a city (by introducing a special scheme for parameterizing the impact of urban buildings) and the prescription of numerous city characteristics was more efficient to reduce the error (to 1 C on average and by 4 C for individual cases) than the improvement of the boundary layer scheme. The description of subsequent work in this direction is given in [24]. The authors of [34] improved the forecast for Beijing by the more accurate description of anthropogenic latent and sensible heat fluxes from buildings in the IUM operational system based on the application of the WRF model (ARW, version 3.51) to three nested grids from 9 to 1 km. This increased the accuracy of short-range forecasting of minimum and maximum values of surface air temperature by 1–2 C.

Paper [22] describes the integrated analysis of the results of the unique numerical prediction using the ICON model over the big territory (entire Germany), with the consecutive nesting of grids with the spacing of 625, 312, and 156 m (the grid with the spacing of 156 m covers almost the whole territory of Germany), with 150 vertical levels to the height of 21 km. The comparison with maximum available meteorological information was performed. The studies revealed that the model with such high resolution significantly improves the forecasts of mesoscale variability, which proves the ability to simulate well the atmospheric processes, primarily convective ones, on such scales.

The results of modern studies in urban meteorology for Moscow were generalized by the specialists of Lomonosov Moscow State University [5]. Paper [6] presents the firsts results of developing the NWP system prototype based on the nonhydrostatic atmospheric model improved by the homonymous international consortium COSMO (COnsortium for Small-scale atmospheric MOdeling) [9, 10] Roshydromet has participated in since 2009. In accordance to the results of operational testing [11], the COSMO-Ru regional NWP system [3, 6, 7] is a base short-range NWP technology for Russia and its regions. The need in developing the improved NWP technology for Moscow based on the higher-resolution model considering the impact of urban development is due to the ability of the atmosphere model COSMO-Ru2 with the grid spacing of 2.2 km for adequate reproduction of the features of the meteorological regime of the megacity (currently, this model is used for producing forecasts for the European part of Russia and neighboring areas [7]). An increase in the resolution is required to take into account the strongly pronounced mosaic pattern of urban landscapes (caused by the alternation of areas with more or less dense building, industrial zones, forest parks, reservoirs) as well as to provide more adequate simulation of atmospheric processes, for example, the formation of convective systems and related weather events (wind gusts, local heavy showers, thunderstorms, etc.). The features of urban surface and the aggregated impact of the city as a heat island can exert considerable influence on the atmospheric processes over it, in particular, on the formation of severe weather events [25]. These features may be considered when including mathematical description (parameterizations) of the corresponding factors of the urban environment–atmosphere interaction to the model [6].

The present paper deals with the issues of developing the operational NWP technology based on the results of the experiments with the model adapted to the Moscow megacity in the framework of the COSMO-Ru short-range NWP system [6].

2. TESTING AND SETUP OF THE PROTOTYPE OF THE OPERATIONAL NWP MODEL FOR MOSCOW MEGACITY

The testing of the prototype of COSMO-Ru1Mp nonhydrostatic model with the grid spacing of 1 km (see its description in [6]) was carried out to determine its ability to reproduce the spatial (horizontal and vertical) distribution of meteorological parameters for urban conditions and to refine the model setup and parameters for improving the quality of forecasting.

The COSMO-Ru1Mp model setup was tested using the periods when the most strongly pronounced thermal inhomogeneity (in particular, the effect of the Moscow heat island: the difference between temperature in the city center (Balchug station) and its mean values for the surrounding rural areas) was observed in the Moscow region. Such conditions are typical of the periods of fair and mainly calm weather, thus favoring an increase in the diurnal amplitude of temperature and the manifestation of local climate features. When selecting the periods, availability of observational data needed for verification was taken into consideration. As a result, two periods for the warm season (May 17–29, 2014 and May 10–25, 2017) and one interval for the cold season (January 1–17, 2017) were chosen. The latter is characterized by the presence of extreme frosts during January 6–10, when temperature in the Moscow region dropped to –35 C and the strongly pronounced heat island was observed over the city [13]. The analysis of the results paid basic attention to the values of air temperature, its spatial differences, and characteristics of thermal stratification in the lower atmosphere.

The results were verified using data from 33 Roshydromet stations including automatic weather stations and 41 Mosekomonitoring automatic air quality control stations (AAQCS) [2, 7, 30]. Additionally, observational data on temperature in the lower atmosphere from the network of MPT-5 meteorological profilers were used. Such observations in the recent 20 years have been conducted at some points in the Moscow region. The previously obtained results were numerously used to analyze thermal stratification conditions of the Moscow heat island [4, 13, 23]. The authors of this paper used data of synchronous measurements at four points: the northern agglomeration (Central Aerological Observatory, Dolgoprudny), the eastern agglomeration (Mosekomonitoring observation station in the Kosino district), the background territory (Zvenigorod scientific station of Obukhov Institute of Atmospheric Physics (IAP)), and the Moscow center (the roof of the IAP building). The observations at the last point have been carried out and processed by the IAP specialists since 2016 to monitor and to analyze atmospheric stratification conditions directly over the megacity center. This data is especially valuable for the model verification, because it allows assessing the differences in the atmospheric stratification between the city center and suburbs. The atmospheric layer with the depth of 1000 m (in Zvenigorod, 600 m) is covered with the mentioned measurements using profilers with a vertical step of 50 m and a time step of 5 minutes.

The test numerical experiments with different configurations of the COSMO model [10] were performed for the purpose of dynamic detailing of the ERA-Interim reanalysis for the Moscow region (for more detail see [2, 31]). Three cascade nested simulation domains with the grid spacing of 12, 3, and 1 km were used. The latter is the operational domain of the COSMO-Ru1Mp model configuration with the size of 200 200 km.

The experiments were performed for three model configurations. The first two experiments utilized the COSMO-Ru1Mp prototype configuration based on the COSMO-CLM climate model supplemented with the TERRA_URB urban parametrization [32, 33]; it was supplied by the parameters of urban environment derived for Moscow [6]. Two series of experiments were performed using this model version: v5_REF and v5_MOD. The v5_REF experiments correspond to the original configuration of COSMO-Ru1Mp. The v5_MOD experiments used the model modernized considering the experience of climatic studies for the Moscow region [30, 31]. The model modifications for v5_MOD imply a decrease in the minimum values of eddy diffusion coefficients and in the scale of subgrid thermal inhomogeneities according to [2, 16], the use of the new parameterization of bare soil evaporation [28] and the new parameterization of the vegetation canopy (the skin-layer temperature scheme) [29], as well as the use of exponential distribution for the root density instead of the linear one.

The third series of experiments v5.05_REF, the configuration COSMO-Ru-M v5.05urb[VM2] of the recent version v5.05urb of the COSMO model was used. Modification of COSMO v5.05urb was obtained from COSMO v5.05 by including the TERRA_URB module from the climate version of the COSMO-CLM (or CCLM) model and making the necessary changes related to it, for example, implementing a tiled representation of the Earth's surface. For operational use, the COSMO v5.05urb model was provided to the meteorological services of the consortium members in 2019. Unlike the previous model versions, the version COSMO v5.05urb has the block of physical parameterizations updated using the experience of the ICON seamless model development [21, 35]. In particular, it contains essentially modified parameterizations of vertical eddy diffusion in the atmospheric boundary layer. The COSMO-Ru v5.05 configuration also included the most of above modifications tested during the modernization of COSMO-Ru1Mp (experiments v5_MOD). The parameters of the urban surface in the experiments were specified identically and coincided with those prescribed in the COSMO-Ru1Mp prototype.

The results obtained for May 17–29, 2014 (Figs. 1a, 1b, 1c, and 1e) indicate that the use of modifications of COSMO-Ru1Mp significantly improves the original variant. The analysis of the results revealed

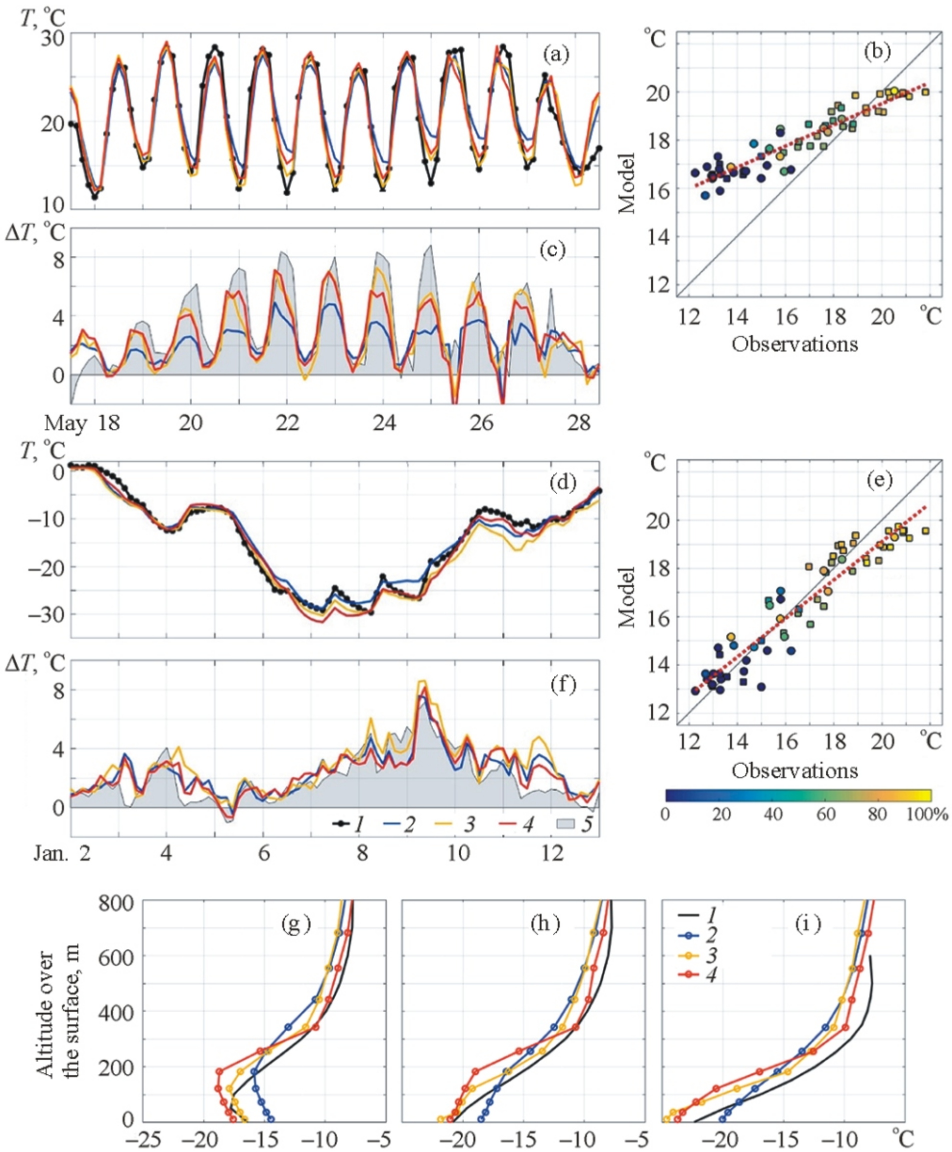

Fig. 1. The comparison of (*1*, *5*) observed and (*2*, *4*) simulated air temperature: the variation in (a, d) average suburban air temperature and (c, f) heat island intensity for the city center in (a, c) May 2014 and (d, f) January 2017; the values of nighttime air temperature (for 00:00 UTC) averaged for May 20–27, 2014 according to observations at AWS (the round markers) and AAQCS (the squared markers) and according to model data for the (b) v5_REF and (e) v5_MOD experiments; (*1*) the observed and (*2*–*4*) simulated mean vertical profiles of temperature for January 9, 2017 (g) in the city center (IPA), (h) Kosino, and (i) Zvenigorod. The experiments: (*2*) v5_REF; (*3*) v5_MOD; (*4*) v5.05_REF. In figures b and e the color scale shows the fraction of urban area.

that nighttime temperature for poorly urbanized conditions (mean temperature for 9 suburban weather stations nearby Moscow is shown) and heat island intensity are better simulated in v5_MOD and v5.05_REF than in v5_REF. This provides more realistic simulation of the spatial variability of air temperature in the Moscow region.

The comparison of model simulations with profiler data revealed that the original variant of COSMO-Ru1Mp (v5_REF experiment) simulates too strong mixing of the lower atmosphere at night and, consequently, underestimates the intensity of nighttime cooling inversions. The other two experiments simulate more intensive temperature inversion. Data obtained for the period of May 10–25, 2017 are close to the considered ones.

For the winter test period of January 1–17, 2017, differences between the configurations are much smaller than for the summer episodes, with a slight advantage of the modernized versions (Figs. 1d and 1f). Despite the simplicity of specifying the anthropogenic heat flux in the TERRA_URB (the average annual value and annual variation are specified [6, 20, 32]), that plays a key role in the formation of the winter heat island, all configurations realistically simulated the intensive heat island which was observed at the peak of the cooling on January 9, as well as the atmospheric stratification conditions in the city center (IPA), in the suburb (Kosino), and over the background territory (Zvenigorod) (Figs. 1g, 1h, and 1i). Thus, the results indicate a higher quality of simulation and prospects of using the setup of the modernized version of COSMO-Ru1Mp, as well as the prospects of transferring operational simulations in the framework of the COSMO-Ru system to the updated version of COSMO v5.05urb (hereinafter, COSMO-Ru1M, unlike the COSMO-Ru1Mp prototype). It should be noted that the new version of COSMO v5.05urb allows specifying the same spatial differentiation of morphometric parameters of built-up environment (the height of buildings, "urban canyon" aspect ratio, building density) which affect interaction between the urban surface and the atmosphere.

Currently, the ongoing work is aimed at the development of spatial databases containing the values of required morphometric parameters of the built-up environment averaged over the cells of grids with the spacing of 1 km and 500 m [27]. At the same time, information about the urban area fraction is refined using the most modern data and methods. The higher accuracy and reliability of the results is provided by the synthesis of data from different information sources: OpenStreetMap data [12], that are available in vector format; raster data on the surface types Copernicus Global Land Cover [8] with the grid step of 100 m; and raster data on vegetation with the grid step of 10 m obtained as a result of processing Sentinel-2 satellite images.

3. EFFECT OF CHANGING THE GRID SPACING FROM 1 km TO 500 m AT SIMULATION OF CONVECTIVE PROCESSES IN THE MOSCOW REGION

A need in applying smaller and smaller grid steps for the numerical prediction of rapidly developing severe weather events is caused by the scales of intense convective processes in the mid-latitudes. For example, the models with the grid spacing from 500 to 30 m are used to solve research problems in the area of modeling mesoscale convective systems (MCS). In case of operational NWP, a compromise is required between the desired forecast skill and the feasibility of calculations. Each two-fold decrease in the simulation grid spacing under the same number of levels and territory, as well as under the ideal parallelization of the computational process increases the run time by 8 times and the required external and random access memory by 4 times.

For example, let us consider a case of the forecast of the convective system and weather phenomena in the Moscow region on May 30, 2019 produced with the COSMO-Ru1Mp and COSMO-Ru0.5Mp versions with the grid spacing of 1 km and 500 m, respectively. The results of the modeling with the step of 1 km were presented in [6]. The simulations were performed in the framework of the COSMO-Ru system using data received in operational mode in the framework of the "cascade detailing" technology from COSMO-Ru6ENA to COSMO-Ru1Mp [6]. The COSMO-Ru0.5Mp variant is not a prepared version for obtaining operational numerical weather forecasts, because this version provides the setting for the grid spacing only, and all the other parameters including the urban building coincide with those used in prototype COSMO-Ru1Mp.

From 11:30 to 14:00 UTC, local showers and thunderstorms were registered in Moscow and the Moscow region, eyewitnesses reported the cases of hail and squall. The maximum registered wind gusts were equal to 17 m/s at Vnukovo weather station and 15 m/s at Sheremetyevo station.

According to 1-km model data [6], the formation of the mesoscale convective system was expected on the front over the northeastern border of Moscow by 13:00 UTC on May 30, 2019 (Fig. 2b). Wind gusts up to 25 m/s were predicted at the rear of the supercell that was situated over the central districts of the city (Fig. 2e). The forecast of the front position was quite close to reality (the front was clearly observed on the streamline charts in Fig. 2e). The situation numerically predicted with the lead time of one day provided important information for forecasters concerning the risk of formation of severe weather events over the city and suburbs. In reality, many small convective cells that caused intense rains in many parts of the city were formed over Moscow and neighboring areas during the passage of the cold front on May 30, 2019. This was clearly observed on the map of radar reflectivity for 13:00 UTC on May 30, 2019 (Fig. 2a), no signs of MCS were detected. Actually, the wind strengthening in the region was much weaker than the

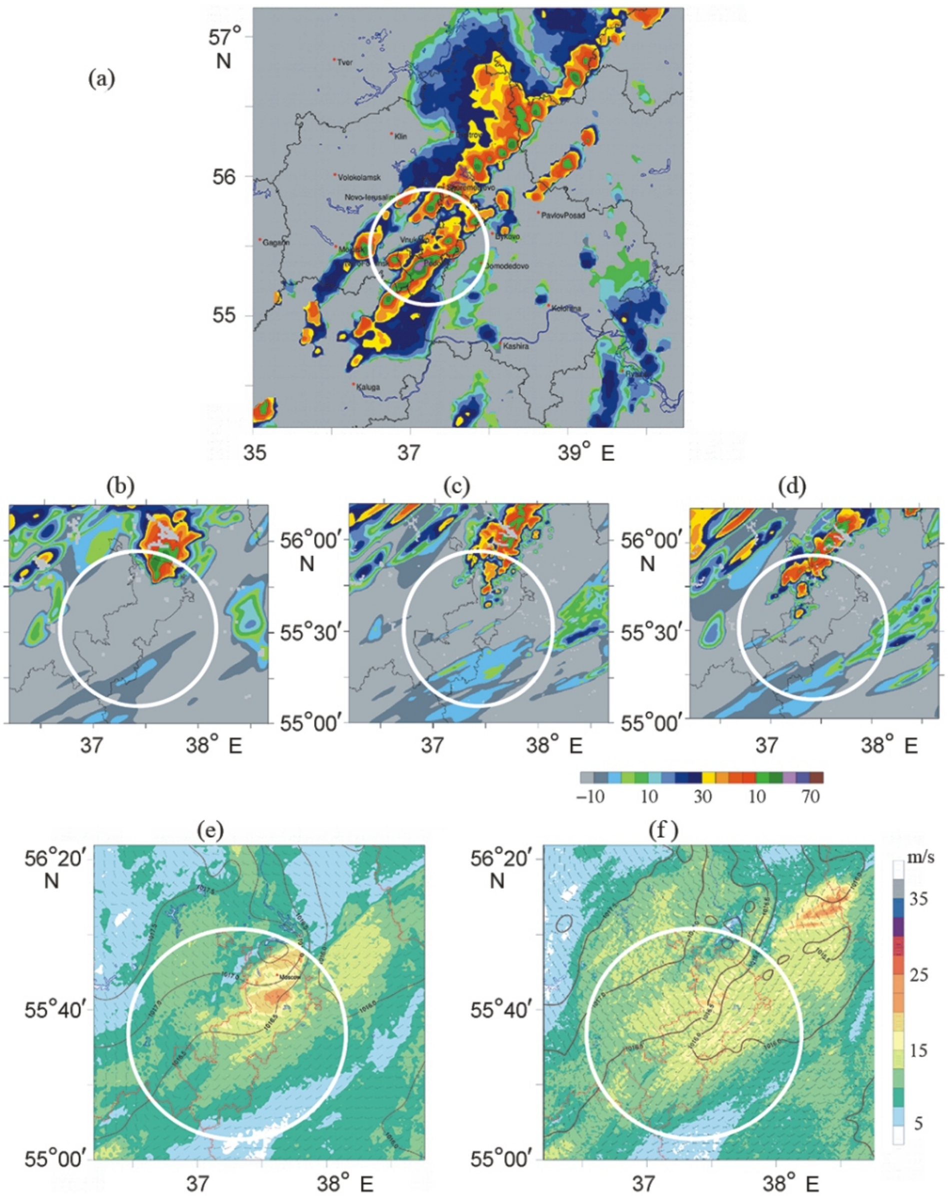

Fig. 2. (a) Maximum reflectivity according to DMRL data; forecasts based on initial data for at 13:00 UTC on May 30, 2019 and the results of the numerical experiment: forecasts from initial data from 12:00 UTC on May 29, 2019 for 25 hours (for 13:00 UTC) with the grid spacing of (b) 1 and (c) 0.5 km and (d) for the period of 24 hours 40 minutes with the grid spacing of 0.5 km; forecasts of 10-m wind gusts for 25 hours from the initial time of 12:00 UTC on May 29, 2019 with the grid spacing of (e) 1 and (f) 0.5 km. The analyzed domain is marked with the white circle.

predicted one. The model did not predict the zones of intense convection in many city districts and, hence, showers and thunderstorms along the front line southwest of the supercell remained unpredicted.

According to the data of simulations with the same initial time and lead time of the forecast but with the grid spacing of 500 m, convective phenomena over the Moscow region had a fudamentally different structure: they appeared to be divided into many individual clusters over many areas of the city (Fig. 2c). The MCS was not observed but there was a number of rapidly developing and moving cloud clusters which were smaller but strong. The forecast for the earlier time period (12:40 UTC) indicates still better agreement with radar data (Fig. 2d).

In the analyzed case, the COSMO-Ru0.5Mp configuration simulated the formation of convective cells in the atmosphere over Moscow and the Moscow region more realistically than the 1-km model. This corresponded with the expansion of territories within the city where the actually observed showers and wind gusts of 15–20 m/s were predicted, with the absence of the false storm wind strengthening (>20 m/s) in the forecast that was not confirmed by observational data, and with the more realistic coincidence with radar data in the size and relative positions of convective cloud clusters.

The results of the analysis for an individual case may be an important argument of the need in the further development and investigation of the 500-m model version as a potential effective tool for the prediction of adverse and severe weather events of convective origin.

4. INTEGRATION OF COSMO-Ru1M CONFIGURATION TO THE OPERATION-TECHNOLOGY LINE AT HYDROMETCENTER OF RUSSIA

The technological chain of short-range weather forecasting with COSMO-Ru1M, the configuration of the model COSMO v5.05urb (note that COSMO-Ru1Mp is the configuration of the model COSMO v5.05urb) with the grid spacing of 1 km was integrated to the operation-technology line for the production of numerical forecasts at the Hydrometcenter of Russia in the framework of the COSMO-Ru system [1, 7]. The formation of initial and boundary conditions for COSMO-Ru1M is based on the cascade approach of the consecutive telescoping of calculations. The boundary and initial conditions in COSMO-Ru6ENA (the grid spacing is 6.6 km, the territory of Europe and Northern Asia) are prepared using interpolated data of the ICON global atmosphere model [21, 35], and initial data for the other configurations are prepared according to the following scheme:

COSMO-Ru6ENA   COSMO-Ru2   COSMO-Ru1M.

To provide forecasters with timely results of simulations, it was necessary to configure the procedures of the COSMO-Ru1M system so that forecast products were calculated as quickly as possible. For this purpose, the optimization of all stages of the technological line of COSMO-Ru linked to COSMO-Ru1M was carried out by reducing the waiting time for lateral boundary conditions from the parent configuration, the calculation time for each configuration by selecting the optimum decomposition of forecast domains, and, finally, the parallelization of the process of visualizing weather forecast results.

The optimization by applying the file waiting module. The file waiting module was developed at the stage of input data preparation. Lateral boundary conditions were received from the data of parent configuration COSMO-Ru2 with the grid spacing of 2.2 km whose run is equal to 60 minutes. Since the file waiting system also operates at the stage of simulation, the process of preparing input data functions in parallel with it, thus allowing computation of forecasts of the child configuration COSMO-Ru1M in parallel with the computations for the parent configuration, it is not necessary to wait for the end of COSMO-Ru2 forecast calculations. As lateral boundary conditions of COSMO-Ru1M are updated every hour, the COSMO-Ru1M run was organized with the one-hour lag behind the parent COSMO-Ru2 using the file waiting module. This reduced the time of reception of COSMO-Ru1M forecasts nearly one hour.

The optimization of weather forecast domain decomposition. The numerical experiments using not more than 144 cores (4 nodes with two processors each and 18 cores for each processor) were performed to choose the optimum decomposition scenario. In methodological calculations, the decomposition parameters changed along the *x*- and *y*-axes. The run time for 1-hour forecasts was estimated. The results of the COSMO-Ru1M performance tests can be judged by the following data:

Number of cores									
along the *x*-axis	1	2	4	6	8	9	12	16	18
along the *y*-axis	144	72	36	24	18	16	12	9	8
Run time, s	5135	3032	2169	2047	1991	2018	2060	2146	2252

The range of values of the run time from the quickest run to the slowest one varies from 1991 to 5135 s (i.e., by more than 2.5 times). The above data show that the decomposition of 8 18 with 8 intervals along the *x*-axis and 18 intervals along the *y*-axis is optimal. In this case, the run time is 1991 s 33 minutes. It is interesting that the run time required for the symmetric decomposition of 18 8 is by 13% greater.

In the future, it is planned to increase the number of cores and, perhaps, to extend the forecast domain.

Operative aspects and the optimization of the postprocessing stage. The postprocessing issue aims at the transformation of results of direct model simulations into the products delivered to the user. The progress at this stage was made as a result of dividing all postprocessing tasks to the groups with subsequent parallel solution. This reduced the time of visualization and conversion of data from 80 to 20 minutes. The resulting characteristics of the simulation system for the Moscow region for COSMO-Ru1M in the framework of the COSMO-Ru system are presented in the Table.

Table. The characteristics of configurations in the COSMO-Ru system on the CRAY XC40-LC ("Roshydromet") supercomputer

Characteristic	COSMO-Ru6ENA	COSMO-Ru2	COSMO-Ru1M	COSMO-Ru0.5M
Initial conditions	ICON	COSMO-Ru6ENA	COSMO-Ru2	COSMO-Ru2
Boundary conditions	ICON	COSMO-Ru6ENA	COSMO-Ru2	COSMO-Ru2
Time step, s	60	20	10	6
Grid spacing	0.06 (~6.6 km)	0.02 (~2.2 km)	0.009 (~ 1 km)	0.0045 (~500 m)
Number of grid points *X*, *Y*	2000 1000	1200 1400	200 200	400 400
Simulation domain size, km	11542.3 6631.9	1750.9 2032.7	197.1 191.1	197.1 197.1
Number of levels	40	50	50	50
Time, UTC hour	00:00, 6:00, 12:00, 18:00	00:00, 6:00, 12:00, 18:00	00:00, 6:00, 12:00, 18:00	Research mode
Forecast lead time, hour	120 (78)	48	48	36
Number of cores	1944	2880	144	576
Run time, minute	75	60	44	72
Run start, UTC hour:minutes	3:00	3:15	3:30	Research mode
Time to get the results:				
after the observation time	4:05	4:15	4:15	Research mode
for users	5:20	4:40	4:40	Research mode

It is clear that the operational simulations with the COSMO-Ru1M configuration (the grid spacing is 1 km) with a lead time to 48 hours included to the quasi-operational run mode are available to the users in 4 hours 40 minutes after the observation time, i.e., after 00:00 UTC (7:40 Moscow time). According to the Table, if the 500-m model is included to the operational run, the expected time of product reception may increase by a half an hour (that is not principal in a quick run case). However, the presented estimates of astronomic time can be reduced in case of using additional parallel processes on the supercomputer.

Figure 3 presents an example of the forecast of wind gusts as an operational product of COSMO-Ru1M for forecasters for 12:00 Moscow time on March 13, 2020. It is clear that the wind strengthening to 20 m/s and more was predicted in the whole city and region. The wind strengthened to 26 m/s at 12:30 in Domodedovo, to 22 m/s at 11:00 in Vnukovo, and to 23 m/s in Sheremetyevo. In the city, weather stations did not register wind speeds above 17 m/s; however, in some city areas wind gusts led to the falling of trees and loss of life, which indicated the actual local wind strengthening to the speed of at least 20 m/s.

5. CONCLUSIONS

In 2019, the COSMO-Ru1M configuration with the grid spacing of 1 km for Moscow megacity was implemented to the quasi-operational run mode at the Hydrometcenter of Russia. The configuration included the parameterization of urbanized areas, some modernizations of the description of processes in soil and vegetation, and the refined prescription of urban environment parameters. The use of observational data from the dense weather monitoring networks and profilers demonstrated the efficiency of the model simulation of temperature regime over Moscow, heat island effect, and thermal stratification over the city and suburbs. Works on the implementation of the 500-m version started, they include the preparation of data on the urban environmental parameters with respective detailing. The use of these new tools will improve the reliability of forecasting severe weather events in Moscow megacity, which is proved by numerical experiments.

The proposed methodological, scientific, and technological aspects considered in the present paper were discussed in detail both with Russian researchers and forecasters and with foreign specialists from the leading national meteorological services, in particular, in the framework of the Roshydromet cooperation in the COSMO international consortium and Short-Range Numerical Weather Prediction Programme (European Union) [26] and the bilateral cooperation between Roshydromet and China Meteorological Administration. It was found that the implemented direction and the obtained results correspond to the world level and will effectively improve the resolution of simulations at the next stages, i.e., will increase the adequacy of description of meteorological conditions, in particular, those leading to rapidly developing severe and adverse weather events for such complex megacity as Moscow.

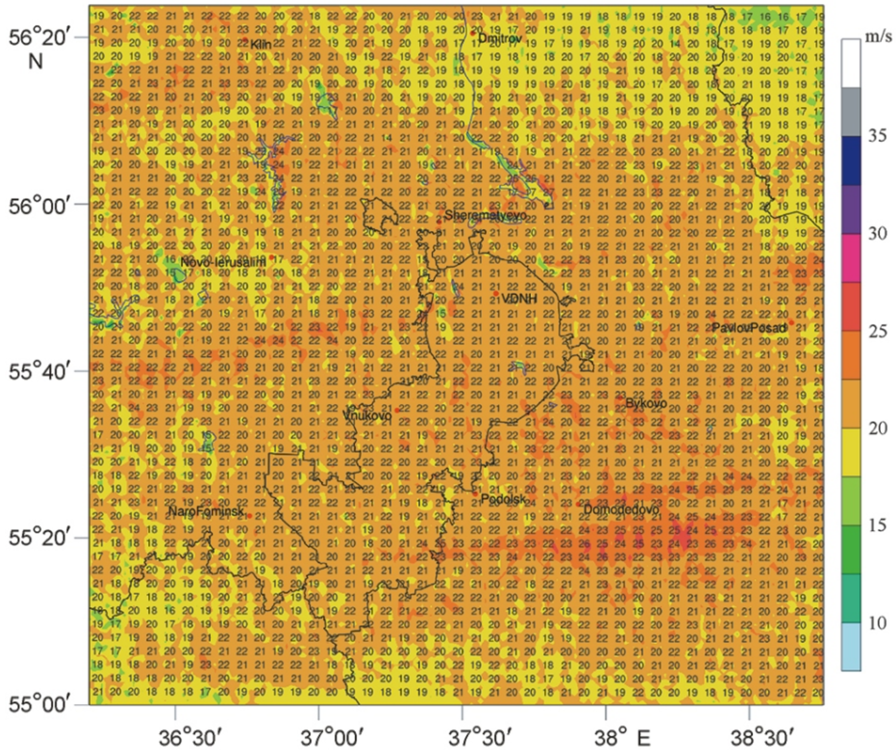

Fig. 3. The example of COSMO-Ru1M products: the forecast of wind gusts for 9:00 UTC on March 13, 2020 from initial data for 00:00 UTC.

For models with a grid spacing of 200–500 m, only studies are currently being carried out (for example, [17, 19, 24, 34]); therefore, a quasi-operational weather forecast with a grid spacing of 500 m for Moscow is innovative not only for Roshydromet, but also for other national meteorological services.

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