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The System for Numerical Prediction of Weather Events (Including Severe Ones) for Moscow Megacity: The Prototype Development

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Abstract—The COSMO-Ru1Mp prototype of the numerical weather prediction system for the Moscow region with a grid spacing of 1 km and with the included and adapted TERRA_URB parameterization module for the urban areas is implemented. The module is provided with necessary information on the urban development and on the sources of anthropogenic heat based on the adaptation of open data. The module is interfaced with the COSMO-Ru operational system for the regional numerical weather prediction developed in the Hydrometcenter of Russia. The primary testing of the COSMO-Ru1Mp is performed, including daily forecasts based on operational data. The advantage of this forecast system and the prospects of its further development are revealed.

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1. INTRODUCTION

The high performance of modern computing systems inspires the development of more detailed atmospheric models. This process was named "the quiet revolution" in [8]. For example, only recently the term "mesoscale model" was applied to the numerical weather prediction limited area models (regional models). Now in all leading numerical weather prediction centers the global models have a grid spacing of 9–13 km and can predict not only -scale (the range of 200–2000 km) but also partly meso- -scale (20–200 km) processes [26]. The transition to the nonhydrostatic approximation to describe circulations with the size of <100 km became urgent for global numerical weather prediction. For example, the ICON nonhydrostatic operational global model (DWD, Germany) [29] utilizes a grid with the spacing of 13 km (for several regions including Europe, the spacing is 6.5 km). At the same time, in the recent decade, during the development of numerical prediction technologies, many models with the spacing of several kilometers (in the best cases, 1–2 km) have been implemented in the national meteorological services. Increasing weight is given to the detailed forecasting of weather events, and not only of their formation conditions. Special attention is paid to the weather forecasting for megacities [7, 27].

The Moscow region can be called a ground for the generation of severe weather events, from freezing rains to tornadoes. Several air masses with contrast properties formed in the geographic regions from the tropics to the Arctic can be involved into circulation systems in the center of the Russian Plain. This can lead both to dramatic temperature changes, frontal heavy precipitation, etc. and to the formation of the hardly predictable complex pattern of meteorological fields which favors the rapid development of local weather events including severe ones. Data assimilation systems do not always register the features of the

Table 1. The databases used to form the external parameters of the COSMO-Ru1Mp model

Database	Data description	Spatial resolution
ASTER orography	Land surface orography	1 (~30 m)
GlobCover-2009	Vegetation cover types	10 (~300 m)
GLCC land use	Land use	30 (~1 km)
HWSD	Soil types and characteristics	30 (~1 km)
NDVI Climatology, SEA WiFS	Vegetation cover types and characteristics	2.5 (~4.6 km)
CRU near surface climatology	Near-surface climatology	0.5 (~55 km)
GACP Aerosol Optical Thickness	Aerosol optical thickness	4 5 (~440 550 km)
GLDB	Lake parameters	30 (~1 km)
MODIS albedo	Surface albedo	5 (~9 km)

three-dimensional structure of meteorological fields. The complexity of the situation is aggravated by the megacity impact. The urban heat island is the known fact, and urban effects on the regimes of wind, precipitation, cloudiness, and different phenomena including convective ones were also revealed [2, 3, 21, 24, 26].

The forecaster's skill consists in the execution of the complex analysis of numerical weather prediction outputs and fine features of synoptic conditions, the structure of air masses and atmospheric fronts, and urban effects. The fullest actual information and high-detail numerical forecasts in accordance to the world's practice are needed to improve the forecasting efficiency.

The improvement of the weather prediction system for Moscow is a complex problem which combines scientific, technological, and operation-production tasks. The Roadmap on the Development of Severe and Adverse Weather Monitoring and Forecasting System in the framework of the state program of Moscow "The Safe City" was prepared by Roshydromet jointly with the Government of Moscow in 2017 in order to solve the above problem. To create the scientific and technological basis for this project, the observation network in the region will be modernized and developed. The following systems will also be developed: the system for the high-resolution (with the grid spacing of 1 km) numerical short- and very-short-range weather forecasting and the system for the probabilistic ensemble forecasting for the estimation of the risk of severe weather events on the base of the Hydrometcenter of Russia. The implementation of the roadmap activities started in October 2018.

At the first stage, it was planned to develop a prototype of the required nonhydrostatic atmosphere model for the Moscow megacity with the 1-km grid spacing. For this purpose, the COSMO nonhydrostatic atmospheric model was chosen which is developed by the international consortium COSMO (COnsortium for Small-scale MOdeling) [12]; Roshydromet (represented by the Hydrometcenter of Russia) has been a member of this consortium since 2009. The national system for the short-range regional numerical weather prediction under development is called COSMO-Ru [4] in accordance to the consortium regulations: the first letters of the country name are added to COSMO. According to the resolutions of the Roshydromet Central Methodical Commission in 2011, 2016, and 2018, the COSMO-Ru was recognized as the base technology of numerical weather prediction for Russia and its regions based on the analysis of skill scores of forecasts of weather elements and on the speed and reliability of operational computations. The use of the COSMO-Ru as a base for high-detail numerical forecasts for the Moscow region will provide the proven high world level of the new system.

The present paper deals with the description of the COSMO-Ru1Mp model prototype for the Moscow region with the grid spacing of 1 km and the new module for the description of urbanized areas. The prototype is interfaced with the COSMO-Ru system and is developed in the Hydrometcenter of Russia.

2. METHODICAL BASIS OF THE MODEL PROTOTYPE DEVELOPMENT FOR THE MOSCOW MEGACITY

General information about the COSMO and COSMO-Ru models. The COSMO atmosphere model is intended for limited-area simulations on the grid with the spacing of <15 km to the height of 25–30 km in atmosphere and in the soil layers (with account of the vegetation cover) to the depth of 14 m. The corresponding documentation is presented at the website [12]. Data of both global and regional (limited-area)

Table 2. The external parameters used in the COSMO-Ru and COSMO-Ru1Mp

Parameter	Unit
Fraction of land in a grid element	1
Height above sea level	m
Geopotential height	m^2/s^2
Roughness length	m
Standard deviation of subgrid scale orography	m
Anisotropy of subgrid scale orography	d/v
Mean slope of subgrid scale orography	rad
Angle between principal axis of orography and east	rad
Type of the soil (numbers 1–5)	d/v
Fraction of land (sea) covered by ice	1
Fraction of plant cover during the vegetation period	1
Fraction of plant cover out of the vegetation period	1
Leaf area index of plants during the vegetation period	1
Leaf area index of plants out of the vegetation period	1
Minimum stomata resistance	s/m
Fraction of urbanized territory	1
Ground fraction covered by deciduous forest	1
Ground fraction covered by evergreen forest	1
Thermal surface emissivity	d/v
Depth of the roots	m
Normalized difference vegetation index	1
Temperature of the lower soil layer	K
Lake fraction in a grid element	1
Fraction of a grid element occupied by the certain land surface type	1
Surface albedo (monthly mean values)	d/v
Surface albedo in the near IR and UV regions (monthly mean values for each type)	d/v
Aerosol optical thickness for soot, organic, sulfate, dust, and marine aerosol (monthly mean values for each type)	d/v

Note: d/v is dimensionless value.

models can be used as boundary conditions for the COSMO model. Tables 1 and 2 present the lists of international datasets and required external parameters recommended by the consortium. The sets of external parameters adapted for a specific model version depend on the set of parameterizations and are prepared with account of model grids.

The main features of the COSMO model are as follows:

—the model is nonhydrostatic (it can describe some convective motions such as deep convection at the grid spacing of not more than 3 km);

—the similar size of grids over the whole integration domain due to the use of shifted spherical coordinate system (the equator passes through the domain center);

—the solution is based on the method version developed by G.I. Marchuk and based on the splitting into fast and slow processes;

—the adaptability of codes to the problems of operational runs with the effective use of methods for the parallelization and optimization of simulations.

When creating operational technologies for the numerical weather prediction based on the COSMO model, the national meteorological services jointly solve the problems of preparation and obtaining of external parameters, initial and boundary conditions, testing of results, improvement of algorithms, postprocessing improvement, and methods for the presentation of model outputs to users.

The COSMO-Ru system for the high-resolution short-range numerical weather prediction for Russia and neighboring regions developed by the Hydrometcenter of Russia has operated since 2009, its operational runs are supported by the Roshydromet Main Computing Center [4]. The technological complex of the COSMO-Ru includes all stages of the numerical forecast production: from data assimilation to the presentation of output products and the monitoring of their quality. Four times a day, the COSMO-Ru system computes forecasts on the grids with the spacing of 13.2 and 6.6 km (for entire Russia and neighboring territories), 7 km (from Eastern Europe to the Urals), 2.2 km (for Belarus and the central regions of Russia, for Tatarstan and a part of the North Caucasus), and 1.1 km (experimental versions for Sochi and Krasnoyarsk) based on the principle of "nested" domains. The daily COSMO-Ru products (about 8000 maps of meteorological fields of more than 50 types, tens of series of prognostic aerological diagrams, meteograms for 1500 settlements in Russia, Belarus, and Central Asia) are used in more than 70 weather forecasting centers in Russia and the CIS [1].

Substantiation of the COSMO-Ru1Mp configuration. Grid spacing. The grid spacing of 1 km was chosen as the main position of the model prototype configuration. In 2018, the highest detailing of grids for the operational numerical prediction for the Moscow region was equal to 2.2 km (the COSMO-Ru2 subsystem for the forecasting in the Central Federal District). Such grid spacing allows describing circulation processes with the size of 12–20 km, because the atmosphere model can simulate atmospheric circulations with a horizontal size that by 6–10 times exceeds the spacing of simulation domains (this is the actual model resolution). The modeling of weather events caused by the circulation whose scale is comparable to the size of Moscow administrative districts (~5–10 km), requires higher detailing, i.e., the use of grids with the spacing of not more than 1 km. The simulation of mesoscale convective systems with the size of 2–10 km which allows predicting some severe weather events, requires still smaller grid spacing.

Some meteorological services, for example, in Great Britain, Switzerland, France, Canada, and the USA have already successfully tested the operational numerical prediction systems with the grid spacing close to 1 km. In Russia, the positive effect on the grid with the spacing of 1.1 km was obtained during the forecasting of precipitation and wind fields for the Sochi-2014 Winter Olympic and Paralympic Games [6, 19]. Nevertheless, for the grids with the spacing of about 1 km, any experience of implementation is pioneering especially for megacities, because local features are manifested on such scales.

The transition to the grid spacing of 1 km as compared to the 2.2 km grid extends the high-frequency part of the range of simulated atmospheric motions and increases the reliability of forecasting of some weather phenomena and temperature regime features, in some cases with the successful detailing of numerical forecasts to the large parts of a megacity. However, the formation and location of local phenomena (showers, thunderstorms, or wind gusts induced by the building configuration) are still beyond the capabilities of the modeling.

The selection of the simulation domain size is defined by two opposite conditions: the saving of computation efforts for as early as possible delivery of products to forecasters and by the sufficient size to "push" the effect of boundaries (~10–20 km) away from the central regions. The authors of [6] showed a possibility of using the domain with the size of 200 200 km with the grid spacing of 1.1 km for the precipitation forecast for the period to 18 hours without the noticeable quality loss as compared to larger computation domains. Proceeding from this, the domain of 180 180 km was chosen for the COSMO-Ru1Mp as the minimum possible one.

Revision of "physical content." The increasing resolution of numerical weather prediction systems requires the revision of algorithms for some parameterizations and external parameters (Table 2) and the provision of model runs with necessary information [5]. In the context of the problem of numerical weather prediction for Moscow, the most important point is that the description of the interaction between the urban environment (being a special type of land surface) and the atmosphere is included to the COSMO-Ru. The neglect of effects of the special heat and moisture exchange between the city and the atmosphere reduces the reliability of high-resolution forecasts for the megacity and its suburbs; therefore, the inclusion of the scheme for the description of the urban environment to the model is the major component of the COSMO-Ru1Mp development.

Consideration of urbanized territories based on the TERRA_URB parameterization. The schemes of "urban" parameterizations are actively developed by the world research teams due to the complexity and absence of universality of the urban development. At the current level of development of numerical weather prediction, the explicit consideration of heat exchange between buildings and the air flowing around them is impossible. At present, so called urban environment models are used assuming that a part of the model cell can be occupied by homogeneous environment with a specified set of "urban" characteristics. Some parameterizations of the urban environment with different degrees of complexity have already been developed [20, 24]. The COSMO-Ru1Mp utilizes the TERRA_URB CLM parameterization [28] developed in the framework of the COSMO-CLM community on the regional climate modeling [17]. The positive effect is achieved when the degree of urbanization, the geometric features of buildings, and anthropogenic heat emissions are taken into account. The TERRA_URB belongs to the class of the simplest models of urbanized areas. More complex multivariable schemes with the heat budget modeling for walls and roofs of buildings, road surface, etc., cannot specify accurately some parameterizations. Unlike such schemes, the TERRA_URB simulates heat and moisture exchange by means of several additional relationships using the semiempirical values of the small number of parameters for urbanized surfaces. The TERRA_URB is computationally cost-effective, rather realistically describes the thermal impact of the megacity on the meso- -scale atmospheric processes, and is easily integrated into the atmospheric model.

The use of the COSMO-CLM climate model version with the TERRA_URB module performed well in the previous studies on the climate modeling in the Moscow region. The possibility of simulation of the urban heat island and dry island, wind anomalies induced by the urban effects, cloudiness, and precipitation was demonstrated in [2, 23, 26].

The features of the TERRA_URB module are the following.

1. Consideration of the mosaic structure of territories within the city. The COSMO model with the TERRA_URB module takes into account the alternation of built areas and green zones (parks, boulevards, garden squares, etc.) using the "mosaic" approach. For each model cell, the equations of this module are solved twice: for natural and urbanized surfaces. The resulting flows from the cell to the atmosphere are calculated by the weight summing of flows from both types of surfaces.

2. Presentation of urbanized areas. Buildings, roads, sidewalks are considered as solid moisture-resistant slabs laid on natural soil. The Surface Area Index (SAI) defines the fraction of the area covered by them.

3. The characteristics of urbanized areas for heat budget calculation: effective heat capacity C_{ef}, thermal conductivity $_{\mathrm{ef}}$, albedo A_{ef}, and emissivity $_{\mathrm{ef}}$.

4. Turbulent heat exchange with the atmosphere. The parameters of aerodynamic roughness (as a function of building height) [24] and thermal roughness [9] are introduced. The algorithms for calculation of heat balance components used in the TERRA_URB are somewhat different from those of the TERRA base version.

5. Water balance. The urbanized surface is moisture-resistant but allows the formation of puddles of various depths which dry out in different time periods. The probability distribution function (D) for the puddle depth D is introduced to describe this process. If precipitation fills in the maximum puddle capacity, the moisture excess is liquidated from the model water balance similar to the description of surface runoff for natural surfaces.

6. Additional external parameters. Additionally, two electronic maps are specified: the fraction of the area of urbanized territories and the average annual anthropogenic heat flux whose current values are determined with account of annual and diurnal cycles.

Due to the above properties, the TERRA_URB provides a difference in the values of the following factors whose contribution varies depending on synoptic conditions and time:

—more effective absorption of solar radiation by the city and its corresponding heating, including the effects of reemission and re-reflection between the buildings due to the modified thermophysical and optical properties of artificial surfaces;

—the high roughness of urban land surface defines more active turbulent heat exchange and, hence, the atmosphere heating over the city;

—the modified relation of sensible and latent heat fluxes in the heat budget due to the presence of moisture-resistant artificial surfaces;

—heat generation by transport, industry, heated buildings, etc. as an additional component of heat budget.

The current anthropogenic emissions are calculated using average annual values; in the future, the authors plan to develop the algorithm of emission determination depending on specific weather conditions.

3. THE COSMO-Ru1Mp AS A MODEL PROTOTYPE FOR THE MOSCOW MEGACITY

Setting of parameters for the TERRA_URB in the COSMO-Ru1Mp. According to [28], the following values of radiation and thermophysical characteristics were specified for the COSMO-Ru1Mp: $A_{\mathrm{ef}} = 0.1$, $_{\mathrm{ef}} = 0.86$, $C_{\mathrm{ef}} = 0.777$ W/mK, $_{\mathrm{ef}} = 1.25 \quad 10^6$ J/m^3 K. The distribution for the map of average annual heat emissions was specified in accordance to [11].

The original technology developed in [22, 23] was used to determine the building parameters. It is based on the GIS analysis of the objects of OpenStreetMap [18] being the open cartographic database updated by

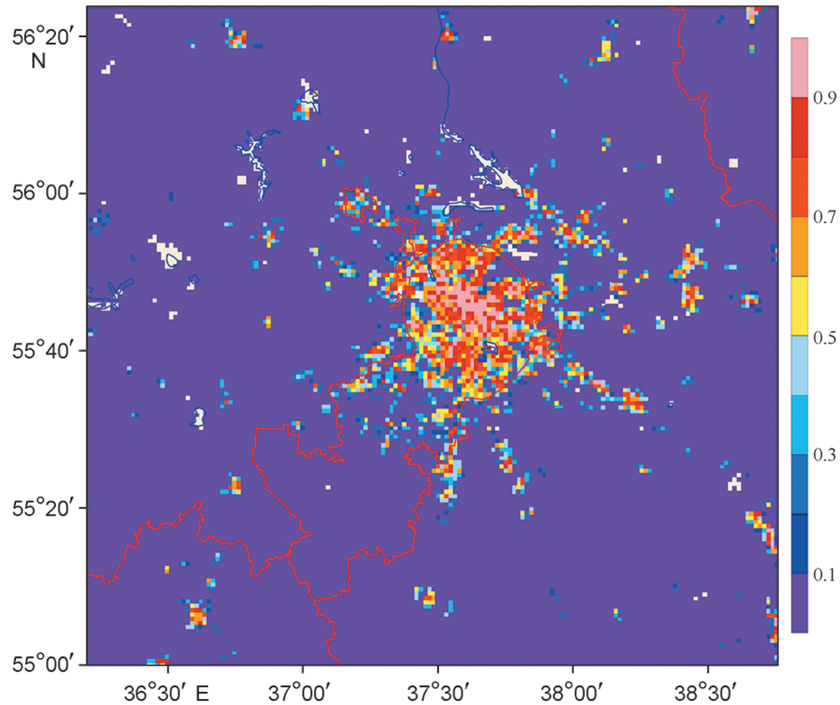

Fig. 1. The simulation domain and the fraction of urbanized areas in the COSMO-Ru1Mp (the water bodies are shown with the white color, and the natural landscapes are shown with the violet color).

users and containing information on each separate building, road-and-street network fragments, and segments of territories with different land use (domestic and industrial areas, water bodies, green spaces, etc.). The use of OpenStreetMap was caused by the comparison of SAI obtained on its base with the values obtained from GlobCover-2009 [13, 14]. The comparison revealed that GlobCover-2009 interprets almost the whole territory of Moscow within the Moscow Automobile Ring Road as completely urbanized, which is evidently false. The representativeness of OpenStreetMap for Moscow was proved by the comparison with data provided by Geocenter-Consulting. The GIS analysis was applied to calculate the characteristics of buildings and land use. Parameters of the Moscow region for the TERRA_URB were obtained with considerable efforts on verification and correction of data, with the subsequent interpolation to the model grid. The SAI map introduced to the technology of regular model runs for the COSMO-Ru1Mp is presented in Fig. 1.

Interfacing of the COSMO-Ru1Mp configuration with the COSMO-Ru system. An important stage of the COSMO-Ru1Mp development is its testing in the framework of the COSMO-Ru system which is fully possible only based on real data. For this purpose, the following technological chain of consecutive “telescoping” was implemented:

the results of the DWD ICON global modeling: initial and boundary forecast data (the grid spacing is 13 km, the time step between the forecast lead times is 3 hours, data are received as soon as each lead time is ready) COSMO-Ru6-ENA (the grid spacing is 6.6 km, the time step is 1 hour) COSMO-Ru2 (the grid spacing is 2.2 km, the time step is 1 hour) COSMO-Ru1Mp (the grid spacing is 1 km).

The real-time test simulations with the COSMO-Ru1Mp system prototype were carried out on the Cray-XC40-LC supercomputer. For the 1-km grid the outer parameters were adapted. (Tables 1 and 2). In particular, the comparison of data adapted to such grid with the parameters for the 2.2-km grid revealed significant differences in the terrain fields in the valley of the Moscow River and water bodies, because some reservoirs which adjoin the northern part of Moscow and can exert essential influence on wind and on the development of convective processes, are absent in the 2.2-km version.

The routine COSMO-Ru1Mp model runs since February 2019.

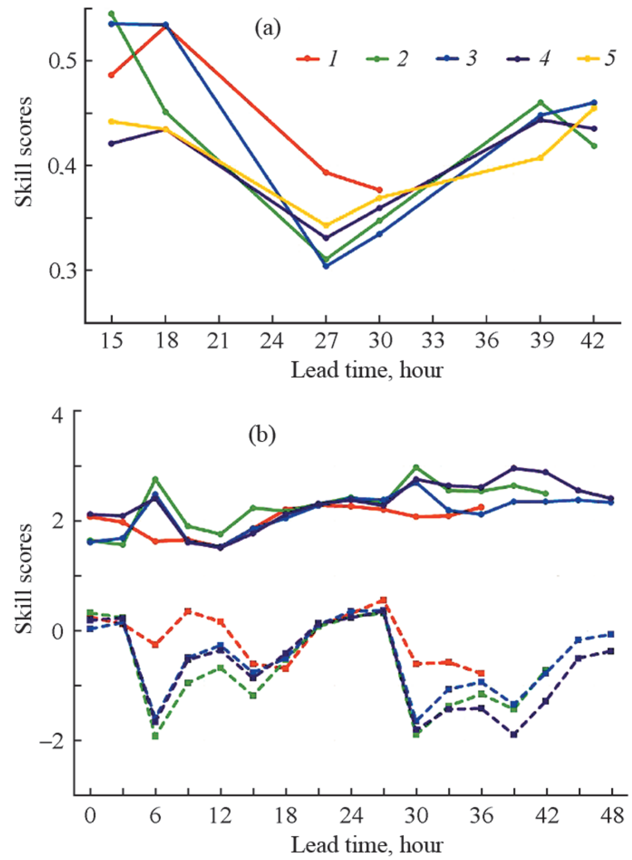

Fig. 2. The skill scores of COSMO-Ru1Mp forecasts for April 2019 as compared to the other COSMO-Ru components (the mean for April 2019, the 00:00 UTC run): (a) 12-hour total precipitation; (b) 2-m air temperature. (*1*) COSMO-Ru1Mp; (*2*) COSMO-Ru; (*3*) COSMO-Ru7; (*4*) COSMO-Ru13; (*5*) COSMO-Ru6. The solid lines show the root-mean-square error (RMSE), the dash lines represent the mean error (ME).

4. RESULTS OF COSMO-Ru1Mp PRELIMINARY TESTING AND THEIR DISCUSSION

At the stage of the prototype creation, the objective of the developers was to prove its efficiency. At the further stages, it is planned to estimate the skill scores and to improve the prototype with account of monitoring results.

The calculation of the set of skill scores as compared to the other COSMO-Ru configurations has been carried out on a daily basis since March 2019; after that, the monthly averaging is applied. At the same time, the additional improvement of algorithms and information required for the COSMO-Ru1Mp operation is executed. In general, the testing results showed that the COSMO-Ru1Mp configuration more realistically predicts precipitation and temperature in the Moscow region as compared to the operational COSMO-Ru configurations with the larger values of grid spacing which do not include the parameterization of urbanized areas. The set of skill scores for the numerical forecast of weather elements was calculated in accordance to [16].

For example, let us present skill scores for April 2019 based on data from 42 weather stations located in the COSMO-Ru1Mp simulation domain: for the forecasts of precipitation (Fig. 2a) and temperature (Fig. 2b) with the COSMO-Ru1Mp and COSMO-Ru13, COSMO-Ru7, and COSMO-Ru2. It is seen that the COSMO-Ru1Mp has the best or identical ETS (Equitable Threat Score) (it shows how precisely the forecasts agree with actual weather with the deduction of random hits) for 12-hour total precipitation starting from the lead time of 18 hours. The scores for surface air temperature (Fig. 2b) also demonstrate the advantage of the COSMO-Ru1Mp configuration, with the smallest values of RMSE (root-mean-square error) and ME (mean error). In particular, as the COSMO-Ru1Mp considers urban effects, the accuracy of temperature forecast in the morning and in the daytime is higher.

The certain "restrained" skill of COSMO-Ru1Mp precipitation forecasts during the initial forecast hours draws attention. At the next nearest stages, it is planned to modify the technology to reach the full

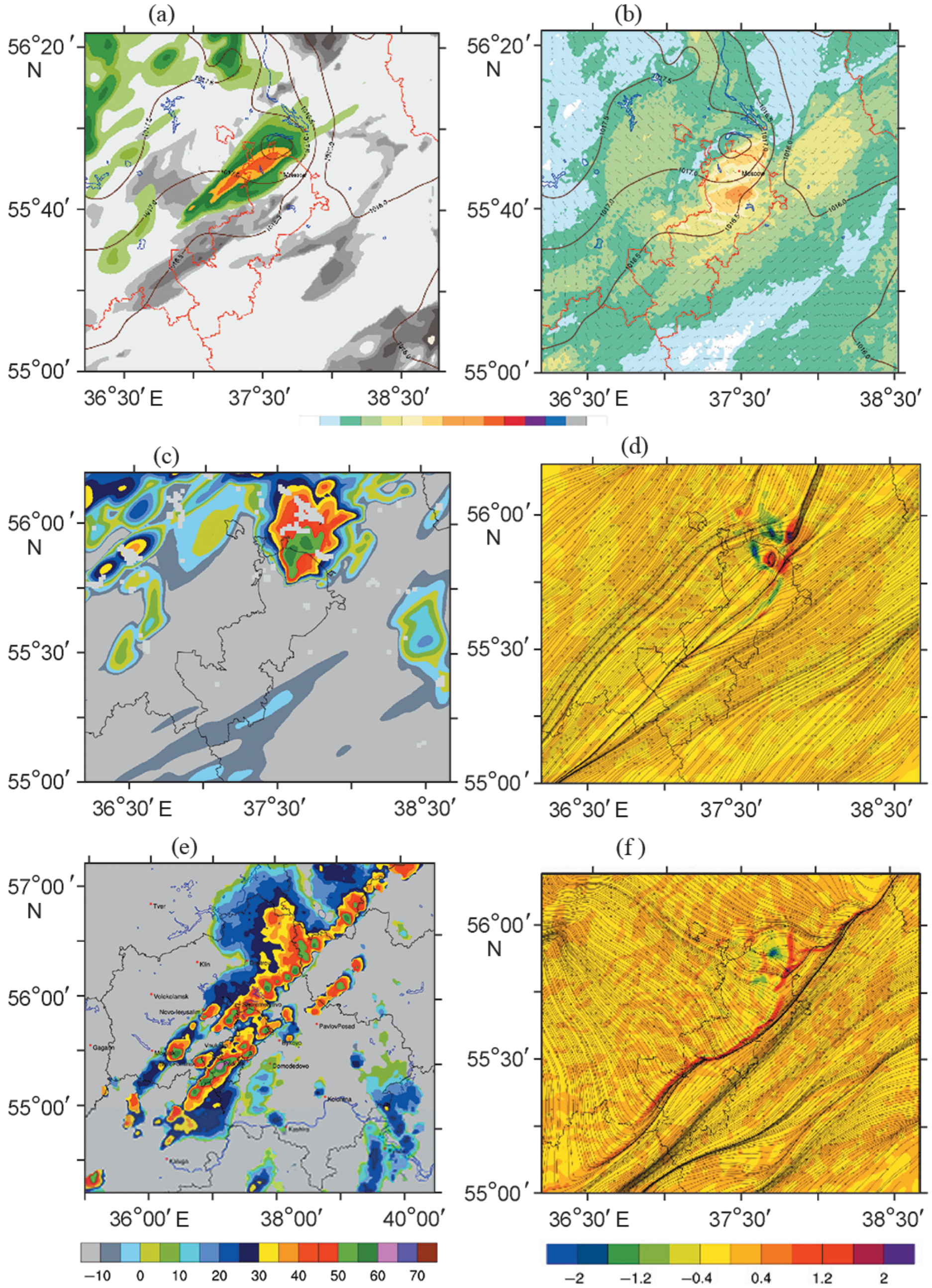

Fig. 3. The 25-hour forecast of convective phenomena in Moscow for 16:00 Moscow time on May 30, 2019: (a) 12-hour total precipitation and sea-level pressure; (b) wind gusts and sea-level pressure; (c) maximum reflectivity; (d) streamlines at the level of 2500 m and vertical motions; (e) Doppler weather radar reflectivity map for the Moscow region; (f) streamlines at the level of 500 m and vertical motions.

agreement between the COSMO-Ru1Mp fields and data of “parent” models so increasing the skill at the early stages of precipitation forecast.

An interesting example is thunderstorms and showers which suddenly occurred over Moscow and the Moscow region on May 30, 2019. On that day, the cold front with temperature contrasts of about 10 C passed over the region. The mesoscale convective system resembling a supercell (Fig. 3) where the surface air pressure drops by ~0.5 hPa (Fig. 3a), was formed in the COSMO-Ru1Mp forecast for 24–26 hours (the start was at 12:00 UTC on May 29). Based on the analysis of model fields of reflectivity and wind, this convective system can be considered as a supercell [10, 25]. This is indicated by the presence of the hook echo on the reflectivity map, by the configuration of the zones of updrafts and downdrafts, and by the mesocyclone observed in the wind field at the height of 2000 to 5000 m (for 2500 m see Fig. 3d). On that day, from 14:30 till 18:00 Moscow time (with good agreement with the time of weather events predicted by the model) heavy showers with thunderstorms, in some places with squalls and hailstorms, were registered in the Moscow region. Approximately at that time, wind gusts reached 17 and 15 m/s at Vnukovo and Sheremetyevo airports; no thunderstorms and wind strengthening was observed in Zhukovsky and Domodedovo airports, which is consistent to the configuration of simulated weather phenomena. However, numerous small convective cells rather than the large mesoscale convective system along the front were registered over Moscow and the Moscow region on the map of actual reflectivity (Fig. 3e). The comparison of the model front position (Fig. 3f) and actual reflectivity indicates good agreement between them. The significant underestimation of powerful clouds along the whole length of the front draws attention. This underestimation as well as the certain displacement of the precipitation zone (approximately by 5–7 km relative to their actual zones) is seen from the comparison of maps of actual and prognostic reflectivity (Figs. 3c and 3e). Several reasons can be suggested: it is quite possible that measurement data are not sufficient for the adequate simulation of humidity by the model; in principle, this obstacle can be partly eliminated by the assimilation of radar information in the COSMO-Ru1Mp and in the “parent” COSMO-Ru2 and, in the future, by the observation network development.

5. CONCLUSIONS

The prototype of the COSMO-Ru1Mp numerical weather prediction model with the grid spacing of 1 km including the TERRA_URB parameterization of urbanized areas was developed on the Cray-XC40-LC supercomputer; the necessary parameters of the Moscow urban environment characterizing the urban terrain and the intensity of urban heat emissions adapted for the TERRA_URB were prepared. The adaptation of external parameters of land surface from available datasets for the territory of the Moscow region for the grid spacing of 1 km was carried out.

The developed model was interfaced with the operationally functioning COSMO-Ru system, and the testing started of the new real-time subsystem for the numerical weather prediction based on the COSMO-Ru1Mp prototype with the 1-km grid spacing.

The first results of the testing were obtained by the analysis of the skill scores and individual forecasts based on the COSMO-Ru1Mp. The results demonstrated a possibility of forecasting convective systems and the advantage over the other COSMO-Ru subsystems which have lower resolution and do not consider the effects of urbanized areas.

The work was completed in a short time frame thanks to the team with the great experience of implementation of COSMO-Ru configurations for different regions working in the Hydrometcenter of Russia; due to the work with the TERRA_URB parameterization scheme developed in the COSMO-CLM community and tested in the context of climatic research for the Moscow region; using of the new Roshydromet Cray-XC40-LC supercomputer with the peak performance of 1.3 Pflops and with the performance of 1.2 Pflops during the LINPACK tests.

The further testing of individual cases and the monitoring of skill scores are planned; based on its results, it is planned to correct the technology, algorithms, and parameters of the COSMO-Ru1Mp including the TERRA_URB for the Moscow megacity.

The modeling with the grid spacing of 1 km is the starting stage for more detailed numerical weather prediction technologies for big cities. For example, currently, the operational numerical weather prediction system with the grid spacing of 300 m is developed for London [15]. It will produce forecasts for different districts of the city with the simulation of atmospheric processes with the size of 2–3 km. For a further increase in the forecast resolution for Moscow, it is planned to prepare the technology on the grid with the spacing of hundreds of meters.

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