New Operational Short-Range Numerical Weather Prediction System of Khabarovsk Regional Specialized Meteorological Center

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Abstract

A description of new operational short-range numerical weather prediction (NWP) system of the Regional Specialized Meteorological Center of Khabarovsk, Russia is presented in this article. Proposed NWP system is based on nonhydrostatic Weather Research and Forecasting model of atmosphere with horizontal grid spacing of 4.5 km and 51 vertical levels. The model is run on cluster CRAY XC-40 four times per day and will replace current short-range forecasting system of 'Khab-15' after an extensive testing. It is shown comparison of forecast skill between the NWP systems of 'Khab-4.5' and 'Khab-15' for winter and spring months of 2019. Samples of product are given. Further development of the 'Khab-4.5' model system is discussed.

1 Introduction

High-performance computing system and modern nonhydrostatic atmospheric models are widely used for numerical weather prediction (NWP). Computing equipment and models are integrated to an operational NWP system. A NWP system is a foundation for weather guidance. The following objectives need to be fulfilled by NWP system: managing the interactions between the parts of technology (these parts may require various computational resources); synchronization and monitoring a calculation cycle; processing typical errors like network delays, missing of require data etc; send out forecasts to end users and tracking it delivery status.

In the article a description of new short-range NWP system of the Regional Specialized Meteorological Center of Khabarovsk, Russia (RSMC Khabarovsk) is presented. Requirements of aviation meteorology [1] lead to necessity of improvement of current NWP system 'Khab-15' of RSMC Khabarovsk [2] in particular to increase refresh rate and reduce the total time of calculations. Rapidly changed weather conditions especially during severe weather events also require frequently refreshed forecast data for automated prediction methods [3]. Another problem which will be solved by new NWP system is a forecasting of adverse weather conditions for large industrial centers of eastern part of Russia to reduce air pollution from harmful industrial emissions [4].

2 Numerical Weather Prediction System of 'Khab-4.5'

NWP system of 'Khab-4.5' is new technology to replace current prediction system of RSMC Khabarovsk named 'Khab-15'. Both systems produce forecasts for the territory of Russian Far East and Eastern Siberia (Fig. 1). The geographical domain of 'Khab-4.5' (in Lambert conformal conic projection) is slightly reduced compared with 'Khab-15' to decrease calculation time due to a significant increasing in a number of grid points (horizontal grid spacing is reduced from 15 to 4.5 km). However, vertical resolution of new NWP system is greatly expanded to improve the representation of a state of atmosphere, especially, vertical profiles of temperature, humidity and wind which are crucial for aviation meteorology and forecasting of atmospheric convection.

Maximum lead time for both systems is still the same (72 hours) and completely covers the period of short-range weather forecasting [5]. Calculations of 'Khab-4.5' run four times per day (0000, 0600, 1200 and 1800 UTC). This feature is also every important for aviation: first, automated forecasts are produced continuously with overlapping; second, model output data allows producing operational terminal airport forecasts (TAF) [1] for standard times of a given lead time.

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The Advanced Research version of Weather Research and Forecasting model (WRF-ARW) [6, 7] is used as a basic numerical model in both NWP systems of RSMC Khabarovsk. The WRF model is started to develop in 1990s in the United States of America (USA) by group of various organizations. Today it is used by wide range of specialists for numerical simulations of atmospheric phenomena in idealized or real cases and it is suitable for weather forecasting. Source code of WRF-ARW is open. The WRF model is a main part of the High-Resolution Rapid Refresh model [3] of National Centers of Environmental Prediction (NCEP, USA) as well.

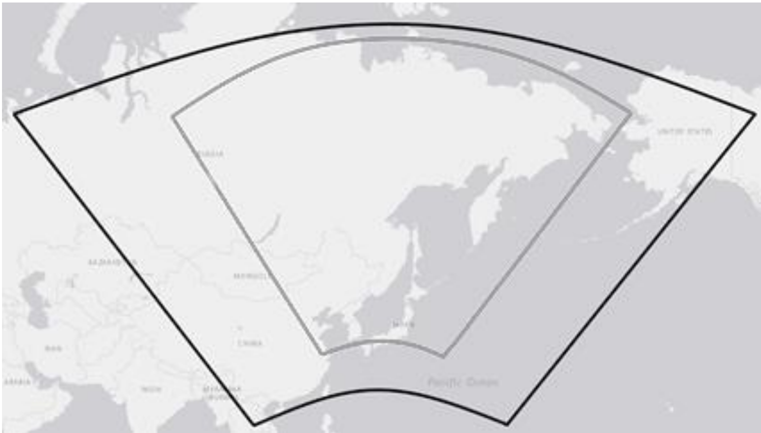

Figure 1: Horizontal domains of the 'Khab-15' (black) and 'Khab-4.5' (grey) NWP systems

Operational initial and lateral boundary data for WRF-ARW model provides from output of Global Forecast System (GFS, NCEP) [8]. GFS data with grid spacing of 0.5° updated every 3 hours during the calculation of the 'Khab-4.5' system.

In Table 1 technical characteristics of 'Khab-15' and 'Khab-4.5' NWP systems of RSMC Khabarovsk are presented. WRF-ARW release was transited from version 3.4.1 to 3.9.1. The last version of WRF is 4 but the WRF version 3.9 has been intensely tested. WRF-ARW model of version 3.9.1 has new parameterizations of atmospheric processes and some old schemes were updated to increase the accuracy of a simulation. In NWP system of 'Khab-4.5' WRF-ARW model uses Thompson microphysics parameterization and does not apply any convection scheme due to grid step of 4.5 km. The short- and longwave radiation balance is calculated by rapid radiative transfer model. Mellor-Yamada-Nakanishi-Niino scheme is planned to use to figure out turbulent kinetic energy budget in planetary boundary layer (PBL). The Noah land-surface model of four soil levels performs parameterization of surface layer processes and provides surface sensible and latent heat fluxes and upward short- and longwave radiation fluxes to the parent atmospheric model. These parameterizations are recommended to use [6].

Table 1: Technical characteristics of 'Khab-15' and 'Khab-4.5' NWP systems of RSMC Khabarovsk.

NWP system	Geographical domain	Grid points and spacing	Vertical levels	Time step, s	Lead time, hours	Runs per day	WRF version
Khab-15	30°-70° N, 80° E-170° W	501 x 401, 15 km	31	60	72	2	3.4.1
Khab-4.5	38°-68° N, 100°-180° E	1451 x 1181, 4.5 km	51	25	72	4	3.9.1

2.1 A Calculation Cycle of the 'Khab-4.5' NWP System

The NWP system of 'Khab-4.5' is specially designed for new high-powered computing platform based on cluster CRAY XC-40 which is installed in 2018. This cluster includes 60 nodes of two 18-cores Intel Broadwell processors with Dragonfly topology and has total peak performance of 76 TFlops. Network storage under parallel-distributed file system of Lustre serves to implement parallel input and output operations to accelerate calculations of the WRF-ARW model. Output files of the WRF-ARW model have large size (each of it takes near 8 GB of memory storage). However, a file has to be written in parallel to cut saving time. The saving time of one model output file was shortened from 23-25 to 1.8-2.2 s by using parallel netCDF library [9].

The calculations of the NWP system of 'Khab-4.5' will start automatically four times daily (every 6 hours from standard times of 0000, 0600, 1200 and 1800 UTC at 0430, 1030, 1630 and 2230 UTC respectively). At present the system starts twice a day in quasi-operational regime (from 0000 and 1200 UTC).

One run of the NWP system 'Khab-4.5' includes three main steps: WRF preprocessing, calculation of the WRF-ARW model and post-processing. These steps are joined and maintained by main script of bash and python. The major functions of the main script are managing the interactions between parts of technology; synchronization and monitoring a calculation cycle; processing of typical errors. The main script keeps track statuses of running programs, manages start of applications and proceeds intermediate data between parts of technology. Log messages of the NWP system are stored to database and an operator in charge may view it on-line.

The programs of the first step of preprocessing decode initial and boundary data and interpolate it to the grids of WRF-ARW model. Furthermore, surface observations in code forms of SYNOP and METAR are processed on this stage. Weather reports are used to determine the accuracy of previous model forecasts and, moreover, it is transferred to data assimilation system to initialize new run of a numerical model. However, the procedure of data assimilation is still under development and NWP system of 'Khab-4.5' does not implement it at the current state. The WRF-ARW model is run on the second stage. Programs of post-processing start at the same time as numerical model to handle new raw forecasting data of parallel netCDF format on the fly. WRF-ARW model uses Message-passing interface and OpenMP subroutines to conduct calculations in parallel on cluster CRAY XC-40. Post-processing programs are also written with OpenMP calls and mostly implement procedures of various methods to produce forecasts of clouds, make special weather prediction for aviation and prepare simulated data for other models of RSMC Khabarovsk (i.e. sea level model). Weather maps, meteograms (weather forecast figure with charts for a special point of interest), text messages and other visual products are produced on post-processing stage. These products are published on special web-sites (khabmeteo.ru, meteo-dv.ru and ferhri.org) and distributed to end users by e-mails, ftp and internal network.

Programs of WRF preprocessor [6] includes following items: geogrid.exe to process statical data like orography and soil types to the horizontal model grids; ungrid.exe to unpack downloaded GFS data of GRIB2 format; metgrid.exe to horizontally interpolate unpacked GFS data to the WRF-ARW model grids. All these programs run on 10 nodes of CRAY XC-40 cluster. This step is fulfilled in 15-20 minutes. Then, program real.exe is started to vertically interpolate all prepared data to the WRF-ARW model levels. This operation demands high-performance computing; it uses 15 nodes of CRAY XC-40 cluster and requires 20 minutes. Following these actions the WRF-ARW model is ready to run on 40 nodes of CRAY XC-40 cluster; model works near 90 minutes (depends on maximum lead time). At the same time bash script of post-processing is started to handle WRF output on fly. Programs of post-processing run on a front-end server of two 18-cores Intel processors; therefore, it may use up to 36 threads of execution. Post-processing is a complex set of procedures. It includes following main actions: calculation of methods to diagnose weather parameters and meteorological fields (cloud cover, icing, atmospheric pressure adjusted to mean sea level, position of zero-isotherm, type of precipitation, TAF etc.); interpolation of WRF data to standard pressure levels (1000, 850, 700, 500, 300, 150 hPa etc.); conversion of interpolated data to GRIB format; distribution of products to end users; preparation of meteograms, various weather maps, tables and automated text messages; publication of forecasts on specialized web-cites (i.e. meteo-dv.ru and ferhri.org); store of output model data for further estimation of forecasts' accuracy). For some operations like conversation to GRIB format and interpolation to pressure levels unified post processor [10] is used. Post-processing programs work in parallel; therefore, they will have finished in 20 minutes after last WRF output file would have fulfilled.

In conclusion, one run of NWP system of 'Khab-4.5' gets near 2 hours without taking into the account the period of time to download input GFS forecasts available online on NCEP servers.

2.2 Output Products of the NWP System'Khab-4.5'

The NWP system of 'Khab-4.5' releases wide range of automated output products. It includes binary messages of GRIB format, set of weather maps, meteograms for points of interest and group of text messages (special tables, warning messages, TAF etc.). Weather maps include slides for the layers of free atmosphere, planetary boundary layer and surface. This information generates in automatic by fortran and python programs. Slides are plotted with calls of matplotlib library [11] in parallel (package multiprocessing). Our aim is making specialized products for end users depending on their demands.

Binary messages of GRIB format are published. Messages include meteorological fields (geopotencial height, u- and v-wind components, temperature, humidity, divergence, vorticity etc.) on surface and standard pressure levels. These data are converted to lat-lon projection with horizontal grid step of 0.5°.

Maps of geopotential height and horizontal wind vector (with emphasizing of strong wind) are produced for standard isobaric surfaces of 100, 200, 300, 500, 700, 850, 925 and 1000 hPa. One type of surface weather map depicts cloud cover, areas of precipitation and pressure reduced to mean sea level (pmsl) (Fig. 2a). Another surface weather map shows air temperature on 2 m above ground layer (AGL) and 10-m horizontal wind vector (with emphasizing of strong wind). Furthermore, maps of total accumulated precipitation are prepared for hydrological applications.

In addition 'Khab-4.5' produces some special weather maps for aviation sector. These slides depict pmsl by standard atmosphere, areas of possible icing, heights of zero-isotherm, index of convection, areas of low-level turbulence etc. In the near future output production will be expanded by forecasts of clear-air turbulence and mountain waves.

Meteograms (Fig. 2b) are also produced by NWP system of 'Khab-4.5'. One figure includes 3 panels. The first panel shows surface forecast: timelines of 2-m air temperature, 2-m dew point, pmsl and wind shift near surface (or horizontal wind vector on 10 m AGL). Next panel depicts timelines of 3-h liquid and solid precipitation and characteristics of clouds: top and bottom heights of clouds, position of zero-isotherm, cloud cover and index of convection. Last panel illustrates timeline of air temperature, humidity and wind vectors on specific vertical levels.

Text messages includes fixed-term data like 2-m air temperature, psml (or surface pressure), 10-m wind vector and pmsl with a step of 1, 3, 6 etc. hours for points of interest.

The products of NWP system of ‘Khab-4.5’ may use as input data for specialized forecasting models. For example, current sea level model of RSMC Khabarovsk [12] uses as input 10-m wind and pmsl fields of ‘Khab-15’ NWP system.

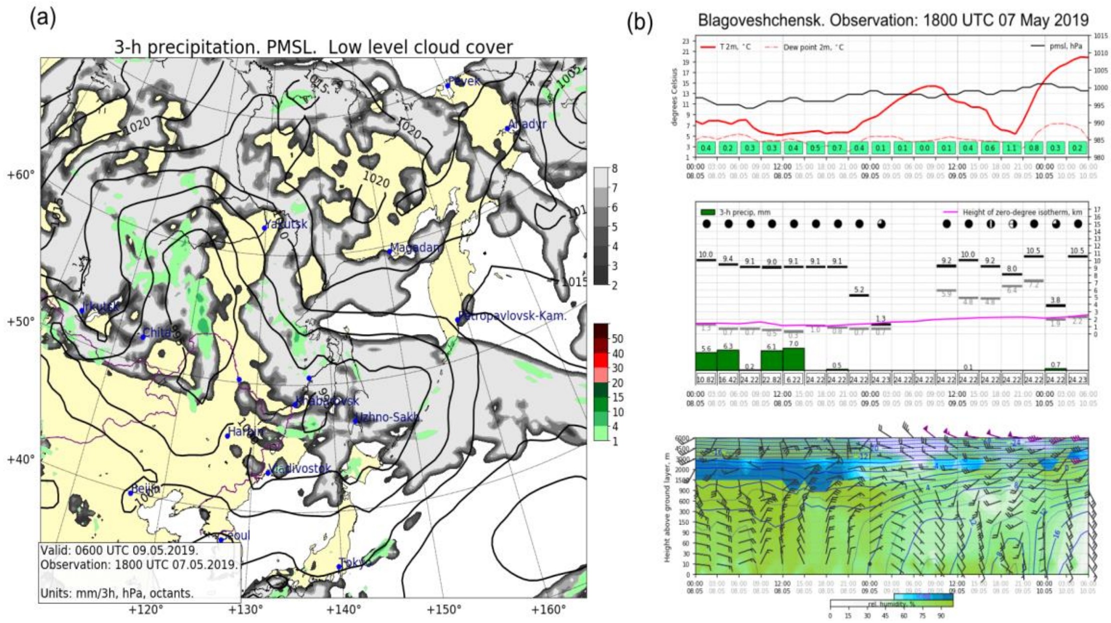

Figure 2: Sample products of the NWP system of ‘Khab-4.5’,
(a) surface weather map, (b) meteogram for the city of Blagoveshchensk

3 Verification of the ‘Khab-4.5’ forecasts versus ‘Khab-15’

The NWP system of ‘Khab-4.5’ works in quasi-operational regime from the beginning of 2019. Examination of forecasts from both NWP systems of RSMC Khabarovsk allows to obtain objective measurement of models’ skill. Comparison of surface forecasts between NWP systems of ‘Khab-4.5’ and ‘Khab-15’ was conducted for the period of time from 14 January to 14 April, 2019 for 130 points of Amur, Sakhalin, Primorskiy and Khabarovskiy regions of Russia. Surface observations are available 8 times per day. However, numerical forecasts were matched with observations every 12 hours for lead times of 12, 24, 36, 48, 60 and 72 hours to shorten calculations. Surface observations have diurnal variations. However, reduction of observation times does not significantly affect result due to the fact that the time period of 12 hours provides forecasts’ estimations for day as well as night; mentioned above regions of Russia are located in 3 time zones (from +9 to +11 UTC). Forecasting of surface wind speed and direction on 10 m above AGL, 2-m air temperature and surface pressure are key parameters for weather guidance.

The accuracy of forecasts was estimated by calculation of mean errors (ME), absolute errors (ABSE) and root-mean-squared errors (RMS).

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(f_i - o_i), \quad (1)$$

$$\mathrm{ABSE} = \frac{1}{n}\sum_{i=1}^{n}| f_i - o_i |, \quad (2)$$

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(f_i - o_i)^2}{n}}, \quad (3)$$

where n – number of pairs ‘observation – forecast’, f – forecast, o – observation.

Comparison of errors in surface forecasting of ‘Khab-4.5’ and ‘Khab-15’ NWP systems is shown on Fig. 3. Forecast in a point of interest corresponds to the data from the nearest grid point. Accuracy of forecasts does not reduce uniformly with the passing of time and both models show very close estimations. Occasionally night errors is worse than day. Almost all values have diurnal fluctuations, especially, errors of 2-m temperature forecasts.

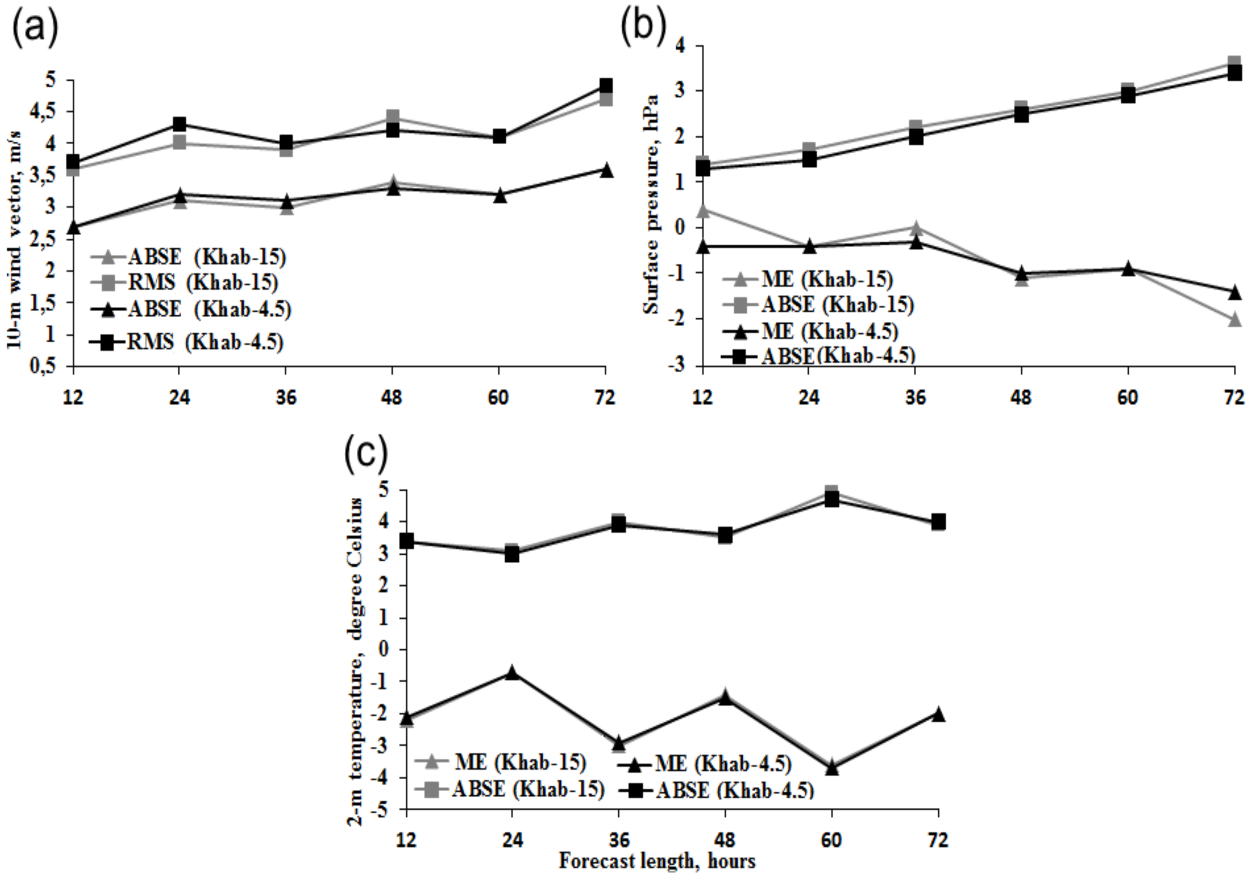

Figure 3: The accuracy of surface forecasts of NWP systems 'Khab-15' (grey) and 'Khab-4.5' (black), (a) 10-m wind vector (m/s), (b) surface pressure (hPa), (c) 2-m temperature (degrees Celsius) for the period of time from 14 January to 14 April, 2019

Absolute errors of 10-m wind vector forecasts (Fig. 3a) slightly increase from 2.5 to 3.4 m/s for lead times from 12 to 72 hours. Most rapidly the accuracy of forecasts is getting worse between 12 and 24 hours and from 60 to 72 hours; most stable estimated values are for lead times from 24 to 60 hours. It is necessary to remember that the estimations have been obtained for the cold period of a year. Wind is mostly determined by dynamical factors (not temperature) in this period of year. However, errors show the quality of model's forecasting which is not affected by error coming from simulated convective processes. Errors show the simulated surface wind on average is a little bit greater than observed data.

Absolute errors of surface pressure forecasts (Fig. 3b) steady increase from 1.2 to 3.3 hPa and mean errors fall unevenly to -2 hPa for the lead time from 12 to 72 hours. However, ABSE of surface pressure is under the value of 1.8 hPa and mean error is near 0 hPa for the first day of forecasting. Forecasts of surface pressure with these errors are suitable for aviation (TAF messages are mostly published for the period of time from 6 to 24 hours). Both models show similar quality of surface pressure forecasting. However, mean errors of 'Khab-4.5' surface pressure forecasting is better than 'Khab-15'.

Prediction of 2-m temperature is the most complex task for NWP system especially in cold season. Variation of surface temperature is defined not only by the state atmosphere but also orography and vicinity of seas. Temperature inversions often have place on the territory of Russian Far East in cold season. This process is very hard to predict. Figure 3c shows that the accuracy of 2-m temperature forecasts is better for day period not night. Absolute errors of 2-m forecasts gradually increase from 3.2° to 4.9° for the lead time from 12 to 72 hours.

Amount of observations for the territory of Russian Far East is not enough for such vast area. Therefore, initial data also has errors in surface temperature and 'Khab-4.5' cannot neglect it well. The accuracy of 2-m temperature prediction in cold season reveals the necessity of data assimilation system for the NWP system of 'Khab-4.5'. Mean errors of 2-m temperature forecasts are not stable; therefore, model output statistics will not have good results for these forecast data. Amplitude of simulated daily run of surface temperature is insufficient in comparison with the observed data.

In conclusion, forecasting in cold season is most complex task in comparison with warm period of a year. The errors in forecasting of ‘Khab-4.5’ NWP system will be decrease in warm period of a year as previously shown for the ‘Khab-15’ NWP system [2].

4 Future of ‘Khab-4.5’

The ‘Khab-4.5’ NWP system will provide improvement to short-range weather forecasting of RSMC Khabarovsk including forecasts for aviation and prediction of severe weather events. The configuration of coastal line and mountain regions is much improved in ‘Khab-4.5’ according to transition of horizontal grid step from 15 to 4.5 km. Increase in the number of vertical levels without doubt improves the representation of a current state of atmosphere in the model.

Current experiments show negligible advantages in surface forecast skills as opposite to current ‘Khab-15’ NWP system. However, this fact means the necessity of fine tuning of new model system. Tests of new microphysics and PBL parameterizations will be implemented to select more suitable schemes for small-scale processes. Another way to improve the accuracy of surface forecasts lies in enchantment of procedure to produce weather prediction in a point of interest. The area of a grid cell with horizontal step of 15 km is 225 km^2. However, the area for a grid cell with horizontal resolution of 4.5 km is only 20.25 km^2. Therefore, a forecast from the nearest grid point to a particular spot may be of insufficiently accurate in comparison with a forecast from the nearest grid point in height or an averaged value obtained from 9 or 16 points of the encirclement.

NWP system of ‘Khab-4.5’ has great potential for weather forecasting; it is flexible in configuration and provides possibility to include new prediction methods to a calculation cycle.

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