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Quality of precipitation prediction by the NWP model WRF-ARW with preliminary data assimilation

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Abstract. This paper represents a new method of improving a precipitation prediction by the WRF-ARW model which is based on a preliminary assimilation of GFS objective analysis and forecast data. The article is devoted to a comparison of the quality of precipitation prediction by the WRF-ARW run in 2 modes: using a preliminary data assimilation and using a common approach. It was found out that the preliminary assimilation of GFS objective analysis and forecast data allows one to improve the prediction quality of precipitation fact, which is assessed by precipitation fact (absence), forecast reliability and precipitation fact (absence) warning. These quality characteristics increase by 2-4% in case of preliminary data assimilation. An increase in the prediction quality of precipitation amounts is observed using preliminary data assimilation. The absolute error mean of precipitation amounts forecast is 2.13 and 2.03 mm using the preliminary data assimilation and the standard approach, respectively. Furthermore, the preliminary data assimilation helps improve the prediction quality of heavy precipitation (≥ 15 mm/12 h) fact. The heavy precipitation forecast reliability and warning increase by 5 and 9%, respectively, using the preliminary data assimilation. Additional characteristics of heavy precipitation prediction quality, i.e. Pearcy-Obukhov and ETS criteria, increase by 0.10 and 0.03 in comparison with the standard approach, respectively.

Introduction

The problem of quality of precipitation prediction using mesoscale hydrodynamic models, including the WRF-ARW model, is now widely covered in the literature [1]-[13]. In the Russian Federation, studies on this topic were conducted for different regions with different model settings, but most of them were limited to a small sample of prognostic data, often making a forecast of rainfall for several cases.

According to most studies, the WRF-ARW model satisfactorily reproduces the actual precipitation amounts, but the average prognostic precipitation amounts are greater than the actual ones. Errors in the prediction of precipitation amounts are largely due to the inaccuracy of the initial data of global hydrodynamic models, in which the position of atmospheric fronts and convergence zones can be determined with an error of 50-100 km, which is unacceptable for a qualitative forecast by the mesoscale model [13]. The quality of the forecast of heavy precipitation remains low, which may be due to the above circumstances, and is especially typical for cases of intensive convection in summer.

In this paper, the authors propose a way to improve the quality of precipitation forecast by the WRF-ARW model by applying preliminary data assimilation, objective analysis and forecast of the global model GFS. The purpose of using preliminary data assimilation is to reduce prediction errors (especially in terms of precipitation zones) due to the lack of accuracy of the global model data used as a starting point for the WRF-ARW model. The main objective of the study was to assess the quality of a precipitation forecast carried out according to [14], as well as with the use of additional characteristics [2] for two variants of calculations: by the standard method and with the use of preliminary data assimilation. The influence of different initial data variants on the quality of the forecast of meteorological quantities on the WRF-ARW model has not been studied before, since the main attention of the researchers was paid to the selection of optimal combinations of parametrizations of physical processes [10]-[12] or to the study of the effect on the quality of the forecast of the grid step of the model and the method of parametrization of convective processes [13].

Materials and research methods

In the research process of the forecast precipitation quality the WRF-ARW model (version 3.8.1) was used; it is a mesoscale hydrodynamic model of atmosphere state forecast designed to meet the needs both in the operational forecast and in the solution of research tasks. The basic principles of the WRF-ARW model 3.8.1 as well as its differences from the previous versions are described in detail in [15]. The software package of the WRF-ARW model is installed on a multiprocessor computer system (MVK) with a hybrid architecture named "PSU-Kepler".

Precipitation forecasts by the WRF-ARW model were implemented in two variants of calculations (by the standard method and with preliminary data assimilation) for the territory of Perm region for July 2017. In the process, 64 daily forecasts were prepared (32 of them with preliminary data assimilation and the other 32 ones without it) covering the period from 00 h UTC on 30.06.2017 to 03 h of UTC on 01.08.2017. In the summary table for assessing the quality of forecasts, 124 semi-diurnal intervals have been included (62 of them with preliminary data assimilation and 62 ones without it) covering the period from 15 h UTC on 30.06.2017 to 15 h UTC on 31.07.2017.

For comparison of predictive and actual precipitation amounts, the data of 25 meteorological stations provided by the "Ural Department of Hydrometeorology and Environmental Monitoring" in Perm region were involved. Measurement of semi-diurnal precipitation amounts at the meteorological stations in the second metazone was taken between 03 and 15 h UTC. The output GRIB2 files of the WRF-ARW model provide only the summation of precipitation starting from the model start at 00 h UTC, and so in the process it was necessary to solve the problem of obtaining semidiurnal predictive amounts of precipitation (for periods of 03-15 h UTC and 15-03 h UTC). This task was accomplished through the processing of predictive data using NDFD tkDegrib 2.02 and ArcGis 10 (ESRI, USA).

The estimated area was 278×278 points with a horizontal resolution of 7.2 km and with the center in Perm. The number of vertical levels was 38. Parameterization of the physical processes (Table 1) was chosen taking into account the experience of using the WRF-ARW model in Perm region [13] as well as the recommendations of the direct developers of the model set out in [16].

Table 1. Applied physics options in WRF-ARW.

Physical process	Type of parameterization
Cloud microphysics	Thompson's Scheme
Long-wave radiation	RRTM (Rapid Radiative Transfer Model)
Short-wave radiation	Dude's Scheme
Processes in the surface layer	Monin-Obukhov's Scheme with a viscous Carlson-Boland sublayer and standard similarity functions
Planetary boundary layer	Scheme of Yonsei University
Underlying surface	Noah's Model
Convection	Direct simulation (without parameterization)

The model WRF-ARW was initialized using the results of objective analysis and forecast of the global GFS model (Global Forecast System) in the GRIB2 format. This data is provided by NCEP (National Centre for Environmental Prediction, USA) and is publicly available. The GPS data has a spatial resolution of 0.5×0.5°, a time resolution of 3 h; the number of vertical levels is 32.

In the standard variant of calculations, the WRF-ARW model was launched from 00 h UTC up to a 27-h period. When using preliminary data assimilation, calculations were performed from 12 h UTC on the previous day up to a 39-h period. In the calculations with preliminary data assimilation, 10 files of GFS forecast were used from 00 h UTC up to a 27-h period, and the predictions from 12 and 18 h UTC on the previous day, up to a 3-h period (4 files). In the standard version of calculations, only 10 GFS forecast files from 00 h UTC up to a 27-h period were used.

The preliminary data assimilation in the first 12 hours of calculations of the WRF-ARW model is, in fact, an analysis of the observed fields of meteorological quantities, and so both variants of the calculations represent a forecast for 27 hours from 00 h UTC. In the first 12 hours of calculations, the predictive data of the GFS model are replaced by the data of objective analysis (12 and 18 h UTC) and forecasts for 3 hours (15 and 21 h UTC), which ensures greater accuracy of the initial conditions. Increasing the accuracy of GFS data by preliminary data assimilation in the early stages of the WRF-ARW model calculations may result in better quality of forecasts in the next 27 hours by "adapting" the model to the actual data in the first 12 hours of calculations. It should be emphasized that the preliminary data assimilation can be used in practice in operational forecasting, as well as the option with standard initial conditions, because by 00 h UTC GFS forecasts from 12 and 18 h UTC of the previous day will be in open access.

The assessment of the success of the precipitation forecast was carried out for the fact of precipitation (absence), the amount of precipitation, as well as for the fact (absence) of heavy precipitation (≥ 15 mm/12 h). In assessing the quality of forecast for the fact of precipitation (absence) for each semi-diurnal interval, the following characteristics of successful prediction were calculated (%): the overall reliability of the precipitation forecast (U), the precipitation fact forecast reliability (U_p), the precipitation fact warning (P_p), the precipitation absence forecast reliability (U_{np}), and the precipitation absence warning (P_{np}). In addition, the Pearcy-Obukhov criterion (PIR) and ETS were calculated.

The quality of the precipitation forecast was estimated using the arithmetic mean (BIAS, mm) and the absolute error mean (ABS, mm). Also, we calculated the reliability of the forecasts of rainfall by the Instruction (Z) [17] taking into account, strictly speaking, both a fact of precipitation and the number of coarse gradations. To assess the quality of the forecast of the fact of heavy precipitation (absence) (≥ 15 mm/12 h), the following characteristics were involved: heavy precipitation forecast reliability (U_r), heavy precipitation fact warning (P_r), the criterion of Pearcy-Obukhov (PIR), criteria of ETS and Bagrov (Ba).

In addition to the "point" estimation using the amounts of precipitation measured at the network of weather stations, the object-oriented method was used to assess the quality of heavy precipitation forecasts for the case of passing the line of squalls through the southwestern and central regions of Perm region on 22.07.2017. The object-oriented method implies a comparison of the actual (determined by satellite observations and DMRL) and predictive positions of deep convection systems. The evaluation criteria are the distance between the centers of gravity of objects on the actual data and the results of modelling, as well as the maximum values of the estimated variables: the height of the upper cloud boundary and the air temperature at this level (H_{top}, T_{top}), the maximum radar reflectance (Z_{max}). In contrast to the point estimation according to weather stations, this method allows one to divide the forecast error into two components: the error in the amplitude (intensity) and in the position of the object. When using the object-oriented method, radar data (DMRL Izhevsk) and satellite (Meteosat-8) observations were involved.

Results and discussion

Assessment of the quality of precipitation forecasts based on observations at meteorological stations

The use of preliminary data assimilation allows obtaining a better prediction of precipitation (absence), which is confirmed by Table 2 data. The overall reliability for the precipitation forecast (U) while using preliminary data assimilation has increased slightly and is 76%. A more significant increase in the quality of the forecast is observed when considering the precipitation fact (absence) forecast reliability and the precipitation fact (absence) warning. The values of these characteristics while using the preliminary data assimilation increased by 2-4% compared to the standard version of the calculations.

Table 2. Prediction quality of precipitation fact (absence).

Characteristic	Variant of calculation	
	Without assimilation	With assimilation
U, %	75	76
U_p, %	57	59
P_p, %	61	64
U_{np}, %	74	77
P_{np}, %	66	70
PIR	0.25	0.31
ETS	0.16	0.19

The Pearcy-Obukhov criterion characterizing the coincidence of actual and prognostic areas of precipitation has increased while using preliminary data assimilation by 0.06 and reached 0.31. The values of the ETS criterion also increased by 0.03 and are equal to 0.19. For the ETR, PIR, and ETS criteria were defined in [2]. During the summer period of 2013, according to 640 weather stations their values were 0.57 and 0.35, respectively. The prediction quality characteristics (the PIR and ETS criteria) obtained for Perm region are slightly lower than those previously identified for the ETR.

The reliability of the forecasts according to Instruction (Z) while using preliminary data assimilation increased from 76 to 77% (Table 3). The average absolute error of the forecast was 2.13 mm in the standard version of the calculations and 2.03 mm with the use of preliminary data assimilation. The arithmetic mean (systematic) error in the application of preliminary data assimilation increased by 0.08 mm and reached -0.20 mm. Preliminary data assimilation allows for more successful precipitation forecasting than the standard calculation, although improvements in the quality of the forecasts are generally small. Using both calculation variants leads to a systematic slight underestimation of precipitation, more pronounced in the application of preliminary data assimilation.

Table 3. Prediction quality of precipitation amounts.

Characteristic	Variant of calculation	
	Without assimilation	With assimilation
Z, %	76	77
BIAS, mm	−0.12	−0.20
ABS, mm	2.13	2.03

The values of Z, BIAS, and ABS obtained for Perm region in this study are in satisfactory agreement with the earlier data on the quality of the precipitation forecast for the ETR. The following estimates were obtained in [2]: Z - 79%, BIAS - 0.35 mm, and ABS - 1.65 mm. It should be noted that the absolute error for Perm region compared to the ETR increased slightly (by 0.48 and 0.38 mm for the standard version of calculations and for calculations with preliminary assimilation of data, respectively), and different signs of the systematic error at close values in the module were observed. For Perm region, the WRF-ARW model systematically underestimates the amount of precipitation in both versions of the calculation, while the ETR showed an overestimation of the amount of precipitation.

Using preliminary data assimilation allows increasing the forecast reliability of the rare event "heavy rain" (U_r) by 5% and heavy precipitation warning by 9%. The value of the Pearcy-Obukhov criterion (PIR) while using preliminary data assimilation increased from 0.04 to 0.14 (Table 4). The value of the ETS criterion also increased, but not so much: from 0.03 to 0.06. The most significant improvement in the quality of forecasts is observed according to the criterion of Bagrov (Ba), the values of which increased from -0.41 to -0.20.

Table 4. Prediction quality of heavy precipitation (≥ 15 mm/12 h).

Characteristic	Variant of calculation	
	Without assimilation	With assimilation
U_r, %	5	10
P_r, %	11	20
PIR	0.04	0.14
ETS	0.03	0.06
Ba	-0.41	-0.20

The use of preliminary data assimilation can significantly improve the quality of the forecast of heavy precipitation. However, the quality of forecasts of this phenomenon remains low for both calculation options, as evidenced by the low values of the heavy precipitation forecast reliability and its warning, as well as the values of the PIR, ETS, and Ba criteria. This statement is consistent with earlier findings on poor quality of the forecasts of heavy precipitation in the ETR. In [2] it is established that for the WRF-ARW model the reliability and warning of heavy rain are equal to 10 and 17%, respectively. The ETS criterion is 0.09 and the Bagrov criterion is 0.17. The values of most of the considered criteria for the quality of heavy precipitation forecast are close to those previously established for the ETR, with the exception of the Bagrov criterion. In the standard version of the calculations, as well as in the application of the preliminary assimilation data, the values of the Bagrov criterion for the Perm territory were lower than for the ETR by 0.58 and 0.37, respectively. The results of the study in terms of the success of the forecast of heavy precipitation for Perm region generally confirm the conclusions obtained earlier for the ETR.

The use of object-oriented method of evaluating the quality of heavy precipitation forecasts for the case of passage of a line of squalls in the afternoon of 22.07.2017

In the morning of 22.07.2017, a mesoscale convective system formed on the cold front passed through the southwestern and central regions of Perm region, which was associated with a complex of dangerous weather phenomena of a convective nature, including heavy rains. The estimation of quality of heavy precipitation forecasts when estimating actual and prognostic amounts of precipitation according to meteorological stations for the period from 03h to 15 h UTC on 22.07.2018 is presented in Table 5.

The data of Table 5 illustrate the earlier conclusion that the quality of heavy precipitation forecasts by hydrodynamic models remains low, although in the case under consideration the advantage of preliminary data assimilation is obvious and is reflected in improving the quality of the forecast for all characteristics. With this information, the weather forecaster would not be able to make a correct forecast of heavy precipitation, because in both versions of the calculations there is a large number of "missed phenomena". Table 6 illustrates the results of modelling the considered line of squalls in the standard version of the calculations and with the preliminary data assimilation.

Table 5. Prediction quality of heavy precipitation (≥ 15 mm/12 h) according to meteorological station observations from 03 to 15 UTC on 22.07.2017.

Characteristic	Variant of calculation	
	Without assimilation	With assimilation
U_r, %	9	22

P_r, %	13	25
ETS	-0.05	0.19
PIR	-0.03	0.13
Ba	-0.25	0.13
Number of "missed phenomena"	7	6
Number of "false alarms"	3	1

Table 6. Convection modeling results[a] by WRF-ARW on 22.07.2017.

Time, h UTC	$T_{вго}$, °C	$H_{вго}$, km	Z_p, dBz	Prediction error of location, km
05	−50/−45/−50	12/10/12	55/30/50	60/140
06	−53/−45/−50	12/10/12	55/25/55	90/130
07	−54/−45/−50	12/10/12	65/40/55	70/100
08	−54/−50/−55	11/11/12	55/45/55	80/90
09	−54/−55/−55	9/12/12	45/45/50	110/90

[a] By slash, the actual and prognostic (in the standard version of calculations, and in calculations with preliminary data assimilation) characteristics of convective clouds are indicated.

The data in Table 6 demonstrates that in both versions of the calculations the errors of the prediction of the object location (the axis of the line of squalls) are quite large and vary from 60 to 140 km. The average error of the location prediction for the standard version of calculations and calculations with the preliminary data assimilation is 80 and 110 km, respectively. In both cases the position of the mesoscale convective system was predicted to the North-East (Figures 1 and 2) than its actual position (Figure 3). In the standard version of the calculations, the error of location prediction increases with time, and for the variant with preliminary data assimilation it is observed to decrease.

In general, preliminary data assimilation allows obtaining quantitative parameters of the development of convective clouds much closer to those actually observed. When applying preliminary data assimilation the accuracy of the forecast is very high, which is especially noticeable in the initial period (05-07 h UTC). In the standard version of the calculations, the intensity of convection by the WRF-ARW model is clearly understated, which is expressed in relatively low prognostic values of Z_{max} (25-40 dBz), H_{top} (10 km), T_{top} (-45 °C). Preliminary data assimilation allows the WRF-ARW model to more adequately reproduce the intensity of convection: the values of Z_{max} (50-55 dBz), H_{top} (12 km), and T_{top} (-50...-55 °C) are close to the actual ones.

Thus, despite a somewhat large error in the prediction of the object location, the use of preliminary data assimilation allowed one to obtain a more objective picture of the development of convective processes in the southern part of Perm region in the morning and afternoon of 22.07.2018. Based on the forecast by the WRF-ARW model using preliminary data assimilation, the forecast of heavy precipitation (up to 30-40 mm/12 h) and other dangerous weather events (such as thunderstorms and hail) in the central parts of Perm region could be given, which cannot be said about the results of calculations by the standard method.

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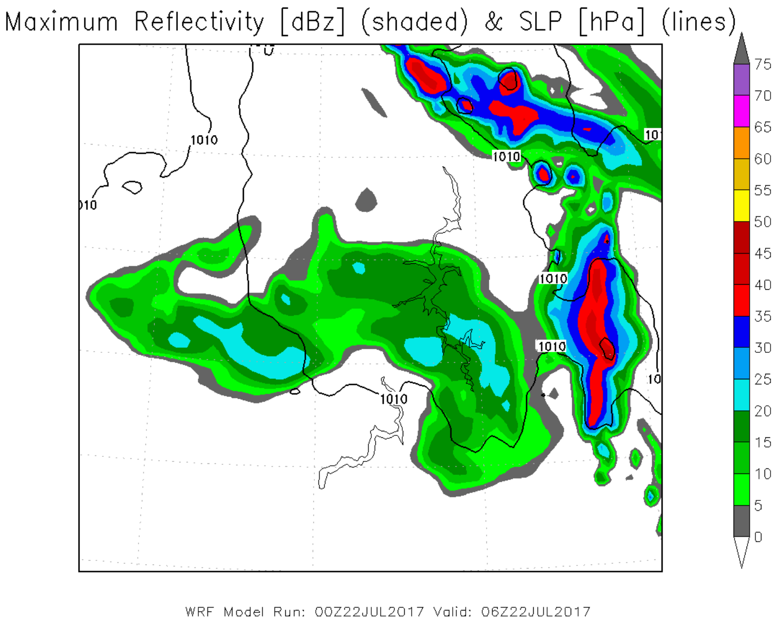

Figure 1. Predicted maximal radar reflectivity at 06 UTC on 22.07.2017 by WRF-ARW using standard approach.

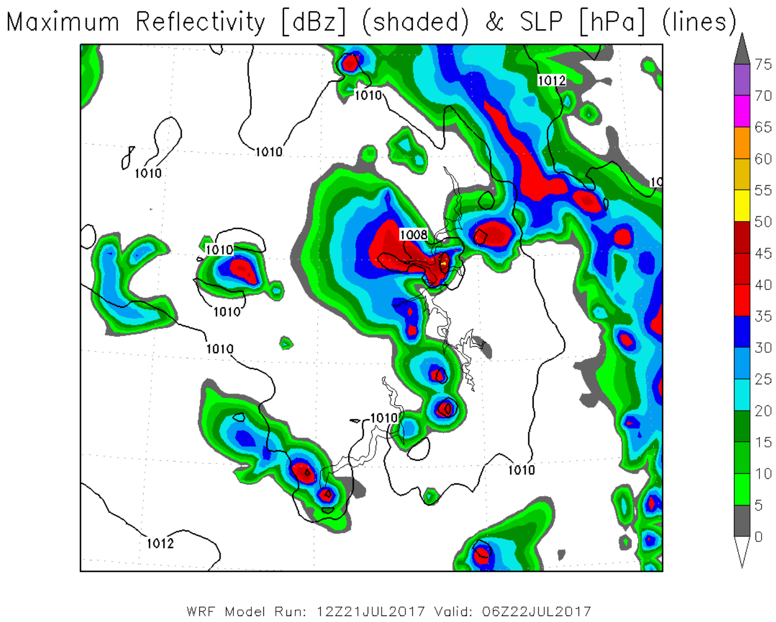

Figure 2. Predicted maximal radar reflectivity at 06 UTC on 22.07.2017 by WRF-ARW using preliminary data assimilation.

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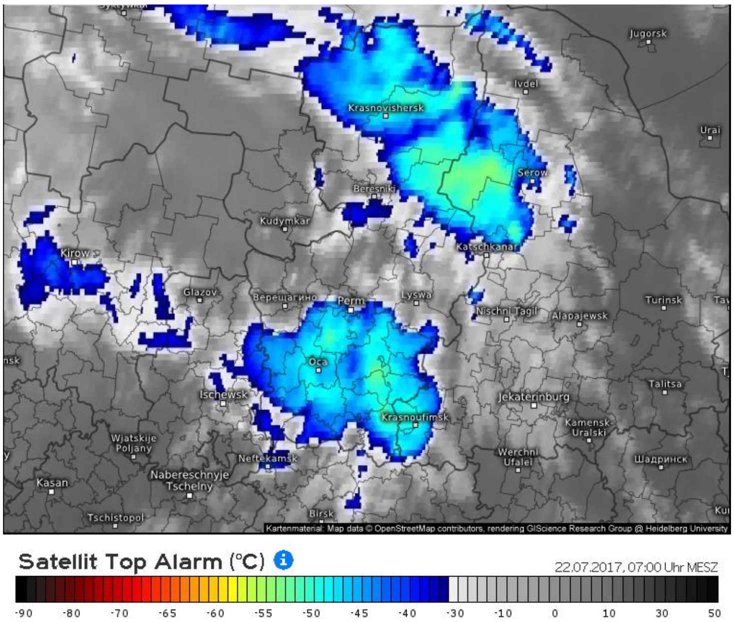

Figure 3. Actual top cloud temperature at 06 UTC on 22.07.2017 by Meteosat-8.

Conclusions

This paper considers the impact of different initial data options on the quality of precipitation forecast (including heavy precipitation) in summer for Perm region using the WRF-ARW model. The estimates of the quality of precipitation forecasts given in this work are in good agreement with the estimates obtained earlier for the ETR in paper [2].

Comparison of the actual and predicted amounts of precipitation obtained using the WRF-ARW model revealed the advantage of preliminary assimilation of objective analysis data and forecast by the GFS global model over the standard version of calculations. In the assessment of fact of presence (absence) of precipitation, the improved quality of the forecast is expressed in increasing the precipitation fact (absence) forecast reliability and the precipitation fact (absence) warning by 2-4% in comparison with the standard method of calculation.

The improvement in the quality of the forecast of amount of precipitation was revealed when using the preliminary data assimilation. The reliability of the forecasts under Instruction (Z) when using the preliminary data assimilation increased from 76 to 77%. The mean absolute error of the forecast averaged 2.13 mm in the standard version of calculations and 2.03 mm with the use of preliminary data assimilation.

The assessment of the success of the forecasts of the fact (absence) of heavy precipitation indicates that the quality of the forecasts of heavy precipitation remains at a low level when using both variants of calculations. However, preliminary data assimilation allows increasing forecast reliability of rare event "heavy rain" (U_r) by 5% and heavy precipitation warning by 9%. An increase in the values of the Pearcy-Obukhov (PIR) and ETS criteria was revealed when using the preliminary data assimilation by 0.10 and 0.03, respectively.

The application of the object-oriented method revealed a satisfactory agreement of the actual and prognostic values of the parameters of convective clouds (Z_{max}, H_{top}, T_{top}) when using the preliminary data assimilation and the importance of forecasts by the WRF-ARW model in operational work for a subsequent forecast of precipitation.

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