Short-range forecast of heavy rainfall over the Kama River basin in 2019 with atmospheric models ICON, GFS and WRF

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Abstract. The summer of 2019 was one of the wettest in the observation history in the western part of the Ural region. Excessive rainfall formed several rain flood events on the rivers of the Kama reservoir basin. In this study, we assess the accuracy of short-range (with a 15–27 h lead time) forecasts of heavy rainfall events observed in 2019 with global numerical weather prediction (NWP) models, ICON and GFS, and a mesoscale model, WRF, launched in a convection-permitting mode. Two metrics, Critical Success Index (CSI) and Extreme Dependency Score (EDS), are used to assess the forecast skills of the global NWP models. Throughout the study period, both global NWP models underestimate the frequency and intensity of heavy rainfall events, mainly due to the omission of local rainstorms. However, heavy precipitation related to cyclones or frontal waves is predicted quite successfully. In addition, we analyse in detail a heavy rainfall event on July 14–16, 2019 which caused a high flood in the western part of the Perm region. The most reliable simulation results have been obtained with the WRF model.

1. Introduction
In the recent decades, the frequency and intensity of extreme precipitation events has increased in the most part of the territory of Russia [1, 2]. The number of days with precipitation amount ≥ 30 mm increased by 20-30% between 1966–1995 and 1986–2015 in some parts of the Ural region [3]. Simultaneously, the contribution of convective precipitation to the total precipitation amount showed a statistically significant increase [4]. Changes in the precipitation regime amplify the risk of rain flood events. These trends are confirmed by several extreme rainfall events that occurred in the Ural region over the past decade and caused floods, e.g. 8-9 August 2013 at the Kartaly weather station in Chelyabinsk region (155 mm/48 h), 25 June 2015 at Gubakha weather station in Perm region (114 mm/12 h), 18 August 2015 at Kytlym weather station in the Sverdlovsk region (147 mm/24 h), 4 September 2017 in the city of Ufa (115 mm/2 h) and 20 July 2020 at the Bisert’ weather station in the Sverdlovsk region (82 mm/2 h).

July and August of 2019 in the Western Ural are characterized by extreme precipitation amount (up to 300% of the mean climatic values). Thus, at the Perm weather station August 2019 became the wettest month in the history of observations. Several other weather stations (Okhansk, Kungur, Bolshaya Sosnova) reported ≥200 mm of precipitation per month in July or in August 2019.

Heavy precipitation combined with relatively low temperature (2° below average climatic values) induced the formation of several rain flood events on the rivers of the Kama reservoir basin. The most damaging flood occurred on July 16-19 on the right-bank tributaries of the Kama reservoir. Three hydrological gauges reported the highest water level in the history of observations for rain flood events (http://svigimet.ru/?p=36704). Houses and roads were flooded in the Kudymkar town, the Kuva and Yurla settlements, 170 people were evacuated [5]. Due to the extreme precipitation amount, water
inflow to the Kama reservoir in August 2019 exceeded the average value by three times. Also, heavy rainfall caused excessive soil moisture over a large area and substantial damage to agriculture in the Perm region.

This study focuses on the accuracy assessment of short-range (with 15-27 h lead time) forecasts of heavy rainfall events observed in 2019 with the use of global atmospheric models ICON (Germany) and GFS (U.S.), and mesoscale model WRF with an ARW dynamic core [6]. In addition, we analyzed in detail the heavy rainfall event of July 14-16, 2019 that caused a rain flood in the Perm region.

2. Data and Methods

The main characteristics of numerical weather prediction (NWP) models which were used for short-range forecasting of heavy precipitation are provided in Table 1.

| NWP model          | Model grid step, km | Number of vertical levels | Grid step of output data | URL for download the data                  |
|--------------------|---------------------|---------------------------|--------------------------|-------------------------------------------|
| GFS (NCEP, U.S)    | 13                  | 64                        | 0.25°                    | http://nomads.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/ |
| ICON (DWD, Germany)| 13                  | 90                        | 0.125°                   | http://ftp-outgoing2.dwd.de/gds/ICON/grib/europe/ |
| WRF v.4 (NCAR/Penn State University, U.S) | 7                   | 60                        | 7                        | -                                         |

2.1. Sampling of heavy rainfall events

We considered the heavy precipitation events that occurred in 2019 (between May 1 and November 30) in the Kama River basin. The observed precipitation data were obtained from 95 weather stations of Roshysromet, 72 of them are located within the Kama River basin and 23 of them near its boundaries. In total, 59 heavy rainfall events (≥30 mm/12 h) and two heavy snowfall events (≥20 mm/12 h) have been reported by the weather stations. Among them, 8 events are associated with stratiform precipitation and 53 events – with convective or mixed precipitation. In 7 cases, the precipitation amount exceeded 50 mm/12 h (the criteria of hazardous weather event accepted by Roshydromet). Heavy precipitation events were observed on 30 different days (1-7 events per day). Most of them were reported between June 29 and August 20, when a long-lived tropospheric cyclone settled over European Russia, and the Kama River basin was regularly affected by quasi-stationary frontal zones or active cyclones moving from south and southwest.

2.2. NWP models data

Short-term forecasts of global NWP models ICON and GFS (in GRIB2 format) were downloaded from FTP servers (Table 1). A Python tool for automated downloading and processing the NWP data (extract variables, cutting and convert data to GeoTiff format) was developed.

The WRF model forecasts were obtained only for several important events when heavy rainfall was observed by several weather stations or the precipitation amount exceeded 50 mm. The WRF model version 4 was launched in a cloud-resolving mode (without parametrization of convection), with the use of ERA-5 reanalysis data as initial and boundary conditions. We do not use any nested domains, the simulation is performed in the single domain with a grid size of 400×400 points, and the grid step is 7.0 km.

2.3. Assessment of forecast accuracy

Due to the absence of weather radar data, comparison of observed and simulated precipitation was performed without using the object-oriented approach. In addition, such approach is usually applied in assessing forecasts of mesoscale NWP models [8]. The NWP model data have been recalculated to a 5 km grid using bilinear interpolation. Forecasts obtained from 12.00 UTC with a lead time of 15 and 27
h were assessed. We considered all dates when a heavy rainfall event was reported at any weather stations or when a heavy rainfall was predicted at least at one station but not observed (so-called false alarms).

To assess the forecast skills of NWP models, we used two metrics, such as the Critical Success Index (CSI) and the Extreme Dependency Score (EDI). More detailed information on these criteria is provided in [9]. It is important to note that EDI is the simplest measure of the accuracy of forecasts of extreme events, which is independent of its frequency. The CSI and EDI metrics were calculated based on the contingency table of predicted and observed heavy rainfall events. The SCI and EDI were calculated as follows:

\[ SCI = \frac{TP}{TP+FP+FN} \]
\[ EDI = \frac{\log F - \log H}{\log F + \log H} \]

(1)

(2)

To calculate the EDI values, it is needed to preliminarily calculate the number of true positive (H) and false alarms (F):

\[ H = TP(TP+FN), \]
\[ F = FP(FP+TN) \]

(3)

(4)

where TP is the number of true positive forecasts, FN is the number of false positive forecasts, FP is the number of false alarms, and TN is the number of true negative forecasts.

We considered as TP all cases when both observed and predicted precipitation amount at the same weather station exceeded 30 mm. We also added several cases when the predicted precipitation amount was < 30 mm but it differed from the observed one by < 1.5 times. In other words, if 32 mm is the observed value and 28 mm is the predicted value, such a forecast is considered as TP.

In addition, we estimated the accuracy of simulation of mesoscale convective systems (MCSs) that induced a very heavy rainfall in the Perm region on July 14-16, 2019 according to the WRF model. We compared the simulated composite reflectivity and the cloud top temperature with the MCSs characteristics observed from Meteosat-8 SEVIRI images. The Meteosat-8 data were downloaded from the EUMETSAT Earth Observation Portal (https://eoportal.eumetsat.int/). The satellite data processing included its reprojection, calculation of the cloud top temperature with the use of the MSG Data Retriever package, and the creation of an HRVcloud RGB image according to [10].

3. Results and Discussion

3.1. General assessment of forecast accuracy according to global NWP models

Table 2 provides the accuracy assessment of heavy rainfall forecast according to ICON and GFS global NWP models with the use of SCI and EDI metrics.

| NWP model | TP  | FN  | FP  | TN   | SCI  | EDI  |
|-----------|-----|-----|-----|------|------|------|
| ICON      | 11  | 51  | 17  | 3436 | 0.14 | 0.51 |
| GFS       | 18  | 43  | 5   | 3450 | 0.28 | 0.69 |

According to Table 2, both models substantially underestimate the precipitation amount. The number of FN approximately twice exceeded the sum of TP and FP. In several cases (23% of all forecasts according to the ICON model and 33% according to the GFS model), heavy precipitation (≥30 mm/12h) was not predicted not only at the weather stations, but also at any location within the study area. Thus, it was underestimation of the precipitation amount and not displacement of actual and simulated zones of heavy rainfall that took place in these cases.

Nevertheless, displacement between simulated and observed precipitation zones is a substantial factor reducing the forecast accuracy. The use of an object-oriented approach to estimate the forecast accuracy could somewhat reduce its impact, but only if the displacement does not exceed 50 km.
In general, the accuracy of forecasts of heavy precipitation events by global NWP models is determined by the nature of these events. Local convective rainfalls that are observed only at one weather station were not reproduced by both models (the number of TP is zero). On the contrary, if heavy precipitation covered large areas (such large-scale events are often related to southern cyclones), a substantial number of forecasts were TP and FP.

Throughout the study period, the obtained values of the SCI and EDI metrics both for the ICON and GFS models indicate rather unsatisfactory forecast skills for heavy precipitation events. On the other hand, the SCI and EDI values are approximately the same as those obtained with the use of the WRF model with various convection schemes [11]. For the most intense rainfall covering large areas and causing rain floods, the forecast accuracy turned out to be much higher than on average.

3.2. Overview of July 14-16 heavy rainfall events

In mid-July of 2019, a very heavy rainfall (up to 108 mm/60 h and 110 mm/72 h) caused a rain flood on the rivers in the western part of the Perm region. The heavy precipitation was induced by a meridionally oriented tropospheric frontal zone and two surface lows which moved from south to north along it.

The first heavy rainfall event occurred at night and in the morning of July 14. It was induced by a wave moving fast along the meridionally oriented quasi-stationary front. Two MCSs formed over northern Bashkortostan and moved through the Perm region between 19.30 UTC on July 13 and 04.30 UTC on July 14. The first MCS is formed on the warm front, and the second is related to the occlusion point. Both MCSs reached a maximum intensity over the southern part of the Perm region, where the cloud top temperature (CTT) dropped to ~60° C, and the MCS diameter was approximately 150 km, according to the Meteosat-8 data. Both MCSs dissipated over the northern part of the Perm region. Not a single weather station or hydrological gauge reported a heavy rainfall event (≥ 30 mm/12 h), but several ones observed a precipitation amount of 20-29 mm/12 h with thunderstorms. Based on the data of the Izhevsk weather radar, it can be assumed that the highest precipitation could be missed by weather stations. The heavy rainfall on July 14, in combination with precipitation during the previous two weeks, caused excessive soil moisture before an extreme precipitation on July 15-16.

The second heavy rainfall event was induced by the MCS which formed on the cold front near the center of a deepening surface low that moved from the northern part of Bashkortostan to the Perm region. The low reached a maximum development stage at a midnight of July 16, with a sea level pressure of 992 hPa. The occlusion point of the polar frontal system passed west of the city of Ufa, and the occlusion loop moved through the northeast of Tatarstan, where 7 weather stations reported heavy rainfall (30-46 mm/12 h).

The MCS which caused a heavy rainfall in the Perm region began to form at 09.30 UTC on the cold front, north of the city of Ufa. At 13.00 UTC, two dominating storms (which then merged into a squall line) moved through the northern part of Bashkortostan. The CTT according to Meteosat-8 images was initially rather high (~50°–52° C), which, however, corresponded to the tropopause temperature according to the sounding data. In the next hours, the CTT gradually decreased to ~60° C. At 13.30 UTC, the MCS with a diameter exceeding 150 km moved over the southern part of the Perm region and generated large hail (20-40 mm in diameter), a severe thunderstorm and a heavy rainfall along its path. The MCS development was supported by a moderate deep layer wind shear (up to 15-18 m/s) and a synoptic-scale updraft on the frontal side of a deepening surface low. Thus, the MCS was very long-lived and generated thunderstorms with heavy rainfall up to 19.00 UTC, moving over the entire territory of the Perm region from south-east to north-west.

The southern and western parts of the Perm region were mostly affected by the MCS. Here, a heavy rainfall was reported at the weather stations and hydrological gauges Okhansk (75 mm/12 h), Bolshaya Sosnova (60 mm/12 h), Karagay (50 mm/12 h), and Vereschagino (49 mm/12 h). As a result, the water level in several rivers (In’va, Obva, Lopva, Kuva, Lolog, Vel’va, and many small rivers) has risen sharply by 2-4 m. Houses were flooded (170 people were evacuated), roads and bridges were destroyed, ponds overflowed, and emergency regime was declared in 5 municipalities.
3.3. Simulation of a heavy rainfall event on July 14-16

We compared the simulated and observed 24-h accumulated precipitation between 15.00 UTC July 14 and July 15, 2019 (Figure 1) and between 03.00 UTC July 15 and July 16, 2019 (Figure 2) according to the ICON, GFS, and WRF models. Note that the forecasts of the different models substantially varied from each other. In the first case (July 14, 2019), the ICON model twice overestimated the maximum precipitation amount (Figure 1a). According to its forecast the MCS track stretched along the western border of the Perm region (50-100 km west of its actual track) and the accumulated precipitation reached 50-55 mm (with a maximum intensity > 30 mm/3 h). According to the GFS model, the MCS track stretched east of its actual location; moreover, its actual and predicted directions of movement did not coincide. The maximum precipitation amount did not exceed 40 mm (Figure 1b).

The WRF model reproduced two stripes with heavy rainfall that stretched along the western border of the Perm region (with a precipitation amount of 15-35 mm) and through its central part (with a precipitation amount up to 40 mm) (Figure 1c). In the western and southern parts of the Perm region, the model reproduced a heavy rainfall in the morning hours of July 14, that coincided with the observed time. The precipitation amount is also close to the observed values. However, the model also reproduced a heavy rainfall event (up to 40 mm) in the afternoon of July 14 in the northern part of the Perm region, which is not confirmed by the observational data. The WRF model reproduced the formation of a MCS with CTT −55…−60°C on the warm front and near the occlusion point in the evening hours of July 14, which corresponds to Meteosat-8 data. In general, the WRF-based simulation is most reliable in this case, although it also does not fully correspond to the observation data.

In the second case (July 16, 2019), the ICON model predicted two large areas with a heavy rainfall over the Udmurt Republic (50-80 mm) and the northwestern part of the Perm region (50-70 mm). Actually, the highest precipitation amount was reported in the southwest of the Perm region, where the simulated precipitation did not exceed 30 mm (Figure 2a). In the northwest of the Perm region, the observed precipitation amount did not exceed 36 mm but, presumably, it could be substantially higher on the eastern slope of the Upper Kama Upland when the rain flood was formed. According to the

Figure 1. Accumulated precipitation between 15.00 UTC July 13, 2019 and 15.00 UTC July 14, 2019 according to the ICON (a), GFS (b), and WRF (c) atmospheric models. Precipitation observed at the weather stations/gauges and flooded settlements is shown.
GFS model, the simulated precipitation amount reached 63 mm over the southwest of the Perm region (which is close to the observed values). In its turn, the model did not reproduce extreme precipitation on the eastern slope of the Upper Kama Upland (Figure 2b). Thus, on the one hand, the GFS model forecast better matches the data of the weather stations but, on the other hand, it did not help to predict the extreme rain flood.

The WRF model generally overestimated the precipitation amount (Figure 2c). In particular, it reproduced a heavy rainfall (50-100 mm and higher) along the western border of the Perm region, when the cold and warm fronts were closed in the evening hours of July 15. Unfortunately, due to low density of the weather stations, it is impossible to correctly assess the simulation accuracy. However, the model does not reproduce extreme precipitation in the southwest of the Perm region.

The WRF model successfully reproduced the start of deep convection over Bashkortostan in the afternoon of July 15 (Figure 3). The MCS timing was correctly predicted, with some displacement (50-100 km) to the east relative to the observed track (Figure 4). Thus, the model reproduced a heavy rainfall in the southwest of the Sverdlovsk region, which was not actually observed. According to the WRF model data, the area with heavy precipitation was stationary for a long time over the western border of the Perm region, which caused extreme precipitation amount (up to 110 mm) in this area.

Figure 2. Accumulated precipitation between 03.00 UTC July 15, 2019 and 03.00 UTC July 16, 2019 according to the ICON (a), GFS (b), and WRF (c) atmospheric models. Precipitation observed at weather stations/gauges and flooded settlements is shown.
Figure 3. Simulated composite reflectivity in July 15, 2019 according to the WRF model: a – 10.00 UTC, b – 12.00 UTC, c – 14.00 UTC, d – 16.00 UTC, e – 18.00 UTC, f – 20.00 UTC.

4. Conclusions
In this study, we assessed the accuracy of short-term forecast of heavy precipitation events with global (ICON, GFS) and mesoscale (WRF) atmospheric models on the example of the unusually rainy summer of 2019 in the Ural region. As expected, the forecast accuracy is mainly determined by the nature of the heavy rainfall event under consideration. If local convective rainfall events are not reproduced by the global NWP models (or their intensity is substantially underestimated), then heavy rainfall events associated with cyclones or frontal waves are predicted quite successfully. In such cases, both overestimation and underestimation of precipitation amount are possible. For the global NWP models, the obtained simulation accuracy generally corresponds to those previously obtained with the WRF model version 3 with various convection schemes [11]. It is also important that the ICON and WRF models have successfully reproduced heavy rainfall in the northwest of the Perm region that occurred on July 15-16, 2019 and caused a high flood.
Figure 4. Comparison of satellite-observed and WRF-simulated characteristics of the MCS at 14.00 July 15, 2019: HRV cloud RGB image (a) and cloud top temperature (b) according to Meteosat-8 data, WRF-simulated and cloud top temperature (c) and composite reflectivity (d).

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