The 2013 Amur River Flood: Operational Numerical Simulation of Prolonged Precipitation

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Abstract

The most severe large-scale flood on record occurred on the Amur River and its main tributaries (the Songhua, the Zeya, and the Bureya Rivers) in August–early September 2013. Prolonged heavy rainfalls over the vast territory of the Amur River basin produced the flood during the summer of 2013.

During the flood monitoring, it was noted that observed precipitation data from the Amur River observational network had not represented areal precipitation over drainage basins of the Amur River and its tributaries well enough. Therefore, operational Weather Research and Forecasting (WRF)-Advanced Research WRF (WRF-ARW) model with grid distance of 15 km was applied for prediction of areal precipitation over that territory.

The results of the simulation were compared with observed precipitation and water level data from the outlet points of partial drainage basins of the Amur River in June–September 2012 and 2013 to discuss the possibility of using numerically simulated precipitation in hydrological applications related to the Amur River basin. During the summer months of those years, an extreme flood occurred in 2013, while the hydrological situation was normal in 2012 on the Amur River.

The results of the comparison show that the amount of precipitation simulated on grid points of partial basins of the Amur River and its tributaries are in better agreement with major flood peaks than precipitation data obtained from the observational network. Additionally, if the five-day total areal precipitation averaged over the territory of a partial drainage basin exceeds 20 mm, the water level on an outlet point of a partial drainage basin of the Amur River monotonically increases independent of any variations of precipitation at an amount above the 20 mm value.

Keywords Amur River; 2013 Amur River flood; large-scale flood; heavy precipitation; numerical prediction of precipitation

1. Introduction

Prolonged and intense precipitation falling over a vast territory may provoke a flood. Thus, it is very important to have accurate analysis and precipitation forecasts for a drainage basin to produce correct predictions of water level in rivers and other reservoirs (e.g., Knebl Lowrey et al. 2008; Westrick et al. 2002). A scarce observation network does not sufficiently represent the total amount of precipitation and its spatial distribution on a drainage basin. The lack of such information can be a reason for under or overestimation of a flood level. Choi et al. (2008) and Keil et al. (1999) have shown that forecasts based on regional weather models with grid spacing of 10–20 km can successfully predict total precipitation and its spatial distribution over a large drainage basin.

A flood scale determines features and grid resolution of a numerical weather model. For example,
prediction or analysis of a flash flood event on a small river produced by short-lived, heavy rainfall requires a high-resolution model data (e.g., Givati et al. 2012; Amengual et al. 2007). However, floods on large rivers expand during long time periods and accumulate precipitation from a vast territory and from the main and numerous minor tributaries. Thus, we assume that for the prediction of a long-term flood, the total amount of precipitation over a partial drainage basin of a large river is more important than the spatial distribution of precipitation over the territory.

Floods caused by heavy rainfall often occur on large and small rivers in the Russian Far East. These events are some of the most severe natural disasters occurring in that territory. The most extreme large-scale flood in the last 120 years occurred on the Amur River and its main tributaries in the summer of 2013. The origin and the nature of the 2013 Amur River flood have been studied by other authors. Danilov-Danilyan et al. (2014) have examined the influence of reservoirs on the Zeya and the Bureya Rivers on the flood dynamics. Berezlnaya et al. (2013a, b) have briefly described and analyzed weather patterns in the territory of the Russian Far East and Northeast China during the summer of 2013. Uporov (2014) has described and examined the mechanism of water level decrease in the lower part of the Amur River.

The main goal of this work is to study the possibility of using areal precipitation values derived from numerical modeling for hydrological applications related to the Amur River basin. Precipitation forecasts by the operational Weather Research and Forecasting (WRF) model (Skamarock and Klemp 2008; Skamarock et al. 2008) using grid spacing of 15 km are applied to determine the amount of areal precipitation over the territory of the Amur River basin. Operational forecasts by the WRF model started in May 2012. The results of the simulation for 2012 and 2013 are presented. During the summer months of those years, the extreme flood was in 2013, while the hydrological situation was normal in 2012 on the Amur River. We have shown the possibility of using the results of the simulation for prediction of coming water levels on the Amur River and its tributaries.

The threshold value of the five-day amount of precipitation averaged over the territory of a partial drainage basin of the Amur River is obtained; an amount of precipitation above this value provokes a systematic increase of the water level in an outlet point of a partial drainage basin.

2. The area under study

2.1. Overview of the Amur River

The Amur River is one of the largest rivers in Asia. It rises at the confluence of the Shilka and the Argun Rivers and flows to the Sea of Okhotsk through the Amur Liman. The length of the river is 2824 km. The Amur River basin covers territory between 41°–56°N and 109°–141°E and has an area of $1.86 \times 10^6$ km$^2$. The Amur River basin is divided between Russia (54 % of the basin area), China (44 %), and Mongolia (2 %). The largest north tributaries are the Zeya, the Bureya, and the Amgun Rivers, and south tributaries are the Songhua and the Ussuri Rivers. These rivers themselves are large rivers of the Russian Far East and Northeast China. Furthermore, the Amur River directly receives numerous minor tributaries.

The Amur River can be divided into three sections according to the structure of the riverbed (Surface-water resources of USSR 1966, 1970). The Upper Amur River (length approximately 900 km) lies between Pokrovka and the city of Blagoveshchensk. The section of the river between Blagoveshchensk and the city of Khabarovsk is called the Middle Amur River (length approximately 1000 km). Three main tributaries (the Bureya, the Songhua, and the Ussuri Rivers) join the Amur River in this section. The Lower Amur River is located between Khabarovsk and the Amur Liman. The last main tributary, which is known as the Amgun River, joins the Amur River near the Amur Liman.

Our division of the Amur River basin into sub-basins is also illustrated in Fig. 1. There are drainage basins of the Amur River origin (the Shilka and the Argun Rivers), main tributaries (the Zeya, the Bureya, the Songhua, and the Ussuri Rivers), and three sections of the main stream (the Upper Amur, the Middle Amur, and the Lower Amur Rivers). The Songhua River is one of the largest rivers of North China, and it is divided into three sub-basins: two basins of its effluents (the Nenjiang and the Second Songhua Rivers) and the basin of the main stream.

Some reservoirs of different types have been built on the tributaries of the Amur River. The largest reservoirs and hydroelectric power plants are situated on the Zeya and the Bureya Rivers. Most of the Russian Far East population resides in the Amur River basin. Several large cities of Russia (Blagoveshchensk, Khabarovsk, and Komsomol'sk-on-Amur) are built on the banks of the Amur River.

Therefore, it is important to develop a method to
produce accurate precipitation forecasts on the territory of the Amur River basin for hydrological application, especially to predict possible flood scaling.

2.2 The Amur River observational network

Existing observational network of the Amur River basin includes 189 observational stations providing data on 12-h amount of precipitation (Table 1). Figure 1 illustrates the location of all observational stations of the Amur River basin. The stations are not evenly distributed over the area. The coverage of the Nenjiang River basin, the confluence of the Shilka and the Argun Rivers, and the Upper Amur River basin is quite poor. As will be shown later, existing observational networks cease to adequately represent the total precipitation over those vast territories.

The group of reference stations (69 stations) is selected from all observational stations. Russian hydrologists consider that these stations produce representative observed data for the Amur River basin. Different characteristics of the Amur River water regime are calculated with the data obtained from the reference stations.

3. Brief description of the Amur River floods

Rainy floods are regular events on the Amur River. The floods occur usually in August (sometimes in early September). The oldest registered extreme flood on the Amur River was in 1861 (Ivanov 1912). The next significant flood occurred in 1897 (Efremova 1992); thereat water level near Khabarovsk had reached 642 cm, the historical maximum before 2013. The last extreme flood before 2013 occurred in 1984 with a water level of 620 cm near Khabarovsk.

The most severe large-scale flood on record occurred in the Amur River basin in August–September 2013. The flood affected more than 1900 km of the Amur River from Blagoveshchensk to the Amur Liman. Furthermore, reported values of water level had exceeded historical maximums by 150–200 cm on the Lower Amur River. The water level had exceeded the historical maximum by 109 cm near Leninskoe, 28 cm near Novosovetskoe, 166 cm near Khabarovsk, and 211 cm near Komsomol’sk-on-Amur (Table 2). Many inhabited localities were inundated; cities of Khabarovsk, Blagoveshchensk, and Komsomol’sk-on-Amur were partially flooded. A number of people were missed in China during the flood on the Songhua River (Qian 2013).

The 2013 Amur River flood was catastrophic because floods were formed on all main tributaries of the Amur River in series and existed over a long time period. Shifted high rise in streamflow (flood wave) from the western part of the Amur River basin superimposed on gave rise to high peaks of water from rivers in the eastern part of the Amur River basin. As a result, flood waves from all main tributaries of the Amur River had joined near Khabarovsk.

Prolonged heavy rainfalls on a vast territory of the Amur River basin were one reason for the flood during the summer of 2013. For example, observational stations reported approximately 33 rainfall events with precipitation intensity up to 90 mm for 12 h over the drainage basins of the Upper and the Middle Amur Rivers. From 140 % to 470 % of the long-term mean precipitation for July and August (i.e., the normal amount of precipitation) fell over the drainage basins of the Zeya and the Upper Amur Rivers during July and the first 20 days of August. Amount of precipitation recorded by observational stations in the Bureya River basin were within the range of 75 % to 150 % of the normal amount of precipitation in the same period of time. Heavy rainfalls fell over the territory of the Songhua River and its tributaries. Observational stations of the Ussuri
River basin recorded 150 %–250 % of the normal amount of precipitation in late July and 200 % of the normal amount of precipitation from 11 to 20 August.

Figure 2 shows anomalies and long-term means of daily precipitation from 11 June to 15 August 2012 and 2013 based on 0.5° interval National Centers for Environmental Prediction (NCEP) reanalysis from 1981 to 2010. The daily amount of precipitation from 11 June to 15 August 2012 on the territory of the Amur River basin is close to the mean long-term values. However, anomalies in the daily amounts of precipitation during the same period in 2013 have relatively significant values in some parts of the Amur River basin (up to 3 mm day⁻¹ and higher).

In light of the above, accurate precipitation forecasts for the drainage basin of the Amur River and its parts are of crucial importance for prediction of the origin and expansion of a flood. Lack of observed information from weather stations leads to further difficulties in flood forecasting.

### 4. Methodological tools

Simulated and observed precipitation data for the summers of 2012 and 2013 are used in this study. We compared data for 2013 and 2012 because the water levels of the rivers of the Amur River basin and the amount of precipitation on this territory were close to mean statistical values in 2012; therefore, 2012 is a year suitable for comparison.

Precipitation forecasts are produced by the advanced research version of the WRF model (v. 3.4.1) with grid spacing of 15 km in operational mode. Calculations, which have been performed by the Khabarovsk Regional Specialized Meteorological Center of World Weather Watch since May 2012, are started every day from 0000 UTC and continuously performed for 72 h. The model is an essential part of the main operational short-term weather prediction system for the Russian Far East (Romanskiy and Verbitskaya 2014).

#### 4.1 The WRF-Advanced Research WRF (ARW) model configuration

Initial and boundary atmospheric and surface data are given by 6-h interval output data from the forecasts of the Global Forecasting System with hori-
Varieties of WRF parameterizations were tested earlier for the Russian Far East territory on the data of 2011 and 2012 (Romanskiy and Verbitskaya 2014). Some selected schemes for the operational configuration of the WRF model are presented in Table 3. Betts–Miller–Janjic convection scheme (Janjic 1994) is selected because its accuracy was verified in many papers. The Noah parameterization of land surface and soil processes (Tewari et al. 2004) is the most universal parameterization of such type in the WRF model. This scheme is in accordance with the Yonsei University boundary layer scheme (Hong et al. 2006) and the MM5 similarity surface layer parameterization (Zhang and Anthes 1982). The Dudhia shortwave radiation scheme (Dudhia 1989) and the rapid radiative transfer model (Mlawer et al. 1997) are chosen because these schemes have been realized in different weather models and tested in many cases. The WRF single-moment 5-class microphysics scheme (Hong et al. 2004) was used because it is suitable for simulations with grid size larger than 10 km.

In this work, the amount of precipitation from the 10th to 34th model hour (corresponding to 1000UTC of the initial day to 1000UTC of the second day) is analyzed in accordance with local time zones and timetables of measurement on gauging stations.

Numerical weather models produce meteorological values in regular grid points. The horizontal grid spacing of 15 km provides a resolution high enough for good coverage and adequate interpretation of meteorological data for the Amur River basin. The rainy flood on the Amur River initially forms on its major and minor tributaries and then expands into an extreme flood or provokes insignificant variations of water level of the main stream. It is important to split the entire territory of the large drainage basin into sub-basins, then estimate the possibility of flood waves forming on the river and its tributaries, and, finally, predict the flood scaling on different parts of the main channel of the river.

Our division of the Amur River basin into sub-basins is illustrated in Fig. 1. It is obvious that for a detailed calculation, more complex division of the Amur River basin is needed. However, we assume that the proposed segmentation of the basin is sufficient for our goals. Lists of grid points of the WRF model covering every selected sub-basin were defined. A description of the sub-basins of the Amur River is shown in Table 1.
4.2 Definition of precipitation amount over a sub-basin

In this study, we used a five-day amount of precipitation averaged over the territory of the sub-basin (denoted by \( Q_5 \)). The five-day period was selected in accordance with the size of the sub-basin and the timescale of synoptic-scale weather variation over a large area. We apply the time series of \( Q_5 \) values in our study because it is used by Russian hydrologists for hydrological forecasts related to the Amur River. Time resolution of precipitation data are empirically defined by hydrologists during the long course of their work.

The simulated five-day amount of precipitation was calculated over all grid points covering the sub-basin and over all observational or reference stations situated on that territory.

The amount of five-day precipitation averaged over all grid points of the sub-basin (simulated \( Q_5 \) values on grid points) was computed as

\[
\frac{1}{N} \sum_{d=1}^{5} \sum_{i=1}^{N} Q_i(d),
\]

where \( N \) = number of grid points in the sub-basin, \( Q_i(d) \) = amount of precipitation over a grid point, and index \( d \) is the number of a day in the five-day period.

The five-day precipitation averaged over observational stations in the sub-basin (observed and simulated \( Q_5 \) values of observational stations) was computed as

\[
\frac{1}{S} \sum_{d=1}^{5} \sum_{j=1}^{S} Q_j(d),
\]

where \( S \) = number of observational stations in the sub-basin and \( Q_j(d) \) = amount of precipitation over an observational station \( j \).

We have to determine an optimal variant of simulated \( Q_5 \) to estimate the possibility of rainy flood formation and predict the flood scaling.

5. Case study

We analyzed characteristics of time series of \( Q_5 \), calculated in different ways for years 2012 and 2013, to define the most suitable variant of \( Q_5 \) for hydrological applications related to the Amur River basin.

5.1 Comparative analysis between time series of \( Q_5 \)

The simulated time series of \( Q_5 \) values have been compared with each other and with observations. Averaged correlation coefficients for all sub-basins of the Amur River are shown in Table 4. The correlation coefficients of the simulated \( Q_5 \) values averaged over reference stations and over all observational stations are close to unity: 0.947 (2012) and 0.927 (2013). Correlation coefficients of simulated \( Q_5 \) values averaged over grid points and simulated \( Q_5 \) values averaged over stations are 0.906 (all observational stations) and 0.963 (reference stations) in 2012; correlation coefficients are 0.842 and 0.928 in 2013, respectively.

The observed five-day precipitation was calculated only over reference stations. The correlation coefficients between observed and simulated five-day amounts of precipitation significantly differ from year to year. These values are slightly lower than the correlation coefficients between simulated
five-day amounts of precipitation, which are calculated in different ways. The correlation coefficients of the observed and the simulated Q5 values of 2013 are smaller than those of 2012, because intense and prolonged precipitation fell over the entire territory of the Amur River basin very irregularly in 2013.

Figure 3 depicts simulated and observed precipitation data for some primary sub-basins of the Amur River. Comparison of precipitation data for 2012 and 2013 shows that the amount of summer precipitation on the territory of the Amur River basin in 2013 was more than in 2012.

Figure 3d illustrates a large amount of precipitation on the Zeya River basin from late July to 20 August 2013. Values of Q5 over the Nenjiang River basin fell over 10 mm after 5 August 2012, as shown in to Fig. 3e. Another situation took place on the Nenjiang River basin in 2013: high precipitation was noted from 25 June to 17 August 2013 except for the period from 11 to 15 July (Fig. 3f). Precipitation over the Songhua River basin was close to 0 mm from 5 to 15 August 2012. However, values of observed Q5 sometimes exceeded 10 mm and simulated Q5 came near 20 mm and above in the same period of time in 2013 (Figs. 3g, h). Decreased precipitation was recorded on the Ussuri River basin from 5 to 20 August 2012, but simulated and observed values of Q5 exceeded 20 mm from 12 July to the end of August in 2013 (Figs. 3i, j).

Table 4. Correlation coefficients between simulated and observed Q5, averaged over all partial drainage basins of the Amur River.

<table>
<thead>
<tr>
<th>Simulated Q5 averaged over</th>
<th>Observed Q5</th>
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<tbody>
<tr>
<td>all observational stations</td>
<td></td>
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<tr>
<td>reference stations</td>
<td></td>
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<tr>
<td>all grid points</td>
<td></td>
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<tr>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>Simulated Q5 averaged over</td>
<td></td>
</tr>
<tr>
<td>all observational stations</td>
<td>0.947</td>
</tr>
<tr>
<td>reference stations</td>
<td>0.947</td>
</tr>
<tr>
<td>all grid points</td>
<td>0.906</td>
</tr>
<tr>
<td>Observed Q5</td>
<td>0.834</td>
</tr>
<tr>
<td>2013</td>
<td></td>
</tr>
<tr>
<td>Simulated Q5 averaged over</td>
<td></td>
</tr>
<tr>
<td>all observational stations</td>
<td>0.927</td>
</tr>
<tr>
<td>reference stations</td>
<td>0.927</td>
</tr>
<tr>
<td>all grid points</td>
<td>0.842</td>
</tr>
<tr>
<td>Observed Q5</td>
<td>0.739</td>
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</table>

5.2 Comparative analysis between time series of Q5 and water levels at the outlet points of the sub-basins of the Amur River

Charts of various simulated Q5 values have been compared with water levels at the outlet points of the sub-basins of the Amur River to reveal the optimal method with which to calculate simulated Q5 values. We determined the lag time, which gives the highest correlation of time series between Q5 and water levels at outlet points corresponding to each sub-basin of the Amur River (Table 1). As a result, we found that a lag of 10 days is most suitable for the proposed partitioning of the Amur River basin (Fig. 1). Thus, the selected sub-basins are uniform with respect to the period of precipitation accumulation to runoff in spite of the difference in morphology and orography of those territories.

The Shilka and Argun Rivers are the most suitable basin for our study. The outlet point of the basin is the origin of the Amur River. The charts of various Q5s and water levels at the origin of the Amur River (Pokrovka) are shown in Figs. 4a and 4b. Unlike the peaks of the simulated precipitation, the peaks of the observed precipitation amounts during the periods of 21–25 July 2012 and 11–15 August 2013 are not verified by the rising of the water level. Increasing and decreasing the five-day amount of simulated precipitation averaged over grid points is confirmed generally.
Fig. 3. Different variants of simulated and observed five-day precipitation averaged over the territory of a sub-basin of the Amur River for 2012 and 2013. (a) (b) the Shilka and the Argun Rivers basin, 2012 and 2013; (c) (d) the Zeya River basin, 2012 and 2013; (e) (f) the Nenjiang River basin, 2012 and 2013; (g) (h) the Songhua River basin, 2012 and 2013; (i) (j) the Ussuri River basin, 2012 and 2013. Black line: simulated five-day amount of precipitation averaged over all grid points of a sub-basin; red line: observed five-day precipitation averaged over reference stations of a sub-basin; green line: simulated five-day precipitation averaged over all observational stations of a sub-basin; blue line: simulated five-day precipitation averaged over reference stations of a sub-basin.
by the fluctuations of the water level near Pokrovka. From 16 July to 10 August 2013 the simulated precipitation exceeded 20 mm (denoted by $Q_{\text{crit}}$), and the water level had been increasing steadily despite the fact that the amount of simulated precipitation slightly decreased from 1 to 5 August while still remaining higher than $Q_{\text{crit}}$. After 11 August the amount of simulated precipitation dropped below 20 mm, and the water level gradually decreased.

Figures 4c and 4d illustrate charts of the water level on the outlet point of the Zeya River basin (Blagoveshchensk). The water level from 1 June to 15 July 2013 was synchronized with variations of Q5 values above and below $Q_{\text{crit}}$, which is 20 mm. However, the water level at the outlet point began to increase steadily from 16–20 July to 10 August when the amount of precipitation had exceeded $Q_{\text{crit}}$. Values of Q5 had been decreasing during 1–10 August 2013 but the water level still had been increasing slowly. After 10 August 2013 the water level regulation procedure was done on the Zeya power plant in an attempt to avoid inundation of Leninskoe, which is situated on the main channel of the Amur River after the outfall of the Zeya River. As a result, the water level at the outlet point of the Zeya River dropped.

Discharge of the Bureya River is regulated by the Bureya hydroelectric power plant. There was no significant influence on water level at the outlet point of the Bureya River by rainwater during the summer of 2012 (Fig. 5a). The Bureya power plant influenced discharge formation in 2013; the water was let out during 21-30 June, and water was kept from 18 July to 20 August. The water level systematically increased at the outlet point of the Bureya River in the summer of 2013. However, it did not reach expected values, based on the amount of precipitation, because of water regulation.

The main effluent of the Songhua River is the Nenjiang River. This river is large and has ramifications of tributaries. The drainage basin of the Nenjiang River had to be split into sub-basins. Unfortunately, due to lack of data, we compared only the amount of

Fig. 4. Comparison of water level on the outlet points of relatively simple partial drainage basins with simulated and observed five-day precipitation averaged over the territories of those basins. (a) (b) the Shilka and the Argun Rivers basin, 2012 and 2013; (c) (d) the Zeya River basin, 2012 and 2013. Black dotted line: simulated five-day precipitation averaged over all grid points of a sub-basin; red dotted line: observed five-day precipitation averaged over reference stations of a sub-basin; brown line: water level on an outlet point of a sub-basin (Pokrovka for the Shilka and the Argun Rivers and Blagoveshchensk for the Zeya River); thin orange line: maximum water level averaged over a long period; thin blue line: threshold value of five-day precipitation averaged over the territory of a sub-basin ($Q_{\text{crit}}$).
precipitation over entire territory of the basin with the water level at the outlet point of the Nenjiang River (Fig. 5b). This comparison shows that formation of discharge of the Nenjiang River is a complex process.

Charts for the Second Songhua River are not shown here because dams and reservoirs of different types regulate the water level of this river. It is too complicated to make any conclusions without information about water control.

The Ussuri River is large and has ramification of major and minor mountainous effluents. It is necessary to split the Ussuri River drainage basin into small sub-basins. Nevertheless, water level reacted on changes of the Q5 values in the 2012 summer according to Fig. 5c. Variations of Q5 values were synchronized with a chart of water level up to 15 July 2013; later water level of the Ussuri River at the outlet point was increasing monotonically when Q5 values exceeded 20 mm (Fig. 5d).

5.3 Influence of the tributaries to water levels at the outlet points of sub-basins of the Amur River

According to Figs. 6a and 6b, discharge of the Upper Amur River is a sum of discharge of the Zeya River (the tributary) and discharge of the origin (the Shilka and the Argun Rivers). Values of Q5 showed a decrease in the amount of precipitation during 11–15 July 2012, but water from the source had supported the flow peak at the outlet point of the Upper Amur River. Moreover, the water level of the Upper Amur River was mostly defined by the discharge of the Zeya River in 2013. However, simulated Q5 values were above 20 mm during 1–10 July 2013 and 21 July–20 August 2013 and the water level increased dramatically during these periods.

The water of the Nenjiang River mostly determines variations of the water level on the Songhua River. However, the influence of significant amounts of precipitation over the drainage basin of the Songhua River is noticeable in Figs. 6c and 6d. However, the
charts of water level and simulated Q5 values in Figs 6c, 6d, 6e, and 6f show a correction to the selected value of Q_{crit} especially during 10 June–6 July 2013 for the Middle Amur and during 21 July–20 August 2012 for the Songhua River. Charts in Fig. 6f show that extremely high water levels in the Upper Amur, the Songhua, and the Ussuri Rivers summed up before Khabarovsk, that every component was more significant in 2013 than in 2012, and that water level had been increasing over a long period of time.

Figures for the Amgun and the Lower Amur Rivers are not presented here. The Amgun River comes to the Amur River near the Amur Liman, and the water from this river influences the total discharge of the Amur River only slightly. Discharge of the Lower Amur River is determined only by the Middle Amur, the Songhua, and the Ussuri Rivers. Runoff of the Lower Amur River particularly does not affect total discharge of the Amur River.

Comparative analysis of water level charts and various variants of simulated and observed five-day amounts of precipitation showed that variations of Q5 values above and below the threshold value of the five-day amount of precipitation (Q_{crit}) correlate with peaks and falls of water level at the outlet points of partial drainage basins of the Amur River quite well. If Q5 values exceed Q_{crit}, then the water level at an outlet point of a partial drainage basin monoton-
cally increased independently of any variations of precipitation amount above $Q_{\text{crit}}$. Comparative and graphical analysis has shown that the value of $Q_{\text{crit}}$ for simulated $Q_5$ values on grid points is almost the same for all sub-basins of the Amur River, and it equals 20 mm. For other variants of simulated and observed five-day precipitation, the value of $Q_{\text{crit}}$ varies depending on years and basins within a spread of approximately 2 mm because the number of observational stations is small and they are not evenly distributed over the area. This result demonstrates that $Q_{\text{crit}}$ is relatively uniform among all sub-basins of the Amur River. After reaching this critical value, which is sufficient for the moistening of a partial drainage basin, precipitation provokes systematic increasing of the water level of a river.

This rule works for a relatively simple riverine basin without large tributaries and artificial constructions (e.g., the Shilka and the Argun Rivers) for both 2012 and 2013 (Figs. 4a, b). Peaks and troughs in the water level are also noticeable for a complex riverine basin (e.g., the Nenjiang River and the Ussuri River). However, Figs. 5b, 5c, and 5d show that values of water level at an outlet point of a complex sub-basin also include discharge of effluents and tributaries. Figure 6 demonstrates that discharge at the outfall points of these basins is the superposition of discharge of tributaries and sources shifted on the lag time. Figures 6e and 6f show that total discharge of the Middle Amur River depends on discharge of its source and tributaries but practically is not affected by its own runoff.

In conclusion, we calculated the arithmetical mean of correlation coefficients of the various $Q_5$ values over the enlarged sub-basins of the Amur River and water levels at the outlets points of these basins during June–August 2012 and 2013 (Table 5). The first enlarged basin includes the Shilka and the Argun Rivers and the Upper Amur River with the Zeya River. The second combined basin corresponds to the union of three sub-basins of the Songhua River. The third sample is data from the Ussuri River basin separately. These combined samples represent main components that determine water level at the outlet point of the Middle Amur River (Khabarovsk).

Arithmetical means of correlation coefficients are not high and differ slightly in 2012 because in that year rainy floods were not extreme and water level corresponded to long-term mean values. The correlation coefficients are much higher in 2013 than in 2012. The five-day amount of simulated precipitation averaged over all grid points is the preferred variant of $Q_5$, especially in comparison with observed precipitation data.

### Table 5. Arithmetical mean of correlation coefficients between various variants of $Q_5$ values over enlarged partial basins of the Amur River and water levels at the outlets points of these basins (the Shilka and the Argun Rivers and the Upper Amur River with the Zeya River; the Songhua River with Nenjiang River; the Ussuri River).

<table>
<thead>
<tr>
<th>Period of time</th>
<th>Observed $Q_5$</th>
<th>Simulated $Q_5$ averaged over all observational points</th>
<th>Simulated $Q_5$ averaged over reference points</th>
<th>Simulated $Q_5$ averaged over all grid points</th>
</tr>
</thead>
<tbody>
<tr>
<td>June–August 2012</td>
<td>0.40</td>
<td>0.41</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>June–August 2013</td>
<td>0.56</td>
<td>0.70</td>
<td>0.65</td>
<td>0.76</td>
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6. Conclusion

The following results were obtained in this study.

Areal precipitation data derived from the numerical WRF-ARW model with grid distance of 15 km has sufficiently representative values for hydrological applications related to the Amur River basin.

The overall period of precipitation accumulation and lag time of runoff to the outlet points of the partial drainage basins is near 10 days for the proposed partitioning of the Amur River basin (Fig. 1).

Variations of $Q_5$ values above and below the threshold value of the five-day amount of precipitation ($Q_{\text{crit}}$) correlate with peaks and falls of the water level at the outlet points of partial drainage basins quite well. If $Q_5$ values exceed $Q_{\text{crit}}$, then the water level at an outlet point of a partial drainage basin increases independently of any variations in the amount of precipitation above $Q_{\text{crit}}$. The $Q_{\text{crit}}$ for all partial drainage basins of the Amur River is equal 20 mm ($\pm$ 2 mm).

This rule works for a relatively simple riverine basin without large tributaries and artificial constructions (e.g., the Shilka and the Argun Rivers) for both 2012 and 2013. Peaks and troughs in the water level
are also noticeable for a complex riverine basin (e.g., the Nenjiang River and the Ussuri River), but the value of the water level at an outlet point is the superposition of runoff and discharge of tributaries and sources shifted by the lag time.

The variant of Q5 most suitable for hydrological applications is a simulated five-day amount of precipitation averaged over all grid points of a sub-basin. Observed values of Q5 do not always correspond to water levels at an outlet point, because the number of observational stations is not sufficient for that vast territory. Simulated Q5 values averaged over all observational or reference stations are verified by observed precipitation data reported from the observational network. Simulated Q5 values averaged over all grid points of a sub-basin correlate with observed data, but the coefficients of correlation are lower than for simulated Q5 values averaged over all observational stations. Simulated Q5 values averaged over all grid points are more relative to dynamics of water level on the outlet points of the sub-basins than simulated or observed Q5 values averaged over all observational stations of those territories.

This study has laid the foundations to use simulated precipitation data for water level prediction on rivers of the Amur River basin. It became possible due to an application of the operational high-resolution weather model in Khabarovsk Regional Specialized Meteorological Center.

Partial drainage basins of the Amur River basin are defined; some of those basins have to be divided into several sub-basins for a detailed description of the runoff formation. Our next study will be dedicated to the partitioning of large partial drainage basins into small uniform areas and to the application of a weather model with higher horizontal grid spacing for precipitation prediction on those small sub-basins.

References


Lowrey, M. R. K., and Z.-L. Yang, 2008: Assessing the capability of a regional-scale weather model to simu-


