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Research Article

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Forecasting the Floods Caused by Strong Atmospheric Convection using output Data of Global Atmospheric Model (GFS) For ER South.

Arthur Kh. Kagermazov, Boris.A. Ashabokov, Lyudmila M. Fedchenko, Alexander V. Shapovalov and Lezhinka T. Sozayeva.

Federal State Budgetary Institution "High-Mountain Geophysical Institute"
2 pr. Lenina, Nalchik, Kabardino-Balkariya, 360030
E-mail: ka5408@mail.ru

ABSTRACT

The relevance of the study is conditioned by the exacerbation of the weather processes accompanied by the increased number of emergencies (floods, waters). Resulting economic losses run into billions of rubles. Social losses are also major: injured people run into thousands and casualties – into hundreds.In this regard, this article uses the estimated products of the Global Forecast System (GFS) to propose a new method of forecasting the rainfall amount and flood risk using the Model Output Statistics (MOS) for ER regions.Statistical forecast models have been built for various climatic regions of the North Caucasus, which models are based on regression analysis and results of shower and flood evaluation results are provided using relevant regression equations for typical regions of the ER south – Western and Central parts of the North Caucasus.The new method of forecasting dangerous convection weather phenomena and associated emergencies using the Global Forecast System of the National Center for Environmental Prediction (GFS NCEP) outputs has proven effective. In line with the MOS (Model Output Statistics) concept, statistical forecast schemes may also be implemented for other dangerous phenomena (hail, mudslide, gale).

Keywords: statistical analysis, flood risk, the global atmospheric model, the output data, the regression equation.

INTRODUCTION

Recent exacerbation of the weather processes has been accompanied with the higher frequency of emergencies. In the south of the European Russia (ER), their risk caused by floods is very high [1-3]. This is preconditioned by the fact that most localities, industrial and agricultural facilities are situated in coastal territories in river valleys. Floods in the region are often disastrous. Resulting economic losses run into billions of rubles. Social losses are also major: injured people run into thousands and casualties – into hundreds. An example of the disaster is a flood that occurred in July 2012 as a result of abundant rainfall that continued for a long time and covered a large area. Heavy rains in the region started on 4 July. In fewer than two days, the rainfall exceeded the monthly norm by 3-5 times. This flood was assigned the status of extraordinary, while foreign mass media dubbed it a "flash flood". As of 11 July, some 200 people died. More than a thousand of people sought medical advice.A section of the North Caucasus Railway was flooded and train service was interrupted. In the disaster area, damage was done to 7,200 domestic buildings; gas, power and water supply systems failed, railway and road service was interrupted.Floods and waters are dangerous in themselves; combined with soil erosion and washaway, they often trigger other hazardous processes, as a result of which the aggregate negative impact on the population and economy of disaster areas rises sharply. This results in emergencies of various levels.

Most frequently, rain floods cause mud flows. These phenomena are typical of many mountainous areas of the North Caucasus – from Dagestan in the east to the Karachayevo-Cherkessian Republic in the west. Slide processes resulting from intensive erosion of valley sides with floods and high water are also typical of the Stavropol Territory. Floods often cause uneven soil settlement.Adverse effects are also observed. For example, in June 2000, a strong mud flow in the Kabardino-Balkarian Republic locked the Baksan river bed with its deposits, which resulted in a retaining lake upstream of the dam. This flooded a large part of Tyrnyauz and resulted in aggravation of the emergency. The aggregate damage caused by the emergency was a lot larger compared to just mud flows.Floods are often related to a good deal of secondary adverse effects. In particular, fires resulting from power grid breaks and short circuits are detrimental. Large-scale pollution of water, human and animal food triggers outbreaks of infectious diseases.Thus, most of the Southern Federal District is under a threat of floods of various origins. Floods and high water resulting from abundant rainfall and melting of the ice and snow cover prevail in terms of frequency and intensity. These phenomena are the most detrimental to the population and economy of flooded areas. Derivative natural processes (mud flows, landslides, subsidence) and secondary negative effects (fires, infections, etc.) caused by floods can significantly exacerbate the emergency.Prevention of the emergencies caused by floods and waters and mitigation of their consequences is a comprehensive problem that requires systemic planned and operational organizational, engineering, technical and information activities that comprise, first of all, monitoring of natural and man-induced processes that cause floods, forecasting the flood scale, designing a system of coast-protecting structures, mobilization of manpower and resources for disaster control.

The main reasons of poor prevention of dangerous phenomena are lack of the source information and inadequacy of traditional approaches for the forecasting of fast local processes. Today, mesoscalemeteorologic models are widely used to study and forecast local atmospheric processes that occur above a confined area. These areas rely on unsteady-state three-dimensional equations of atmospheric hydrothermodynamics and parameterization of atmospheric processes (short- and long-wave radiation flows, convection processes, boundary layer, moisture microphysics, atmospheric turbulence, heat and moisture exchange in the underlying surface). Computer implementation of these models is based on the application of non-trivial computational algorithms and high-end computational resources. Large global centers that study atmospheric processes have designed and freely distribute source codes of programs for the models of this level.At data centers, a good deal of information is generated during measurements from satellites, airplanes, land-based platforms and computer calculations. Archive-related information systems offer the required tools for data analysis, handling time series and visualization. Normally, these are application programs that users may install at their workstations. Recent years have seen the development of Internet access information systems.The procedural framework of forecast hydrologists to make up flood warnings does not suffice. Presently, the best approach to flood forecasting is building computational models of their development for each basin.

Frequency of meteorologically conditioned natural disasters in the North Caucasus in 1998–2017 (% of the total number of occurrences). Frequency of rainfall is 18.3%, floods and waters – 11%, hail – 7.7% of the total number of occurrences.Thus, due to growing likelihood of activation of the dangerous natural processes caused by ongoing misbalance of the Earth’s climatic system, the development of new methods to study dangerous meteorologic processes and phenomena based on achievements in mathematical modelling of atmospheric processes and information technology to enable their availability is a very relevant task.

Due to the above, major changes have been recently observed in information support of the methods to forecast dangerous weather phenomena related to convection atmospheric processes. Booming computer aids, information technology (Internet) and resulting operational availability of global forecast system calculation results offer new opportunities for the development of forecasting methods based on a new information base [4-18]. The hazard level and impact of floods is normally determined, in the first place, depending on the magnitude, by which the highest river water level during flooding exceeds the initial level. The flooded area in the river bottom and, eventually, the damage done to the infrastructure, household and residential buildings are conditioned by the highest water level. This work deals with regions with rivers, the high runoff of which is caused by heavy precipitation (storm rain).

To calculate the predictors used to forecast dangerous weather phenomena, in particular, showers and floods that sometimes accompany them, this work suggests using the output products of the Global Forecast System (GFS NCEP). The global model acquired its main features in the early 1990s after summary works by the authors [19-21]. The global atmospheric model of high spatial resolution (T254) has time increment of 3 hours for the forecast advance time of 0-180 h and 12 hours for the forecast advance time of 180-384 hours. In the latter instance, calculations are made on Gaussian grid (768x384), which approximately matches horizontal resolution of 0.5° of the longitude-latitude grid. The atmosphere mass (from the ground to the height of constant-pressure surface of 0.27 gPa) is vertically divided into 64 layers, with the main countable Sigma levels assigned to midpoints. The coordinate grid is vertically irregular: there is condensation in lower layers where 1.5 km atmospheric boundary layer is described by 15 countable levels and 24 levels above 100 gPa. Orography is based on the global digital terrain model of the US Geological Survey with a horizontal grid of 30 seconds of angle (about 1 km).

The studies conducted [22-24] have shown that the development of convection phenomena (hail, shower, etc.) is mostly affected by the following atmospheric parameters: rate of ordered air lift at a level of 700 mb (V700); aggregate humidity rate in the ground surface layer – 500 gPa (SQZ5); energy response of the subcloud layer (DSS); average humidity deficit in Nk+5 km layer (TDSR5); thermodynamic Miller index (TTMI).

STUDY MATERIALS AND METHODS

The following linear regressive model has been used to identify and describe the correlation between the amount of precipitation QL (dependent variable) and atmospheric parameters (in dependent variables):

$$QL = a \cdot V700 - b \cdot SQZ5 + c \cdot DSS + d \cdot DTRS5 + e \cdot TTMI + const ,$$

where*a, b, c, d, e* are factors, *const* is a constant term.

Actual data on the amount of precipitation observed during showers on different days from 2009 to 2016 has been used as a dependent variable *QL* (mm) [25]. Independent variables (*V700, SQZ5, DSS, TDSR5, TTMI*) have been calculated using global model data [13,14].

The main factor that describes floods is the value of excess of the water level in river beds over the normal water level. On the other hand, flooding conditions develop over a certain period of time – one week more or less. This is why the amount of precipitation 7, 6, 5, 4, 3, 2 days before and on the day of its occurrence has been used as flood predictors. It turned out that the most useful amount of precipitation for flood forecasting is the one three days before the flood (Q3, cm) and on the flood day (QП, cm).

So, the flood forecasting linear regressive model has been built as an equation:

$$H = a \cdot Q_3 + b \cdot Q_П + const ,$$

where (H, cm) is water level excess over normal water level (independent variable),

a, b are factors, *const* is a constant term.

Actual data on water level excess over the normal water level on different days from 2009 to 2016 were used as H (cm) [25]. Output data of the global model were used as independent variables (Q3, cm and QП, cm) [13-14].

Besides, data for shower forecasting were pooled in line with the following areas of ER south and North Caucasus to consider climatic peculiarities of the territory:

- Central part (Stavropol Territory, Karachayevo-Cherkessian Republic, KBR, Ossetia, Chechen Republic);
- Western part (North Caucasus Black Sea coast, Krasnodar Territory, Adygeya);
- Eastern part (Dagestan, Ingooshetia, Kalmykia, Chechnya).

Flood forecasting models were built for the conditions of the Central and Eastern parts of the North Caucasus due to the absence of data on floods in the Western part of the North Caucasus.Regression analysis comes down to the determination of factors and constant term of the equation, calculation of the parameters describing statistical significance and practicality of the model.

RESULTS

Summary table 1 shows parameters of regression equations for the precipitation in different climatic zones observed during showers and its qualitative indicators.

Table 1. Summary table of forecasting the amount of precipitation observed during showers in the North Caucasus

Climatic zones	Model predictors	*Const, a,b,c, d,e*	σ	*beta*	*Tolerance*	*VIF*	*R*	R^2	*DW*	*p*
Central part	Const	-14.411	46.73				0.57	0.32	1.80	0.73
	V700	-0.386	0.215	-0.219	0.84	1.19				
	SQZ5	-1.033	0.573	-0.219	0.85	1.17				
	DTRS5	-2.33	0.735	-0.364	0.95	1.05				
	TTMI	2.030	0.809	0.298	0.89	1.13				
Western part	Const	-295.63	80.91				0.81	0.65	2.06	0.99
	DSS	0.427	0.113	0.826	0.56	1.77				
	DTRS5	7.205	1.591	1.128	0.43	2.31				
	TTMI	6.318	1.524	1.223	0.31	3.25				
Eastern part	Const	77.859	23.91				0.86	0.73	1.67	0.94
	V700	-0.397	0.082	-0.627	0.85	1.17				
	SQZ5	0.955	0.370	0.346	0.79	1.26				
	TTMI	-1.343	0.526	-0.354	0.74	1.35				

Table 1 provides determination coefficients *R* that describe the high correlation ratio between variables in the regression model for the three climatic zones. In the precipitation forecast models under study, values of determination coefficients evidence visible (*R*=0.57) and high (*R*=0.81; 0.86) linear connections between the amount of past precipitation and above atmospheric parameters.

R squarecoefficient as a regression model quality characteristic shows a share of aggregate variation of the dependent variable described by independent variables. Thus, for the Western and Eastern parts of the North Caucasus, R square is 0.65 and 0.73, correspondingly, i.e. 65% and 73% of precipitation variation is explained by joint variation of atmospheric parameters. As for the Central part of the North Caucasus, the regression model describes 32% of cases, which is most probably due to a significant gradient of weather conditions. Normally, this figure must also exceed 0.5.

An important component of regression analysis is analysis of residuals, i.e. deviations of observed values of the dependent variable from the values predicted by the regression model, which requires verification of normalcy of their distribution. Kolmogorov-Smirnov test was used to this end. Disnormality is deemed major with $p<0.05$ (with 95% confidence interval). We have the following values for all the three climatic zones: p=0.73; 0.99; 0.94, i.e. probability of residual distribution disnormality is minor. The condition of residual inter-independency is verified using Durbin-Watson test (DW). For the precipitation forecast models built, *DW* coefficient is close to 2, which is indicative of the absence of auto-correlation of residuals. Standard errors σ show that with the confidence interval of 95%, each coefficient may deviate from the mean by $\pm 2\sigma$. Standardized regression coefficients (*beta*) allow to estimate the degree, to which precipitation values are determined by the values of atmospheric parameters, i.e. they describe specific input of each atmospheric parameter to precipitation variation. Values of tolerance and variance inflation factor (*VIF*) indicators describe collinearity, i.e. connectivity between model variables. The value of tolerance indicator must exceed 0.1, while VIF must be below 10. For all the three climatic zones, the value of tolerance indicator is lower than 0.1, while *VIF* is below 10, which implies that there is no multicollinearity effect.

R determination coefficient in the flood forecast model takes on the values of 76.4% and 89.6% for the Central and Eastern part of the North Caucasus, correspondingly, i.e. the correlation ratio between the values of water level excess over the normal water level and total precipitation for the three preceding days and on the current day of a flood is high (table 2).

Table 2. Summary table of models forecasting the value of excess of the water level over the normal water level in river beds in the North Caucasus

Climatic zones	Model predictors	*const, a,b,c, d,e*	σ	*beta*	*Tolerance*	*VIF*	*R*	*R2*	*DW*	*p*
Central part	Const Q3 QП	-44.451 11.796 -1.241	127.70 4.924 8.549	 0.798 -0.05	 0.469 0.469	 1.13 1.13	0.76	0.58	2.33	0.75
Eastern part	Const Q3 QП	513.031 1.040 -13.897	74.172 1.836 4.138	 0.15 -0.87	 0.986 0.986	 1.01 1.01	0.9	0.80	1.67	0.99

R square coefficient explains58% and 80%, correspondingly, of the variation in values of excess of the water level over the normal water level by joint variation of the total precipitation for three preceding days and on the current day of a flood (table 2). All other model parameters (σ, beta, Tolerance, VIF, DW, p) match the criteria imposed on them.

Table 3 provides forecast values of level water excess over the normal water level (HП) compared to actual values (H). HП values are predicted by regression equations (4) and (5) based on data of the GFS Global model.

Table 3. Actual and predicted values of excess of the water level over the normal water level in river beds in the North Caucasus

No.	DATA	H	Q_3	$Q_П$	HП
Central part					
1	14.06.09	350.00	20.50	4.40	192
2	19.06.10	594.00	56.00	10.00	604
3	21.06.10	275.00	39.90	22.90	398
4	27.06.10	609.00	25.30	12.00	239
5	30.06.10	80.00	21.30	8.20	197
6	09.04.11	749.00	52.00	16.80	548
7	23.05.11	652.00	69.80	37.80	732
8	28.06.11	230.00	24.50	20.20	219
Eastern part					
1	18.06.09	300	35.8	19.5	279
2	19.06.09	465	47.5	3.7	511
3	20.06.09	495	47.3	3.3	516
4	22.06.09	335	9	9.5	390
5	22.06.11	530	35	5.5	473
6	27.08.11	565	21.3	1.1	520

DISCUSSION

Regression equations have been built for the marked climatic zones of the North Caucasus that may be used to forecast the amount of precipitation during heavy showers (mm):

Central part:

$$QL = -0{,}386 \cdot V700 - 1{,}033 \cdot SQZ5 - 2{,}33 \cdot DTRS5 + 2{,}030 \cdot TTMI - 14{,}411 \quad (1)$$

Western part:

$$QL = 0{,}427 \cdot DSS + 7{,}205 \cdot DTRS5 + 6{,}318 \cdot TTMI - 295{,}63 \quad (2)$$

Eastern part:

$$QL = -0{,}397 \cdot V700 + 0{,}955 \cdot SQZ5 - 1{,}343 \cdot TTMI + 77{,}859 \, . \quad (3)$$

It follows from equations (1)-(3) that they differ in absolute terms and a set of independent variables and their coefficients, which implies that climatic peculiarities materially affect the origin of showers. Showers in the North Sea coast are less dependent on large-scale atmosphere circulation (V700 parameter is absent) and are more subject to local conditions.Regression equations have been obtained for different climatic zones of the North Caucasus that may be used to forecast the excess of the water level over the normal water level H (cm) observed during heavy showers (mm):

Central part:

$$H = 11{,}796 \cdot Q_З - 1{,}243 \cdot Q_П - 44{,}451 \quad (4)$$

Eastern part:

$$H = 1{,}040 \cdot Q_З - 13{,}896 \cdot Q_П + 513{,}031 \, . \quad (5)$$

In equations (4) and (5), coefficients also differ in independent variables, which implies differences in flood formation depending on climatic characteristics of the region under study.

Indicators that describe statistical significance and practicality of regression equations (determination coefficient, R square coefficient, analysis of residuals, etc.) imply that equations (1)-(5) may be used to adequately predict the amount of precipitation during heavy rains and the value of water level excess over the normal water level in river beds of the North Caucasus.

CONCLUSION

Thus, statistical schemes of flood risk evaluation have been obtained in line with the MOS concept (Model Output Statistics) using regression analysis (SPSS package). Table 3 shows results of evaluation of shower and flood development by relevant regression equations for typical regions of the ER south – Western and Central parts of the North Caucasus.We note finally that the new method of forecasting dangerous convection weather phenomena and associated emergencies using the Global Forecast System of the National Center for Environmental Prediction (GFS NCEP) outputs has proven effective. In line with the MOS concept (Model Output Statistics), statistical forecast schemes may also be implemented for other dangerous phenomena (hail, mudslide, gale).

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