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Modeling of Stochastic Process of Implementation of Various Combinations of Dangerous Meteorological Phenomena in the Mountains of the Caucasus

Mariam ELIZBARASHVILI[1*], Elizbar ELIZBARASHVILI[2†]

[1]Faculty of Exact and Natural Sciences, Ivane Javakhishvili Tbilisi State University 1, I. Chavchavadze Ave., Tbilisi Georgia
[2]Institute of Hydrometeorology, Georgian Technical University, 150 a, D. Agmashenebeli Ave., Tbilisi, Georgia

Abstract: *The mountainous regions of Caucasus are characterized by the exceptional variety of dangerous meteorological phenomena that often cause significant material damage and human losses. These dangerous meteorological phenomena often occur simultaneously and exacerbate the situation. For example, increased wind during heavy rains, fog during snowstorms, hurricanes with hail, etc. To reduce the negative effects of such phenomena, it is necessary to know their probabilistic characteristics in given area. These meteorological phenomena are independent of each other, therefore the physical process of their occurrence has stochastic nature and it can be investigated as a random process based on the well-known probability theorems of multiplication and addition. Using these theorems, the stochastic process of realizing various combinations of dangerous meteorological phenomena in the Caucasus Mountains is modeled. For the Caucasus Mountains, the most likely is the implementation of snowstorm, hurricane wind or hail in combination with dangerous fog. The occurrence probabilities of one of the complex events, probability of the joint implementation of complex of both events and the periods of risk recurrence are identified.*
Key words: *Meteorological Phenomena, Mountains of the Caucasus.*

1. Introduction

The Central Caucasus is the highest part of the Greater Caucasus between the peaks of Elbrus (in the west) and Kazbegi (in the east). It extends along the Main Caucasus Range between the Azau and Chiper-Azau passes to the Jvari Pass at a distance of about 200 km. The highest peak of the Central Caucasus, like the entire Caucasus, is Elbrus (5642 m).

The Central Caucasus is characterized by an exceptional variety of dangerous, including catastrophic, meteorological phenomena, often causing significant material damage, as well as human casualties (Alibegova and Elizbarashvili, 1980; Dangerous hydrometeorological phenomena in the Caucasus, 1983; Elizbarashvili, 2017). A rather rich literature is devoted to the study of such phenomena (Elizbarashvili *et al.*, 2012; Elizbarashvili *et al.*, 2013; Elizbarashvili *et al.*, 1983; Elizbarashvili and Zubitashvili, 2007; Elizbarashvili and Elizbarashvili, 2012; Elizbarashvili *et al.*, 2014; Elizbarashvili *et al.*, 2018; Varazanashvili, 2012).

Back in the 80s of the last century, for the Caucasus as a whole, such dangerous weather phenomena as extreme temperatures and precipitation, frosts, strong winds, thunderstorms, hail, fogs, blizzards, dust storms, etc. were studied (Alibegova and Elizbarashvili, 1980; Dangerous hydrometeorological phenomena in the Caucasus, 1983). In more detail for Georgia, these phenomena were cleared up somewhat later (Elizbarashvili *et al.*, 2012; Elizbarashvili *et al.*, 2013; Elizbarashvili *et al.*, 1983; Elizbarashvili *et al.*, 2014; Elizbarashvili *et al.*, 2018). The results of these studies were

[*] Mariam.elizbarashvili@tsu.ge
[†] eelizbar@hotmail.com

generalized in a monograph (Elizbarashvili and Elizbarashvili, 2012), and within the frames of the project of the National Science Foundation of Georgia, all natural elemental phenomena characteristic of Georgia, including endogenous and exogenous processes, were studied (Varazanashvili *et al.*, 2012).

As a result of the conducted studies, it was identified that heavy, including catastrophic, precipitations occur mainly during the displacement of cyclones from the Mediterranean and Black Seas and the intrusion of moisture-enriched air masses from the west (Alibegova and Elizbarashvili, 1980). The most heightened characteristics of heavy precipitations, when their daily amount exceeds 30 mm, are characteristic of the Western and Central parts of the Greater Caucasus with the Black Sea coast. Here, over the year, the number of days with heavy rainfall can be about 30, and the highest daily maximum rainfall reaches 120 mm.

In the study area, the average annual number of days with a thunderstorm is 45-50, the total duration of thunderstorms is 90-110 hours, and the average duration of thunderstorms is 1-2 hours (Elizbarashvili *et al.*, 1983).

Over the territory of Georgia, radiation, advective, advective-radiation, frontal and orographic fogs are widespread. Their distribution over the territory is of complex character, which is explained by the variety of physical and geographical conditions and the peculiarities of atmospheric circulation. At the Mamisoni Pass, the average annual number of days with dangerous fog, when the visibility range is less than 50 m, reaches 160 days, and the average duration of such fog per day is 10 hours (Elizbarashvili *et al.*, 2012).

In the study area, on average over a year, there are more than 3 days with a gale-force wind, and the highest speed reaches 45 m/sec (Varazanashvili *et al.*, 2012).

Hail processes are mainly observed in the warm season of the year, and are most active in spring and in the first half of summer, when the favorable conditions are created for the development of convective clouds. The average annual number of days with hail in the study area is 3-4, and the highest – 10. The maximum diameter of hailstones equals to 2 cm.

Snowstorms are observed throughout Georgia, but they are especially dangerous in mountainous regions, in the pass sections of the Greater Caucasus, Achara-Imereti, Likhi, Trialeti ranges and in the southern Georgian highlands, where strong winds prevail. Snowstorms are observed mainly during the intrusion of cold air masses in the Transcaucasia from the west or simultaneously from the west and east. They usually occur during the passage of cyclones before warm fronts, but sometimes they can also occur behind cyclones during the passage of cold fronts. In the high mountainous part of the Greater Caucasus, snowstorms are common and occur throughout the year. Snowstorm activity reaches its greatest activity from December to April. On the Jvari Pass, the average number of days with snowstorms per year is 24, on Mamisoni Pass – 87 and in Kazbegi – more than 100. The maximum number of days with snowstorms reaches 235 (Elizbarashvili *et al.*, 2018).

However, some dangerous meteorological phenomena often occur simultaneously and exacerbate the situation. For example, wind amplification during a rainstorm, fog during a snowstorm, a hurricane during hailstorm, etc.

The following combinations of catastrophic meteorological phenomena are most dangerous for the Central Caucasus:

- Catastrophic precipitation – hurricane wind (R50-Hu);
- Catastrophic precipitation – hazardous fog (R50-Fd);
- Hail – hurricane wind (Ha - Hu);
- Hail – dangerous fog (Ha-Fd);
- Hurricane wind – dangerous fog (Hu-Fd);
- Snowstorm – dangerous fog (B-Fd);

where R50 – is a catastrophic precipitation, when the daily precipitations exceed 50 mm, Ha–hail, and Hu – hurricane wind, when the wind speed exceeds 32 m/sec, B – snowstorm, and Fd –dangerous fog, when the visibility range is less than 50 m.

To reduce the negative consequences of such phenomena, knowledge of the physical process of their implementation in a given area is necessary.

2. Material and Methodology

The listed meteorological phenomena are independent of each other; therefore, the physical process of their occurrence has a stochastic character and it can be studied as a random process based on the theorem of multiplication and addition of probabilities known in probability theory (Kobysheva, 1971):

$$P(AB) = P(A)\,P(B), \quad (1)$$

$$P(A + B) = P(A) + P(B) - P(AB), \quad (2)$$

where A and B – are meteorological phenomena, P – is the probability.

Let phenomena A and B can occur, when a certain set of conditions is fulfilled and make up a system of mutually incompatible phenomena:

$$(AB), (AB\_), (A\_B), (A\_B\_) \quad (3).$$

The first of them means that both phenomena have occurred, the second means that the phenomenon A has occurred, but the phenomenon B did not occur, etc. Phenomena (3) are incompatible and form a complete system of phenomena.

If the probabilities of phenomena P(A) and P(B) are known, then according to the probability multiplication theorem we have (Agekyan, 1972):

$$P(AB) = P(A)\,P(B)$$

$$P(AB\_) = P(A) - P(AB)$$

$$P(A\_B) = P(B) - P(AB)$$

$$P(A\_B\_) = 1 - \{P(AB) + P(AB\_) + P(A\_B)\} \quad (4).$$

In the Central Caucasus, within Georgia the observation data of 5 meteorological stations were available (Figure 1). In the direction from west to east, these are the following stations: Mamisoni Pass (2854 m above sea level), Kazbegi (3653 m), Gudauri (2194 m), Jvari Pass (2395 m) and Pasanauri (1070 m).

One of the basic requirements for the series of meteorological elements is that they must be comparable with each other. Given this requirement, it is desirable to have data for all stations for a single observation period. Therefore, the data for the period 1961-2010 recommended by the World Meteorological Organization (WMO) were used at Gudauri, Jvari Pass and Pasanauri stations. Unfortunately, after the collapse of the USSR, in 1992, some high-altitude meteorological stations were closed, including Kazbegi and Mamisoni Pass, which currently do not function. However, for uniform coverage of the territory with data, the observation data of these stations were also used. The material used is the archive of the Institute of Hydrometeorology of Georgia, which satisfies all the requirements for the series of meteorological elements, as well as literary data (Elizbarashvili *et al.*, 2012; Elizbarashvili and Elizbarashvili, 2012; Elizbarashvili *et al.*, 2014; Elizbarashvili *et al.*, 2018; Varazanashvili *et al.*, 2012).

Figure 1. Research area and location of meteorological stations

3. Research Findings and Discussion

Table 1 presents the probabilities of various hazardous meteorological phenomena in the study area.

Table 1. Probabilities of various catastrophic meteorological phenomena in the Central Caucasus (%)

Stations	Height, m	R50	Ha	Hu	B	Fd
Pasanauri	1070	0.2	0.5	0	0	0
Kazbegi	3653	0,2	0,5	0	28.2	24.7
Mamisoni Pass	2854	0	2.2	0.9	23.8	43.8
Gudauri	2194	0.1	2.5	0	3.3	30.7
Jvari Pass	2395	0	1.6	0	6.5	41.6

From the Table 1 it follows that in the high-mountain zone of the Central Caucasus, the snowstorm and fog are most likely. The probability of a snowstorm is 3-28%, and the probability of a dangerous fog reaches 24-44%. In the mid-mountain zone of the region, these catastrophic meteorological phenomena are absent (Pasanauri). The probability of other hazardous meteorological phenomena is significantly less. The probability of a dangerous fog and snowstorm with the height of the area naturally increases, however, starting from a height of 3000 m, the probability of fog decreases (Figure 2), which is apparently associated with a decrease in cloudiness and precipitations (Elizbarashvili, 2017).

Table 2 presents the results of modeling the stochastic process of implementing various events and combinations of catastrophic meteorological phenomena according to (4) formulas.

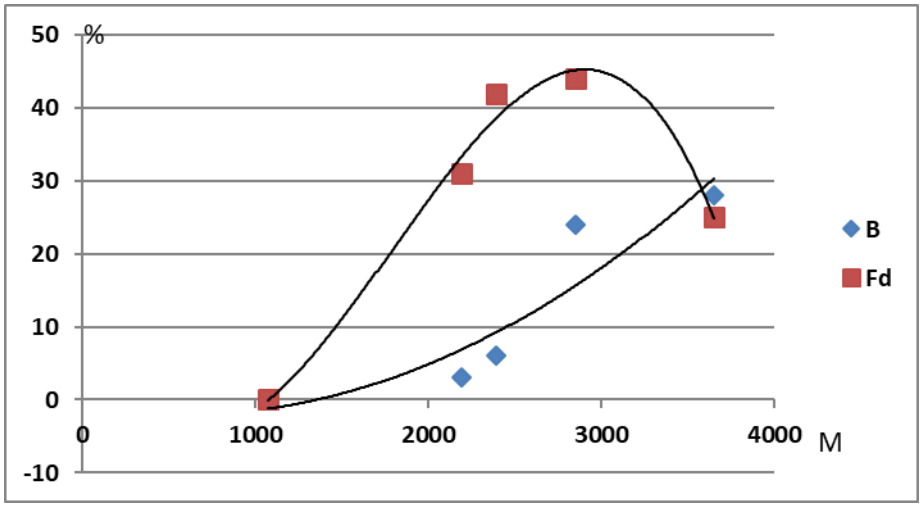

Figure 2. Change in probability of snowstorms (B) and hazardous fogs (Fd) with elevation

Table 2. Model probabilities of various combinations of catastrophic meteorological phenomena (%)

Stations	Event version	R50-Hu	R50-Fd	Ha –Hu	Ha- Fd	Hu- Fd	B- Fd
Pasanauri	P(AB)	0	0	0	0	0	0
	P(AB_)	0.2	0.2	0.5	0	0	0
	P(A_B)	0	0	0	0	0	0
	P(A_B_)	99.8	99.8	99.5	100	100	100
Kazbegi	P(AB)	0	0. 1	0	0. 1	0	7
	P(AB_)	0.2	0. 1	0.5	0.4	0	21
	P(A_B)	0.5	24	0	24	25	18
	P(A_B_)	99.3	75.8	95.5	75.5	75	54
Mamisoni Pass	P(AB)	0	0	0.1	1	0.4	10
	P(AB_)	0	0	2.1	1.2	0.5	13.8
	P(A_B)	0.9	44	0.8	42.8	43.4	33.8
	P(A_B_)	99.1	56	97	55	55.7	42.4
Gudauri	P(AB)	0	0.1	0	0.8	0	1
	P(AB_)	0.1	0.1	2.5	1.7	0	2.3
	P(A_B)	0	30.6	0	29.9	30.7	29.7
	P(A_B_)	99.9	69.2	97.5	67.6	69.3	67
Jvari Pass	P(AB)	0	0	0	0.7	0	3
	P(AB_)	0	0	1.6	0.9	0	3.5
	P(A_B)	0	41.6	0	40.9	41.6	38.6
	P(A_B_)	100	58.4	98.4	57.5	58.4	52.9

From the Table 2 it follows that from the considered complexes of catastrophic meteorological phenomena the most likely complexes for the Central Caucasus are combined with dangerous fog: catastrophic precipitation — dangerous fog (R50-Fd), hail – dangerous fog (Ha-Fd), hurricane wind – dangerous fog (Hu-Fd) and snowstorm – hazardous fog (B-Fd), due to the significant frequency of hazardous fogs. The greatest probability of a snowstorm – hazard fog combination in Kazbegi and in the Mamisoni Pass reaches 7 and 10%, respectively. The complex of catastrophic precipitation-hurricane wind (R50-Hu) phenomena, due to the small probability of its components, is not realized. Complexes of catastrophic meteorological phenomena practically do not form in the mid-mountainous zone (Pasanauri).

Table 3 presents the number of days with a different combination of catastrophic meteorological phenomena occurring in nature, and their recurrence periods calculated by us.

Table 3. The number of days per year with a different combination of catastrophic meteorological phenomena and the period of their recurrence (years / day)

Stations		R50-Fd	Ha –Hu	Ha- Fd	Hu- Fd	B- Fd
Kazbegi	Number of days	0.37	0	0.37	0	26
	The recurrence period	2.7 years	-	2.7 years	-	14 days
Mamisoni Pass	Number of days	0	0.37	3.6	1.5	36.5
	The recurrence period	-	2.7 years	100 days	250 days	10 days
Gudauri	Number of days	0.37	0	0.29	0	3.6
	The recurrence period	2.7 years	-	3.4 years	-	100 days
Jvari Pass	Number of days	0	0	2.6	0	11.1
	The recurrence period	-	-	142 days	-	33 days

From the Table 3 it follows that the catastrophic precipitation-dangerous fog (R50-Fd) complex is implemented at the high-altitude stations of eastern Georgia – Kazbegi and Gudauri with a frequency of 2.7 years, i.e. 0.37 days per year on average. With the same periodicity, the hail – hurricane wind (Ha-Hu) complex is observed only in western Georgia (Mamisoni Pass); here, the hurricane – dangerous fog (Hu-Fd) is also characteristic, which is observed 1.5 times a year on average with a frequency of 250 days. At all high mountainous stations, the hail – dangerous fog (Ha-Fd) combination is observed. Their recurrence period in Kazbegi and Gudauri is 2.7-3.4 years, and in the sections of passes (Mamisoni Pass and Jvari Pass) decreases to 100-140 days. Most often, a snowstorm – dangerous fog (B-Fd) complex takes place in the high mountainous zone of the Central Caucasus. The average annual number of days with a combination of these components is about 4 in Gudauri, 11 – in Jvari Pass, 26 – in Kazbegi, and more than 36 – in Mamisoni Pass. Accordingly, the recurrence period of the complex is 100, 33, 14 and 10 days.

4. Conclusions

1. Among the catastrophic meteorological phenomena in the high mountainous zone of the Central Caucasus, the most probable are snowstorms and fogs. The probability of snowstorms is 3-28%, and the probability of dangerous fogs reaches 24-44%.

2. The most probable are the complexes of phenomena in combination with hazardous fog: catastrophic precipitation — dangerous fog (R50-Fd), hail – hazardous fog (Ha-Fd), hurricane wind – hazardous fog (Hu-Fd) and snowstorm – dangerous fog (B - Fd), that can be explained by the significant frequency of dangerous fogs.

3. Most often, a snowstorm – hazardous fog (B-Fd) complex takes place in the high mountains of the Central Caucasus. The average annual number of days with a combination of these components

is about 4 in Gudauri, 11 – in Jvari Pass, 26 – in Kazbegi, and more than 36 – in Mamisoni Pass. Accordingly, the recurrence period of the complex is 100, 33, 14 and 10 days.

4. The catastrophic precipitation- dangerous fog complex (R50-Fd) takes place at the high-altitude stations of Eastern Georgia – Kazbegi and Gudauri with a frequency of 2.7 years, i.e. 0.37 days per year on average. With the same periodicity, the hailstorm – hurricane (Ha-Hu) complex is observed only in western Georgia (Mamisoni Pass).

5. At all high-altitude stations, the hail – dangerous fog (Ha-Fd) combination is observed. Their recurrence period in Kazbegi and Gudauri is 2.7-3.4 years, and in the sections of passes (Mamisoni Pass and Jvari Pass) decreases to 100-140 days.

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