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Stochastic Modeling of the Process of Realization of the Precipitation-strong wind complex in the Territory of Georgia

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Abstract

Georgia is characterised by dangerous natural meteorological events—extreme temperatures, heavy rainfall, blizzards, fog, strong and hurricane winds, etc., which create emergencies, cause significant material damage, and often cause human casualties. These events frequently occur together, compounding their effects and worsening the situation. The simultaneous occurrence of such events, in particular, strong winds and heavy rainfall, has not been studied for the territory of Georgia. This article looks at the likelihood of the most dangerous combinations of heavy rain and strong winds using probability theory, including the chances of these events happening at the same time, the chances of one event happening, the chances of both events happening if one occurs, and how these chances change over time and space in Georgia. The duration of recurrence periods of catastrophic rainfall and hurricane risk in the different physical geographical conditions of Georgia is also studied. The research utilised observational data from 21 weather stations of the National Environmental Agency, spanning from 1961 to 1990, to analyse strong winds and hurricane-related precipitations. It was identified that the maximum probability of the simultaneous occurrence of a complex of heavy rain and storms on the territory of Georgia is on the Likhi range (Mt. Sabueti) and is 15-23%; the minimum is in June and July, and the maximum is in September, while the probability of only one of the events on the Likhi range varies within 65-75% during the year. When one of the events occurs, the probability that the second event occurs in the Likhi range varies between 42–55%, with a minimum in September and a maximum in March. The highest average annual probability (15-20%) of the realisation of a storm in a complex with heavy rainfall is observed in the Likhi range – about 70 days a year. In the territory of Georgia, the recurrence period for catastrophic rainfalls and hurricanes is shortest on the Black Sea coast and Kolkheti Lowland, at 45 years. The obtained results are important for improving disaster preparedness and resilience in different regions of Georgia.

Keywords: precipitation, catastrophic precipitation, strong and hurricane winds, probability, recurrence.

Introduction

The dangerous and natural meteorological phenomena, such as extreme temperatures, heavy rains, hail, blizzards, fog, strong and hurricane winds, etc., create extraordinary situations, causing significant material damage and, often, even human casualties (World, 2023; NOAA, 2023; WMO, 2023). Some of these phenomena often co-occur, overlapping each other, thereby aggravating the situation (Ali et al., 2023; McPhillips et al., 2018; Zscheischler et al., 2018).

Such compound meteorological extreme events can involve various combinations of weather extremes, such as:

1. Heavy rainfall and strong winds: For example, intense rainfall can occur alongside strong winds, leading to widespread damage from both, flooding and wind-related destruction.
2. Heatwaves and drought: Prolonged periods of extreme heat can exacerbate drought conditions, leading to severe water shortages, increased evaporation rates, and heightened stress on ecosystems and agriculture.
3. Extreme temperature and precipitation: A sudden drop in temperature followed by heavy snow or rain can cause freezing rain events, leading to ice storms that disrupt transportation and power supplies.
4. High temperature and humidity: Heatwaves combined with high humidity levels can result in dangerous heat indices, significantly increasing the risk of heat-related illnesses and fatalities.
5. Storm surge and heavy rainfall: Coastal areas can experience storm surges from cyclones or hurricanes while receiving heavy rainfalls simultaneously, leading to severe coastal and inland flooding.

The compounded nature of these events can magnify their impacts, making them more challenging to predict, manage, and mitigate. Understanding and addressing compound meteorological extreme events are essential to enhancing disaster preparedness and resilience. Worldwide, in the context of global warming, the social and economic costs of natural disasters related to weather and climate have increased significantly over the past 50 years (NOAA, 2023). To reduce the negative consequences of these complex phenomena, it is necessary to know their probability characteristics in each area.

The study of a two-dimensional precipitation-strong wind complex, which poses the greatest threat to Georgia, is the focus of this article. The way independent weather events happen is random, so they can be analysed using the rules of adding and multiplying probabilities from probability theory (Agekyan, 1972).

The probability of the most dangerous combinations of precipitation and strong wind, the probability of simultaneous occurrence of independent events, the probability of one of the events, the probability of the occurrence of a complex if one of the events occurs, and the duration of the periods of recurrence of the risk of catastrophic precipitation and hurricane winds were studied.

The next section of the article considers the study area, method, and data used. The results are then presented and discussed. Finally, conclusions and recommendations for future research directions are presented.

Methods and Materials

Georgia is a mountainous country characterised by complex physical-geographical and landscape-climatic conditions. Characteristic radiation and circulation processes of the atmosphere contribute to the formation of a wide variety of climates. Most climate types observed on the globe are found here (Bolashvili et al., 2018). Georgia is characterised by dangerous and natural meteorological phenomena – extreme temperatures, heavy rainfall, hail, blizzards, fog, strong and hurricane winds, etc. (Elizbarashvili et al., 2017a; Elizbarashvili, 2017b; Elizbarashvili et al., 2022a; Elizbarashvili et al., 2022b).

According to the main principles of probability theory (Agekyan, 1972), the probability of the occurrence of two independent events, A and B, can be calculated using the multiplication rule of probability:

$$P(A\ and\ B) = P(A) \times P(B), \quad (1)$$

The probability of the occurrence of at least one of the events is determined by the addition rule of probability**:**

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

where P*(A)* – is the probability of event *A*, and *P(B)* – is the probability of event *B*.

If we consider the complete system of events *Ai*, where i *i= 1,2,3,.....n*, then the probability of the event *Ai*, given that event *B* has occurred, is calculated according to Bayes' Theorem:

$$P(Ai \mid B) = \frac{P(Ai) \times P(\mathrm{B} \mid \mathrm{Ai})}{\sum_{j=1}^{n} P(Aj) \times P(B \mid Aj)} \quad (3)$$

P (Ai | B) is the posterior (conditional) probability: the probability of event Ai, given that event B has occurred. P(Ai) is the prior probability of Ai – the initial belief about the probability of event Ai before observing B. P (B | Ai) is the likelihood of observing B given Ai. The denominator represents the total probability of B, summed over all possible events Aj, where j=1,2,...,n.

The probability of the most dangerous combinations of precipitation and strong wind in different physical and geographical conditions of Georgia was studied based on the formulas of the theory of probability. The duration of recurrence periods of catastrophic precipitation and hurricane wind risk in different physical and geographical conditions of Georgia was evaluated. Data from observations at 21 weather stations by the National Environmental Agency, covering the period from 1961 to 1990, on strong and hurricane winds and precipitation, were used as the starting material.

Results

Fig. 1 shows the annual course of the probability of precipitation-strong wind combinations in various physical and geographical conditions of Georgia: Samtredia (28 m), located in the central part of the Kolkheti Lowland; Tbilisi (403 m), characterising the lowland areas of eastern Georgia; and Mt. Sabueti (1,242 m), located on the climate-dividing Likhi range.

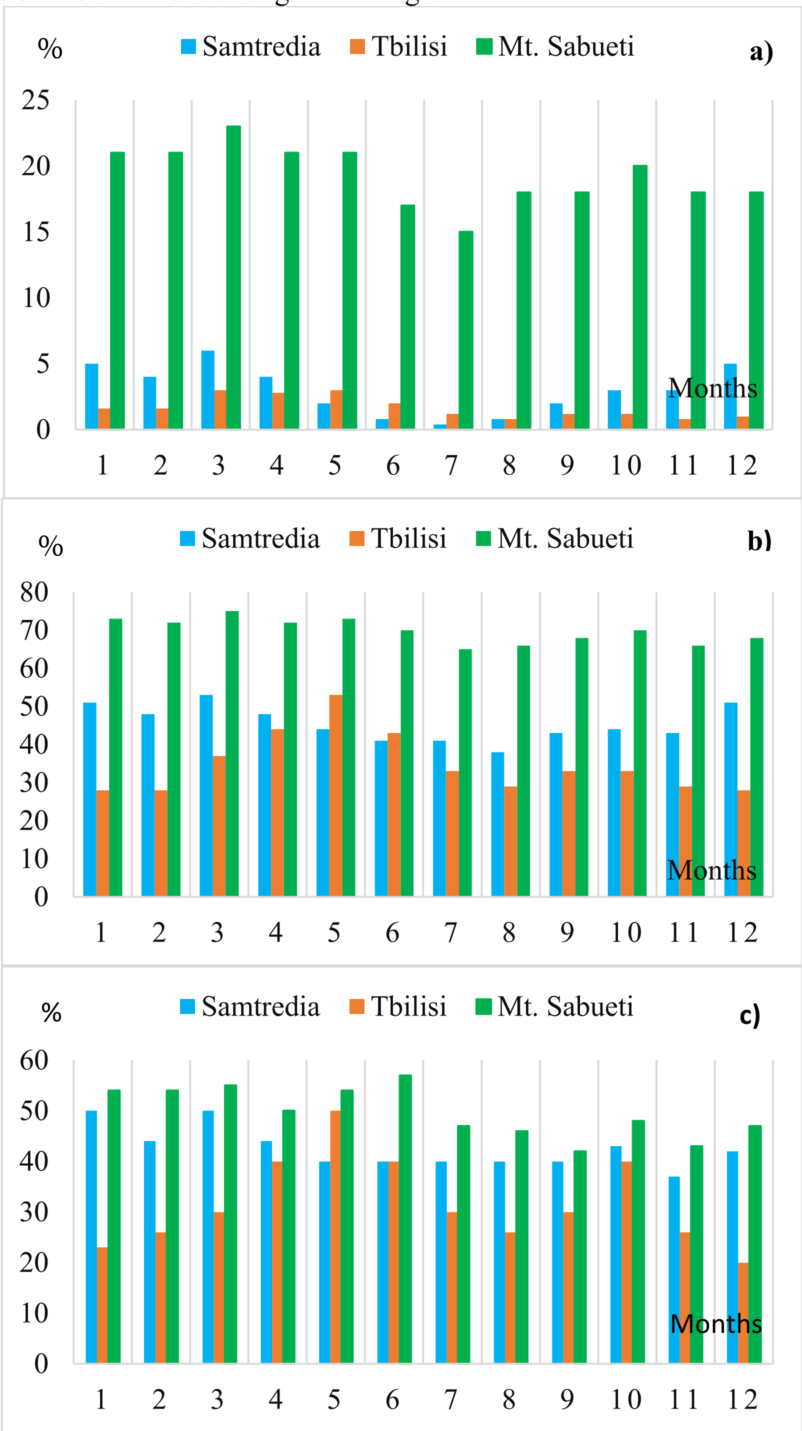

Figure 1. Annual course of the probability of the most dangerous combinations of precipitation-strong wind in various physical and geographical conditions of Georgia: a) - the probability of simultaneous

occurrence of independent events; b) - the probability of occurrence of one of the events. c) - probability of occurrence of the complex, if one of the events has occurred. 1 - Samtredia; 2 - Tbilisi; 3 – Mt Sabueti

Fig. 2 shows a map of the distribution of average annual probabilities of the occurrence of the precipitation-strong wind complex, calculated using formula (1).

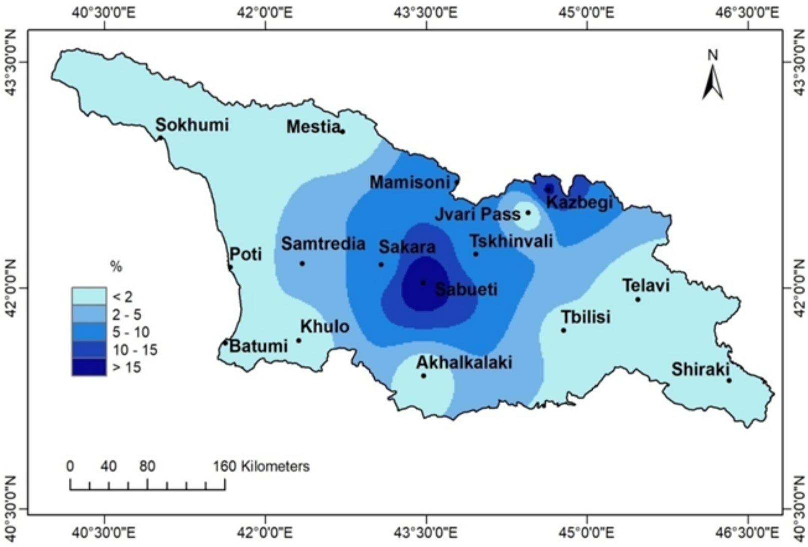

Figure 2. Geoinformation map of the distribution of average annual probabilities of the precipitation-strong wind complex (Elizbarashvili et al, 2019)

If we consider a complex of catastrophic precipitation, when more than 50 mm falls per day, and a hurricane wind, when its speed exceeds 32 meters per second, then the probability of the complex implementation decreases significantly. This is confirmed by Table 1, which presents the relevant materials for various regions of Georgia.

Table 1. Probabilities (P) of combinations of catastrophic precipitation and hurricane winds by regions: 1 - Black Sea coast and Kolkheti Lowland; 2 - Plains and foothills of eastern Georgia; 3 - Likhi and Adjara-Imereti ranges; 4 - Southern Georgian highland; 5 - Greater Caucasus

Probability	Regions of Georgia				
	1	2	3	4	5
$P(A\,B)$	0.004-0.006	0.0002-0.0016	0.0005	0.0012-0.0022	-
$P(A+B)$	1.3-1.8	0.3-11	0.6	0.8-1.3	0.9

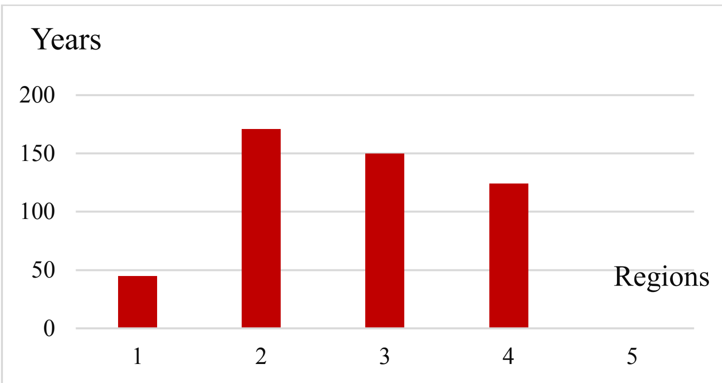

Figure 3. Recurrence of risk of catastrophic precipitation and hurricane winds by regions and years

Fig. 3 shows the minimum durations of the recurrence periods of the risk of catastrophic precipitation-hurricane wind for the entire sample in Georgia's various physical and geographical conditions.

Discussions

It follows from Fig. 1 that the probability of simultaneous occurrence of strong wind and precipitation inon the Kolkheti Lowland (Samtredia) during the year fluctuates on average from 0.4%.4 to 5%, with a minimum in summer and a maximum in December-January or March, while on the plains of eastern Georgia (Tbilisi) the probability of the same complex is 1-3%, with a minimum in August and

November, and a maximum in May. The probability of a precipitation-strong wind complex on the Likhi range (Mt. Sabueti) increases significantly, amounting to 15-23%, with a minimum in June and July, and a maximum in September.

The probability of occurrence of one of the events of the precipitation-strong wind $P(A\ or B)$ complex phenomena on the Kolkheti Lowland fluctuates within 38-51% during the year, with a minimum in August and a maximum in December-January, on the plains of eastern Georgia it is 28-53%, with a minimum in January-February and a maximum in May, and on the Likhi range it fluctuates within 65-75%.

When one of the events of the precipitation-strong wind complex occurs, the probability of occurrence of its second component during the year P (A | B)) on the Kolkheti Lowland fluctuates between 37 and 50%, with a minimum in November-July, and a maximum in December-January and March; on the plains of eastern Georgia, the probability of the corresponding event is 20-40%, with a minimum in December-August and November, and a maximum in March and May, and on the Likhi range it fluctuates between 42-55%, with a minimum in September and a maximum in March.

The highest probability of the complex occurring in a year (15-20%) is observed in the open Likhi range (about 70 days during the year). In the eastern part of the southern slope of the Greater Caucasus, the probability of the same complex is 10-15% (35-50 days). On the Black Sea coast of Georgia, the probability of the precipitation-strong wind complex occurring is 2%, and in a significant part of the territory of the southern Georgian highland and the plains of eastern Georgia, it does not exceed 1%, which corresponds to 7 and 4 days (Fig. 2).

From Table 1 it follows that the probability of the occurrence of one of the events of the catastrophic precipitation-hurricane wind complex over a large territory does not exceed 2%; the probabilities of the occurrence of a complex of phenomena are also small and change little across the territory, increasing somewhat on the Black Sea coast and the Kolkheti Lowland (0.004-0.006%).

The shortest duration of the recurrence period of the risk of catastrophic precipitation - hurricane wind is on the Black Sea coast and the Kolkheti Lowland, and it is 45 years. On the plains and in the foothills of eastern Georgia, the duration of the risk recurrence is maximum, amounting to about 170 years. On the Likhi and Adjara-Imereti ranges, the risk recurrence is about 150 years, and on the southern Georgian highland, more than 120 years. In the Greater Caucasus, the complex of catastrophic precipitation - hurricane wind has not been recorded according to available data (Fig. 3).

Conclusion

The obtained results can be used in planning activities to reduce the negative consequences of the impact of a complex of dangerous meteorological events on the territory of Georgia. The stochastic approach allows us to study the physical process of the simultaneous occurrence of two independent dangerous meteorological events and quantitatively assess the conditional probabilities of its development. The tested approach will be used in a detailed study of the processes of occurrence of the most dangerous meteorological events in Georgia's conditions.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

M.E. and E.E. conceived of the presented idea. E.E. performed the analytic calculations. M.E. took the lead in writing the manuscript. E.E. reviewed and edited the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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