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A METEOROLOGICALLY-BASED STATISTICAL MODEL FOR SHORT-TERM FORECASTING OF SAND AND DUST STORMS IN THE ARAL SEA REGION

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Abstract. *This article examines the formation of sand and dust storms in the Aral Sea region and the possibilities for their short-term forecasting. The study analyzed the duration of dust storm events using meteorological data collected from 2014 to 2023. A model were developed to assess storm risk levels by applying statistical modeling with meteorological data, utilizing the Gumbel distribution and other forecasting algorithms. The results demonstrated the significance of meteorological parameters in forecasting sand and dust storms in the Aral Sea region. This scientific approach provides an effective basis for planning measures to protect environmental safety and public health in the region.*

Keywords: *Aral Sea, sandstorm, short-term forecast, meteorological indicators, statistical model, logistic regression, ecological risk, prediction*

1. Introduction. In recent years, various environmental problems, including sand and dust storms (SDS), have increasingly been observed due to the influence of global climate change and anthropogenic factors related to human activities. In particular, the ecological disaster in the Aral Sea basin has drastically altered the frequency and spatial distribution of SDS, significantly expanding their adverse impacts [1]. The drying of the Aral Sea, the degradation of surrounding soil cover, increased wind erosion, sharp aridification of the regional climate, and the reduction of vegetation cover have contributed to the intensification of sand and dust storms [2]. These events pose serious environmental and public health threats, especially in the Muynak and Kungrad districts and the city of Nukus in the Republic of Karakalpakstan. Sand and dust storms facilitate the long-distance transport of atmospheric particles, which negatively affects human health, agricultural productivity, transport infrastructure, and ecological stability [3].

Studies conducted by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) indicate that SDS can have significant climatic and ecological consequences, not only at the local level but also globally [4]. At the international level, various initiatives have been implemented to monitor, forecast, and assess the risks associated with these events, particularly through the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) [5]. However, research aimed at scientifically forecasting sand and dust storms in the Aral Sea region remains underdeveloped. Most existing studies adopt a general descriptive approach, with insufficient attention paid to regional characteristics, statistical analysis methods, and forecasting methodologies based on extreme value theory. From this perspective, this study aims to conduct an in-depth scientific analysis of the dynamics of sand and dust storms in the Aral Sea region, determine their duration and frequency, calculate return periods, and provide forecasts using extreme statistical modeling. The relevance of this study lies in its provision of a clear and practical solution for statistical modeling aimed at predicting SDS in the Aral Sea region. This analysis also serves as a basis for reducing environmental risks, enhancing storm preparedness, protecting public health, and developing regional climate adaptation strategies.

1.1. Relevance of the research.

The deepening of environmental problems in the Aral Sea region, particularly the increasing frequency, intensity, and negative impacts of sand and dust storms (SDS) on socio-economic life, makes the scientific study and forecasting of these phenomena an urgent priority. Such storms affect public health, agricultural productivity, and the stability of the region's transport systems. Therefore, employing statistical approaches for predicting SDS, particularly using the Gumbel distribution method based on extreme value theory, is of significant importance.

1.2. The purpose of the study.

This article aims to scientifically assess and predict the possible recurrence of severe weather events in the Aral Sea region, Nukus city, Muynak and Kungrad districts, based on the Gumbel distribution. This involves analyzing severe weather events based on meteorological observation data collected during 2014–2023.

2. Methodology

2.1. Research object

The object of this study is to study the occurrence of SDSs observed in the Aral Sea region, in particular, in the Muynak and Kungrad districts of the Republic of Karakalpakstan and the city of Nukus.

2.2. Research methods and methodology

The study used statistical-extreme analysis methods, in particular the Gumbel distribution model. Using this method, forecast values for sand and dust storms were calculated based on the maximum duration indicators for their return periods (2, 5, 10, 20, 50 years, etc.). Microsoft Excel and Python programs were used for calculations and visual analysis, and the forecast results were presented using interpolation and graphical representations. These results allow us to identify the sources of dust particles and assess their interregional impact.

3. Results and analysis

3.1. Forecast based on Gumbel distribution

Based on the Gumbel distribution, the forecast of the hours of the SDSs in the Aral Sea region, in particular in the Nukus, Muynak and Kungrad regions, was carried out. Meteorological data collected for the period 2014–2023 were used as the basis for the analysis. To assess the intensity and duration of SDSs, the return period, the annual probability of exceedance (%) and Gumbel statistical indicators (Z and EV) were calculated. Table 1 below presents the forecast results of the expected SDS hours in each region depending on the return periods.

Table 1. Forecast of SDSs based on the Gumbel distribution

Payback period (year)	Annual probability of exceeding (%)	Gumbel factor (Z)	Gumbel EV (Nukus)	Nukus (hours)	Muynak (hours)	Kungrad (hour)
2	50	0.37	9.9	9.9	11.53	10.53

5	20	1.5	11.4	11.4	13.28	12.28
10	10	2.25	12.3	12.3	14.39	13.39
20	5	2.97	13.2	13.2	15.44	14.44
50	2	3.9	14.4	14.4	16.72	15.72

The results show that with increasing return period, the number of SDS hours also increases. In the Muynak district, the expected storm hours are projected to reach 16.72 with a return period of 50 years, which indicates a high ecological risk of dust storms in this region. In n district, this indicator is 15.72 hours, which is slightly higher than in Nukus (14.4 hours). These results indicate the effectiveness of the Gumbel statistical approach in predicting the frequency and duration of sand and dust storms across regions. This method is especially convenient in long-term forecasts, as it allows taking into account extreme events. In the Aral Sea region, in particular, in the Nukus region, **the Gumbel distribution** based on **the theory of extreme values was used** to estimate the expected future duration or frequency of SDSs. This approach is widely used to model extreme events (e.g., very severe storms , maximum precipitation, temperatures, etc.).

The table above and the graph in Figure 1 below, the duration of the SSRs in the three main regions of the Aral Sea region – Nukus, Muynak and Kungrad – was analyzed based on the Gumbel distribution. This distribution allows us to estimate the probability of recurrence of events based on statistical extreme values (highest cases).

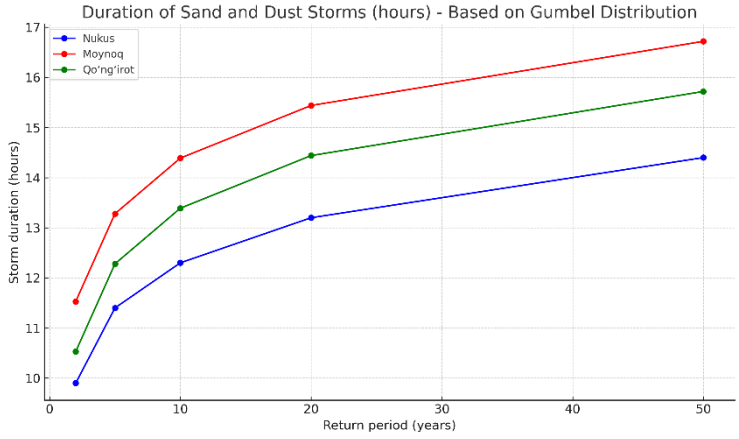


Figure 1. Prediction of the duration of the SDSs (hours) based on the Gumbel distribution – for the example of the Aral Sea region.

be seen from the graph, the highest indicators are recorded in Muynak. Every one return during Fur in the territory forecast being done storm hours other to the regions relatively high . For example, dust storms in Muynak can last up to 16.72 hours during a 50-year return period . This result may be due to the geographical and climatic characteristics of the area, namely the proximity to open deserts and sandy areas.

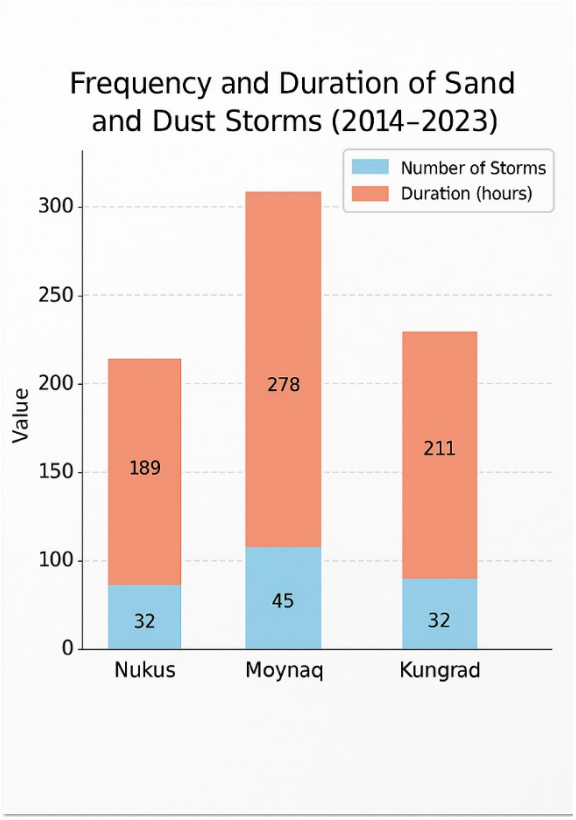
Kungrad is considered a medium risk area, with fewer storms than Muynak but longer durations than Nukus. The terrain and meteorological conditions here are somewhat more stable than Muynak, but still open to dust-carrying winds.

The lowest rates are observed in Nukus. The number of hours of sand and dust storms in Nukus is lower than in other regions. This can be explained by urban infrastructure, more stable soil structure, and the presence of natural and anthropogenic barriers that dampen winds.

The duration of storms increases as the return period increases (for example, from 2 to 50 years). This suggests that extreme events are likely to become more intense in the long term.

The forecasts are based on 10 years of observational data, and extreme events are statistically predicted by fitting the data to the Gumbel distribution. This approach is effective for assessing climate risks and helps to define preventive measures across regions [8].

These forecast results, obtained using the Gumbel distribution, allow for a regional analysis of the susceptibility of the Aral Sea region to dust storms. These data can also be used to support decisions on improving resilience, designing protective structures, and enhancing public warning systems. SDSs, not only their extreme duration, but also their annual frequency and total duration indicators play an important role. These parameters have direct practical importance in assessing the level of environmental risk in the region, monitoring air quality and determining health risk criteria. In particular, the ratio between the number of storms and their total duration shows how vulnerable each region is to sand and dust flows. The graph in Figure 2 below compares the frequency and duration of SDSs recorded in Nukus city, Muynak and Kun'irot districts for 2014–2023 in the form of a bar chart.



The diagram shows the years 2014–2023. during Nukus city , Muynak and Call in the districts observed SDSs general number (frequency) and The duration (in hours) is depicted . Graph columnar apparently to be , every one area according to Non-profit organizations number and this of events general duration hours together shown.

Fur in the district total 45 units storm event record done to be , their general duration 278 hours organization Call 32 in the district storm divided into , total Duration 211 hours , Nukus in the city and 2 storm divided into , total duration 189 hours equal.

Figure 2 Bar chart of frequency and duration of SDSs by region.

Regional advantage from the graph obvious. It seems that Muynak district two indicator according to also leader in place. This results The fur of the fur Island of the sea dried up to the part the most close location, surroundings plant cover shortage and geological - geographical openness with related to be possibility guess The intensity of the storms was calculated by averaging the duration of each storm event:

Fur: 278 hours / 45 pieces ≈ 6.18 hours

Call: 211 / 32 ≈ 6.59 hours

Nukus: 189 / 25 ≈ 7.56 hours

An interesting trend was observed here: Nukus has fewer storms, but their duration is relatively longer. This suggests that dust particles in the city may be coming from local sources, especially paved roads, construction areas, or industrial facilities.

The influence of external factors While in Kungrad and Muynak districts, storms are mainly associated with regional or long-distance dust flows, in Nukus anthropogenic factors, in particular, urbanization, water shortages during the dry season, and changes in wind direction, may have an impact.

Risk assessment and the need for measures Muynak is a high-risk zone, requiring advanced monitoring and warning systems. Kungrad is at medium risk, but regional analysis should continue. Nukus is relatively safe, but due to its long duration, health and environmental monitoring should be strengthened.

This graph shows significant differences in the frequency of storms across regions. Not only the frequency, but also the duration of storms determines environmental and social risks. A higher number of storms means that they release more particles into the air, while their duration means that they have a greater impact on air quality and human health. Therefore, both parameters are important in forecasting models.

3.2. Analysis and discussion

The forecast for the Aral Sea region shows that extreme meteorological events—particularly sand and dust storms—differ significantly across the region. As the return period increases, the predicted storm duration in the Aral Sea region also increases, confirming the high efficiency of the Gumbel distribution in modeling extreme events. Muynak district exhibits the highest forecasted values across all return periods. In particular, the fact that storm durations in this region may reach 16.72 hours during a 50-year return period indicates a high level of ecological risk. Muynak's proximity to the dried-up bed of the Aral Sea, the presence of open lands in the desert zone, and the lack of vegetation create favorable conditions for the formation of dust flows. This situation is directly linked to the geomorphological and ecological characteristics of the region.

Kungrad district has an average risk level, with forecasts indicating that storm durations during a 50-year return period may reach 15.72 hours. Although the frequency of dust storms in this district is lower than in Muynak, the durations are

comparable, suggesting that the terrain in Kungrad is open and susceptible to winds.

Analysis of the diagrams and the average duration indicators confirms that the frequency and duration of sand and dust storms are not always directly correlated. For example, in Muynak, the number of storms is high, but each storm is relatively short in duration. In contrast, in Nukus, storms occur less frequently, but their duration tends to be longer. This indicates that risk profiling should be tailored to the specific conditions of each area.

These forecasts, based on the Gumbel distribution, have significant practical value. They can be utilized to improve early warning systems in areas at high risk of storms, establish environmental monitoring networks, and implement timely social protection measures (such as distributing masks, closing schools, and imposing traffic restrictions). Additionally, they can support the planning of landscape architecture to enhance resilience through the development of green zones and the installation of windbreaks.

The results demonstrate that the use of the Gumbel distribution for forecasting extreme events is highly effective in the Aral Sea region, and this approach can serve as a key component in climate risk assessment and mitigation strategies. Storm forecasting should consider not only frequency but also duration and intensity indicators. Therefore, future studies should focus on developing combined forecasting models, such as utilizing or comparing the Gumbel–Logistic and GEV (Generalized Extreme Value) distributions.

4. Conclusion

The study developed a statistical model based on the Gumbel distribution for short-term forecasting of sand and dust storms (SDS) in the Aral Sea region. Using meteorological data collected from 2014 to 2023, the frequency and duration of storms were analyzed within the framework of extreme value theory. The results indicated that storm frequency and duration were high in Muynak, moderate in Kungrad, and low in frequency but high in duration in Nukus.

Forecasting storm durations over return periods of 2 to 50 years using the Gumbel distribution has proven to be an effective method for assessing climate risks, demonstrating that storm durations increase over longer return periods. This approach can be applied to improve preparedness for dust storms, develop monitoring systems, enhance public warning systems, and implement environmental risk reduction measures.

The study also demonstrated the importance of considering both the frequency and duration of SDS in forecasting and provided scientifically grounded solutions for risk management in the Aral Sea region under conditions of climate change.

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Метеорологически-статистическая модель для краткосрочного прогнозирования песчаных и пыльных бурь в регионе Приаралья

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Аннотация. *В статье рассматривается формирование пылевых и песчаных бурь в Приаральском регионе и возможности их краткосрочного прогнозирования. В исследовании проанализирована продолжительность пылевых бурь на основе метеорологических данных, собранных в период с 2014 по 2023 годы. Разработана модель для оценки уровня риска бурь с применением статистического моделирования метеорологических данных, используя распределение Гумбеля и другие алгоритмы прогнозирования. Результаты показали значимость метеорологических параметров в прогнозировании пылевых и песчаных бурь в Приаральском регионе. Данный научный подход обеспечивает эффективную основу для планирования мероприятий по обеспечению экологической безопасности и охране здоровья населения в регионе.*

Ключевые слова: *Приаралье, песчаная буря, краткосрочный прогноз, метеорологические показатели, статистическая модель, логистическая регрессия, экологический риск, прогнозирование.*

Orolbo‘yi qum-chang bo‘ronlarini qisqa muddatli bashorat qilishning meteorologik omillarga asoslangan statistik modeli

Khalmuratov Batir

Annotatsiya. *Mazkur maqolada Orolbo‘yi mintaqasida qum va chang bo‘ronlarining shakllanishi va ularni qisqa muddatli prognozlash imkoniyatlari o‘rganildi. Tadqiqotda 2014–2023 yillar davomida to‘plangan meteorologik ko‘rsatkichlar chang bo‘roni hodisalari davomiyligi tahlil qilindi. Statistik modellashtirish, meteorologik ma’lumotlar orqali Gumbel taqsimoti asosida ekstremal hodisalarni bashorat qilish va boshqa bashoratlash algoritmlari yordamida bo‘ron xavfi darajasini aniqlovchi model ishlab chiqildi. Natijalar Orolbo‘yi hududida qum-chang bo‘ronlarini prognozlashda meteorologik parametrlarning muhimligini ko‘rsatdi. Ushbu ilmiy yondashuv mintaqadagi ekologik xavfsizlik va aholining sog‘lig‘ini himoya qilish choralarini samarali rejalashtirishga xizmat qiladi.*

Kalit so‘zlar: *Orolbo‘yi, qum bo‘roni, qisqa muddatli prognoz, meteorologik ko‘rsatkichlar, statistik model, logistik regressiya, ekologik xavf, prognoz.*