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Dust migration from expanding deserts near Amudarya: modeling and assessment

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Abstract. The Lower Amudarya Oasis (Karakalpakstan) is increasingly affected by atmospheric dust due to surrounding desert expansion. This study examines long-term and seasonal dust migration patterns, with key drivers including wind dynamics, vegetation degradation, precipitation trends, and desertification processes. Statistical modeling, GIS analysis, and remote sensing data (1961–2024) were applied to quantify near-surface (0–3 m) dust concentrations across the region. Results indicate a rise in high-velocity wind events alongside declining precipitation and vegetative cover, particularly during warm seasons. Spatial analysis identified the northern and western oasis margins as dust hotspots, highlighting intensifying desertification impacts. These findings contribute to improved environmental monitoring and public health strategies in arid regions.

1 Introduction

Atmospheric dustiness (AD) is an essential part of the global problem of environmental pollution. A significant share of pollutants consists of dust of both industrial and natural origin. Natural sources of atmospheric dust (desert areas), compared to industrial ones, have a much greater spatial impact, are less manageable, and involve several poorly studied aspects. AD is a relevant issue for many countries of the world, especially those located in desert zones, including Uzbekistan, where vast territories are covered by the Kyzylkum, Ustyurt, Aralkum, and partly the Karakum deserts.

Protecting and improving public health is a primary state task aimed at sustainable socio-economic development. Accordingly, numerous studies are conducted on the impact of environmental pollution on population health. Diseases associated with atmospheric dustiness arise from inhaling dust particles along with microbes, heavy metals, pesticides, and other pollutants contained in the soil [1-3]. Due to their micro- and nano-size, particles easily enter the lungs and bloodstream. According to expert estimates in 2014, the effect of dust particles caused about 400,000 premature deaths from cardiopulmonary diseases in people over 30 years old. Dust storms contribute to increased cases of asthma, tracheitis, pneumonia, allergic rhinitis, and silicosis [4]. In addition to these well-known respiratory diseases [5-7], mineral dust is considered one of the major risk factors for allergies and

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meningitis in Iran and West Africa [8], as well as for cardiovascular [9, 10], psychological and cognitive [11], and neurodegenerative diseases [12-14].

Currently, AD is the most serious public health problem in the Aral Sea region, as the dust from the dried bottom of the Aral Sea, which contains toxic sulfates, poses a double hazard. The Aral region suffers from low birth rates, high mortality, low health indices, adverse environmental conditions, and socially significant diseases that reduce life expectancy. Cardiovascular diseases, cancers, and tuberculosis are of greatest concern. This issue is especially acute for Karakalpakstan, where the majority of the population lives in the central oasis, which is surrounded on all sides by the Kyzylkum, Karakum, Ustyurt, and Aralkum deserts — powerful sources of large-scale atmospheric pollution during dust storms.

Most research on AD focuses on dust concentrations during dust storms, which have acute short-term impacts on the environment. However, it is known that long-term exposure to even small concentrations of pollutants is more dangerous due to the risk of chronic intoxication. This aspect of AD from deserts remains one of the least studied. As for the Lower Amudarya oasis, where the majority of Karakalpakstan's population resides, as well as the population of Khorezm and Dashoguz province in Turkmenistan, the AD of this region remains almost unexplored (except for salt emissions from the dried Aral Sea bed). Meanwhile, because population health is closely linked to both drinking water and air quality, information about air conditions in the human activity layer is of utmost importance. Therefore, research into the spatial and temporal dynamics of dustiness in the Lower Amudarya oasis, surrounded by powerful dust sources such as Aralkum, Ustyurt, Kyzylkum, and Karakum, is highly relevant. It is clear that such research must also include the dynamics of both dust-intensifying and dust-mitigating factors. Alongside the analysis of long-term AD dynamics (to identify process trends for forecasting), it is also important to study its seasonal variations. This provides scientifically grounded insights into where and when dust concentration exceeds maximum permissible levels in the region.

This research is also relevant for improving the environmental situation in the Southern Aral region. The results of AD zoning can help identify zones for enhanced monitoring by health and environmental authorities. Overall, the patterns and trends of AD may also be useful in climatology, as atmospheric dust is a significant factor in climate change.

Based on the above, the aim of this work is to determine dust concentrations in the human activity layer (0–3 m), identify long-term spatial-temporal dynamics of AD, and analyze the dynamics of factors contributing to dust migration from Aralkum, Ustyurt, Kyzylkum, and Karakum.

2 Materials and Methods

This study employed methods of modeling, statistical analysis, approximation, GIS technologies, and used data from meteorological stations (MS), remote sensing (RS), online databases, the archive of UzHydromet, as well as scientific publications with corresponding references.

The territory of the Southern Aral region, in the model representation, is a system of non-overlapping areas: the Lower Amudarya Oasis (LAO) and the surrounding deserts of Kyzylkum, Karakum, Ustyurt, and Aralkum, which are powerful sources of dust (Fig. 1). The quantization step of the calculation area was 25x25 km.

Fig. 1. Modeling area

The uniqueness of this territory lies not only in its geographical aspect but also in the fact that the Southern Aral region (SAR) is located in the epicenter of the Aral crisis, with all its negative consequences. The flat orography, active wind regime, and low precipitation, which would otherwise clean the atmosphere, create the most favorable conditions for dust emissions from the underlying surface and its transport over long distances.

The dust migration factors in the SAR include wind regime and expanding desert area (intensifying factors), as well as precipitation amount and total projective vegetation cover (mitigating factors).

In this context, the desert area is considered as the area of dust sources. For Ustyurt, Kyzylkum, and Karakum, it is assumed that the dust source intensity, overall projective cover (OPC), and meteorological fields are spatially homogeneous throughout each desert. However, for Aralkum, such an assumption is unacceptable due to the highly dynamic nature of the OPC and, therefore, the variability of dust source intensity. In calculations, we relied on the results of the study of the spatial-temporal dynamics of the total projective cover of the dried bottom of the Aral Sea (DBAS) conducted in the work [15].

The modeling period for the long-term dynamics of AD using the LDAD (Long-Term Dynamics of Atmospheric Dustiness) model [15] was 1961–2024. The period for modeling long-term exposure of dust sources using the LEM (Long-term Emission Model) was one month. The period for modeling short-term dust emissions using the dust storm model was 5–8 hours.

Since dust-related meteorological events mainly occur in the warm season (April–October), calculations were performed only for this period.

3 Results

The study of long-term dynamics of natural processes is necessary to identify stable trends and their dependence on various factors. Moreover, the higher and more diverse the evolution rates of the process, the longer the statistical series must be. The results of such studies are practically significant for forecasting and for developing appropriate measures in response to anthropogenic impacts on influencing factors. Such studies are particularly relevant for regions undergoing dynamic transformations of their natural environment, such as the Southern Aral Region — the epicenter of the Aral Sea crisis.

In this study, the long-term dynamics of atmospheric pollution are defined by the dynamics of the wind regime, precipitation amount, vegetation cover (VC), and desert surface characteristics. Therefore, to quantify long-term atmospheric pollution, a statistical analysis of the dynamics of these factors was carried out, including correlation and regression analysis, distribution function calculations, approximation of time series of factual data, and others.

The emission of dust-sand aerosols into the atmosphere under relevant surface conditions mainly depends on the wind regime, which in turn depends on general atmospheric circulation processes. We conducted a statistical analysis to align time series of factual data, to combine samples, and to determine statistical indicators. The first step was to analyze the long-term data on wind regime (number of days with wind speed >4 m/s) at the four primary dust source locations (Fig. 2).

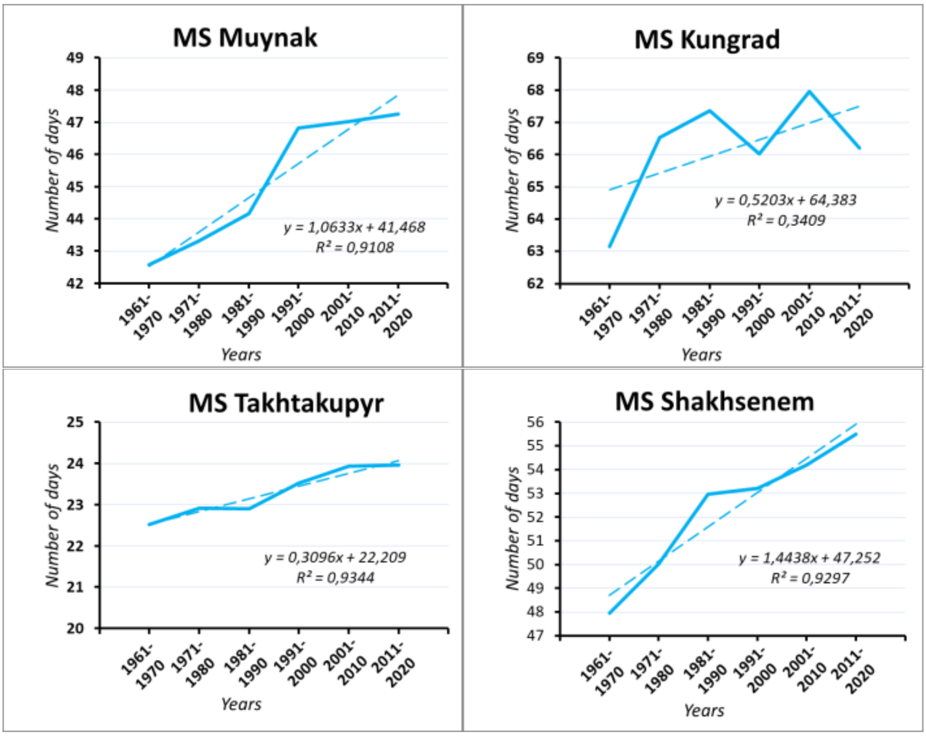

Fig. 2. Number of days with wind speed >4 m/s during the warm season (April–October)

The graph shows slight fluctuations in wind activity (except for MS Kungrad). There is an overall trend of increasing days with wind speed exceeding 4 m/s, which indicates a strengthening of this factor.

Wind rose diagrams of the desert territories surrounding LAO exhibit significant spatial-temporal dynamics, constructed based on data from sourses- Subbotina O.I. and Chanisheva S.G., *Klimat Priaralya* (NIGMI, Tashkent, 2006, in Russian), and open-access meteorological data from the website *Pogoda i klimat* (http://www.pogodaiklimat.ru, accessed July 2025).

Analysis of the dynamics of wind roses in the deserts around LAO shows a growing trend of both stronger winds and an increase in the frequency of wind directions towards the LAO.

Precipitation analysis (Fig. 3) highlighted a significant decline in the number of rainy days during the past decade. This reduction may be attributed to elevated aerosol concentrations (serving as condensation nuclei), which, when exceeding a critical threshold

(100–150 µg/m³), inhibit precipitation formation. Additionally, regional warming of 2–3°C has likely contributed to increased evaporation of falling raindrops before they reach the surface.

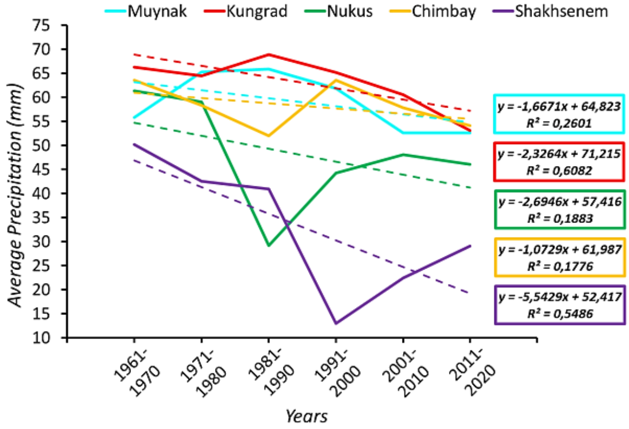

Fig. 3. Number of days with wind speed >4 m/s during the warm season (April–October)

The long-term dynamics of dust source areas, particularly desert expansion, were presented in Figure 4. Ustyurt remained stable due to geographical constraints, whereas Aralkum displayed significant dynamism, approaching a steady-state size. Meanwhile, Kyzylkum and Karakum continued to expand at an average annual rate of approximately 0.75 m/year, corroborated by satellite imagery.

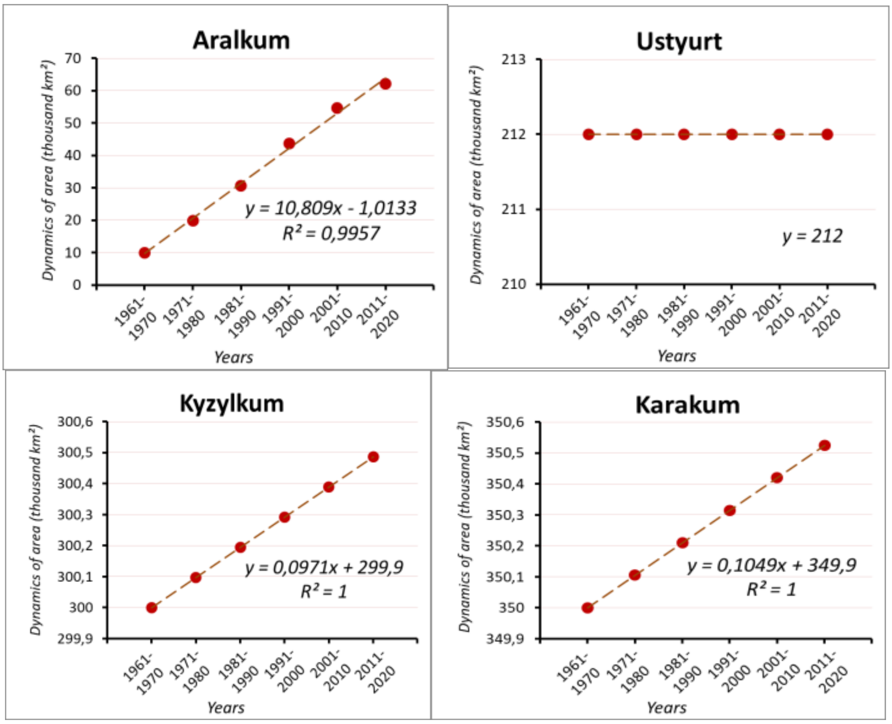

Fig. 4. Long-term dynamics of desert expansion

The long-term dynamics of desert vegetation are the most difficult to assess due to the limited availability of data on OPC. In botanical studies conducted over the past decade, whose routes together cover no more than 20% of the territory of Karakalpakstan, the primary focus has been on species dynamics rather than overall vegetation cover. Furthermore, given that these expeditions were carried out in different years, it can be stated that the data on OPC are not fully representative. Nevertheless, based on the available data and by applying spatial-temporal interpolation, correlation analysis, and factor analysis — and assuming that OPC is directly proportional to plant biodiversity and precipitation levels — we were able to approximately determine the long-term dynamics of vegetation cover in desert areas (Fig. 5).

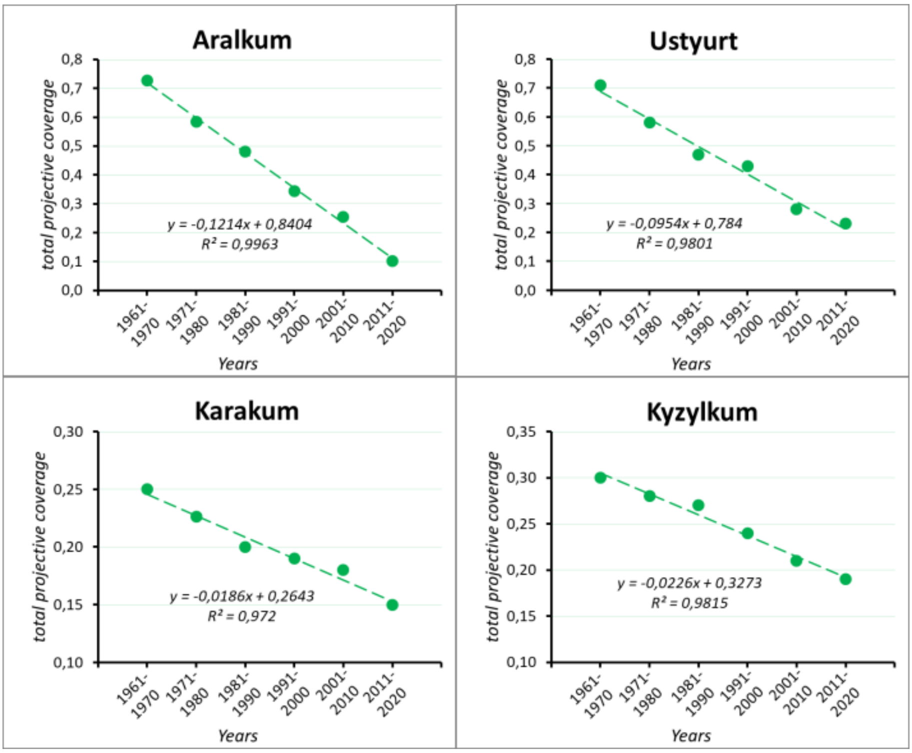

Fig. 5. Dynamics of the average overall projective coverage of deserts

A general decline in OPC was observed across all deserts, mainly driven by climate change, indicating widespread degradation of desert vegetation.

Seasonal OPC dynamics (Fig. 6) demonstrated peak biomass levels in May, followed by decline during the hot season and partial recovery with autumn precipitation. The seasonal pattern was incorporated into the dust migration model due to the vegetation cover's role in suppressing dust emissions.

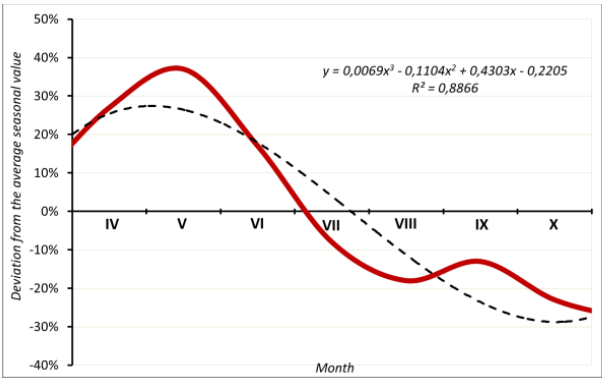

Fig. 6. Seasonal variation of total projective cover (deviation from the seasonal mean)

Biomass reaches its maximum in May, after which vegetation begins to dry out, followed by partial regeneration with the onset of autumn precipitation. Given the critical role of vegetation cover in mitigating dust emissions, the model accounts for the seasonal variation of overall projective cover, which was approximately estimated as illustrated in Fig. 6.

The long-term dynamics of the factors influencing atmospheric dust levels are summarized in Table 1. In this table, the area is reported in thousand square kilometers, OPC is presented as a fraction, the wind regime is expressed by the number of days during the warm season with wind speeds exceeding 4 m/s, and precipitation is measured in mm per year.

Table 1. Long-term dynamics of the factors contributing to atmospheric dustiness.

Desert	Area	TPC	Wind regime	The amount of precipitation
Aralkum	*10.809N–1.0133*	*–0.1214N+0.8404*	*1.0633N+41.468*	*–1.6671N+64.823*
Ustyurt	*212*	*–0.0954N+0.784*	*0.5203N+64.383*	*–2.3264N+71.215*
Kyzylkum	*0.0971N–299.9*	*–0.0226N+0.3273*	*0.3096N+22.209*	*–1.0729N+61.987*
Karakum	*0.1049N+349.9*	*–0.0186N+0.2643*	*1.4438N+47.252*	*–5.5429N+52.417*

Note: *N* refers to the number of the decade.

The trends in meteorological data indicate an increase in the dust migration-enhancing factor — wind regime — and a decrease in the mitigating factor — precipitation, resulting in a nonlinear progression of dust migration from desert areas in the Southern Aral Sea region. Overall, the long-term dynamics of factors influencing atmospheric dustiness are characterized by rising wind activity, desert area expansion, reduced precipitation, and a decline in the overall projective cover of desert vegetation.

Preliminary simulation results from LDAD models are presented below, including calculations of the long-term dynamics of atmospheric dustiness in the Lower Amudarya Oasis (Fig. 7) and the spatial distribution of the average seasonal dust concentration in the Southern Priaralie for 2023 (Fig. 8).

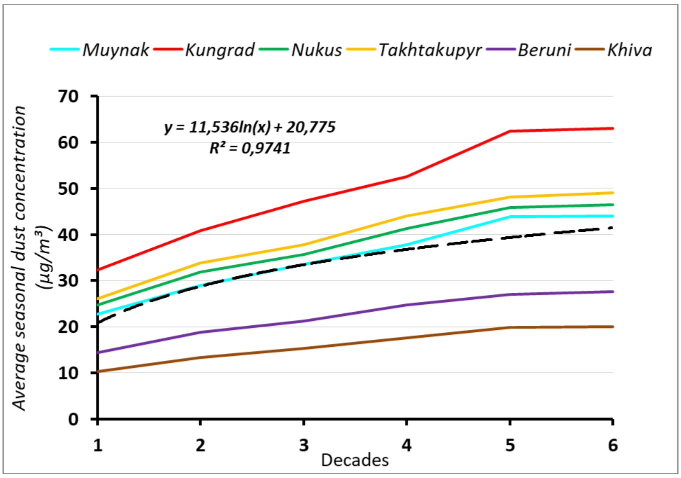

Fig. 7. Dynamics of seasonal mean dust and sand concentrations originating from the desert complex at different sites within the Lower Amudarya Oasis.

The long-term dynamics of dust concentration averaged across the oasis are represented by the following equation (shown as a dashed line):

$$C(x,y,N) = 11{,}536\ln(N) + 20{,}775$$

According to Figure 8, the seasonal mean dust concentration is highest in the Kungrad and Takhtakupyr districts. It is important to emphasize that the proximity of the seasonal mean value to the maximum permissible concentration (MPC) implies a considerable number of days with concentrations exceeding the permissible threshold.

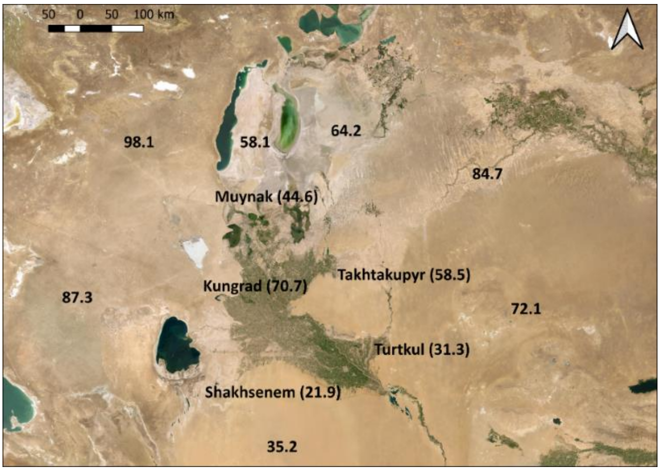

Fig. 8. Dynamics of seasonal mean dust and sand concentrations (μg/m³) originating from the desert complex at different sites within the Lower Amudarya Oasis.

Correlation analysis of atmospheric dustiness dynamics with its contributing factors revealed the following (Table 2):

Table 2. Correlations between atmospheric dustiness (μg/m³) and key factors: wind regime, precipitation, and mean total projective vegetation cover.

Period	**Nukus**	**Muynak**	**Takhtakupyr**	**Khiva**

	Seasonal Mean Dust Concentration (μg/m^3)			
1961-1970	24.7	22.8	26.1	10.2
1971-1980	31.8	29.1	33.8	13.3
1981-1990	35.7	33.5	37.7	15.4
1991-2000	41.4	37.9	44.0	17.5
2001-2010	45.8	43.9	48.2	19.8
2011-2020	46.5	44.0	49.0	20.0
Correlation coefficients				
With wind regime	0.97	0.96	0.97	1
With precipitation	-0.9	-0.61	-0.9	-0.8
With vegetation cover	-0.98	-0.99	-0.98	-0.98

The correlation analysis of atmospheric dustiness and wind activity demonstrated a near-functional relationship (Table 2), indicating that wind regime — particularly the number of days with wind speeds exceeding 4 m/s — is the dominant factor influencing dust levels in the atmosphere. Although the correlation with precipitation showed a strong inverse relationship (average correlation coefficient of -0.8), its overall significance as a determining factor is notably lower compared to wind activity.

4 Conclusion

The following key conclusions were drawn from this study:

1) Atmospheric pollution in Karakalpakstan, excluding salt transport from the dried Aral Sea bed, remains poorly understood. In particular, stationary and long-term dust emissions from desert surfaces have not been adequately studied.

2) Due to the unsatisfactory state of dust monitoring in the region, the application of statistical modeling is essential. The unique geographical and ecological conditions of Karakalpakstan demand the development of models adapted to the specific characteristics of the region.

3) The seasonal and long-term dynamics of desert surface dust emissions, intensified by the Aral Sea crisis, require statistical analysis to assess variability and standardize data series based on meteorological and ecological conditions in the study area.

4) A clear trend has been identified in the increase of days with wind speeds exceeding 4 m/s, indicating the strengthening of this factor. Furthermore, statistical analysis of warm-season precipitation revealed a marked decrease in the number of rainy days in recent decades. Together, these findings suggest a progressive increase in atmospheric dustiness in the Southern Aral Sea region, driven by strengthening dust-mobilizing factors and weakening dust-suppressing conditions.

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