

## ABSTRACT

of the dissertation for the Philosophy Doctor (PhD) degree  
in the educational program 8D05204 – Meteorology

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### **Characteristics of atmospheric droughts and their future projections in Northern Kazakhstan**

**General Description of the Research.** The dissertation is devoted to the study of the formation mechanisms, manifestation patterns, and future variability of atmospheric droughts in Northern Kazakhstan (including Akmola, North Kazakhstan, Kostanay, and Pavlodar regions) under contemporary climate change conditions.

#### **Relevance of the Research.**

Anomalous natural phenomena are recorded annually in various parts of the world. According to reports of the Intergovernmental Panel on Climate Change (IPCC) [1] and numerous other studies [2–4], global warming has a significant impact on increasing the frequency of extreme weather events such as droughts, intense precipitation, floods, and anomalous cold spells. However, up to 80% of economic losses in both developing and developed countries are associated with droughts. Approximately 75% of the territory of Central Asia can be characterized as being exposed to natural disaster risks. A large portion of the Republic of Kazakhstan is located within arid and semi-arid zones, where droughts represent one of the most hazardous natural processes [6]. Agricultural regions, particularly the northern regions of the country, are especially vulnerable to climate risks.

In recent decades, this region has experienced an increase in the frequency and intensity of atmospheric droughts, leading to significant crop losses and posing a threat to food security [7]. According to analyses of adverse agrometeorological phenomena, about 80% of crop losses in Kazakhstan are associated specifically with atmospheric and soil droughts, which underscores the relevance of their detailed study, monitoring, and forecasting.

**The aim of the dissertation** is to identify the patterns of atmospheric drought formation in Northern Kazakhstan based on a comparative analysis of drought indices, to establish their relationships with large-scale circulation processes, and to assess their transformation under future climate conditions. To achieve this aim, the following interrelated objectives were formulated:

- 1) To conduct a comparative evaluation of modern atmospheric drought indices and determine their diagnostic informativeness across different seasons and temporal scales;
- 2) To perform a spatiotemporal analysis of atmospheric droughts in Northern Kazakhstan;
- 3) To determine the influence of teleconnections on atmospheric drought formation in order to identify dominant spatial drought regimes and key climatic predictors;
- 4) To carry out climatic regionalization of Northern Kazakhstan based on drought responses to circulation factors;
- 5) To assess potential changes in atmospheric drought characteristics in the 21st century based on climate projections under SSP2-4.5 and SSP5-8.5 scenarios;
- 6) To develop and test an approach for forecasting atmospheric droughts based on identified climatic predictors using machine-learning methods.

**The object of the research:** atmospheric droughts over the territory of Northern Kazakhstan.

**The subject of the research:** spatiotemporal patterns of atmospheric droughts in Northern Kazakhstan, their relationships with large-scale atmospheric circulation processes, and forecasting potential.

**Data sources:** The primary dataset used in this study consists of monthly and daily air temperature records, precipitation totals, as well as daily maximum and minimum air temperatures obtained from the Republican State Enterprise Kazhydromet of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan for the period 1990–2024 at 11 meteorological stations located in Northern Kazakhstan (<https://www.kazhydromet.kz>).

To assess vegetation conditions and analyze ecosystem responses to drought stress, satellite-based remote sensing products from MODIS and Landsat were employed. MODIS MOD13A2 v6.1 data, including 16-day NDVI composites, were used to calculate the Vegetation Condition Index (VCI) and were obtained from the NASA LP DAAC (Land Processes Distributed Active Archive Center) (<https://lpdaac.usgs.gov/products/mod13a2v061/>). In addition, Landsat 8 imagery (Product: LANDSAT/LC08/C02/T1\_TOA), providing higher spatial resolution for vegetation and land surface thermal parameter extraction, was utilized via the Google Earth Engine platform ([https://developers.google.com/earth-engine/datasets/catalog/LANDSAT\\_LC08\\_C02\\_T1\\_TOA](https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA)).

Future changes in atmospheric droughts were analyzed using outputs from 15 global climate models participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Observational reference data for bias correction of climate model outputs were taken from the global climate archive CHIRTS-daily (Climate Hazards Center, University of California, Santa Barbara) (<https://data.chc.ucsb.edu/products/CHIRTSdaily/>).

Additionally, monthly values of nine large-scale atmospheric circulation indices for the period 1990–2024 were used to characterize dominant atmosphere–ocean circulation regimes, including the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), El Niño Index (ONI), Pacific Decadal Oscillation (PDO), Indian Ocean Dipole (DMI/IOD), Scandinavian Pattern (SCAND), and Southern Oscillation Index (SOI). These data were obtained from the official portal of the U.S. National Oceanic and Atmospheric Administration (NOAA).

**Methodology of the dissertation research:** To identify statistically significant trends in air temperature and precipitation anomaly series, the modified Mann–Kendall test (MMK) was applied, while trend magnitude and direction were assessed using the Theil–Sen slope estimator. Data homogeneity was evaluated using Student’s t-test, Fisher’s F-test, and the Wilcoxon test.

Atmospheric drought assessment was conducted using meteorological indices, including the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Modified China Z-Index (MCZI), and Selyaninov’s Hydrothermal Coefficient (HTC), calculated in RStudio at time scales of 1, 3, 6, 9, and 12 months. Vegetation conditions were analyzed using satellite-based vegetation indices-Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Vegetation Health Index (VHI)-processed within the Google Earth Engine (GEE) cloud-based geospatial platform.

Pearson correlation analysis was used to quantify relationships between meteorological and vegetation indices to identify the most informative drought indicators. Drought episodes were quantitatively characterized using Run Theory, including mean drought duration (MDD), frequency (F), intensity (MDI), and severity (MDS).

To investigate drought formation mechanisms, a set of multivariate statistical methods was applied. Principal Component Analysis (PCA) was used to reduce the dimensionality of SPI1 data and identify dominant spatial drought modes. Maximum Covariance Analysis (MCA) was applied to determine coupled variability between SPI1 and large-scale climate indices (EA, AO, NAO, PDO, etc.), revealing key drought predictors. Time-lagged effects of

teleconnections were assessed using cross-correlation function (CCF) analysis with lags from 0 to 12 months.

Homogeneous subregions with similar drought responses were identified using K-means clustering based on PCA-derived spatial components (PC1–PC3). The optimal number of clusters was determined using the silhouette criterion.

Future projections of atmospheric droughts were assessed using outputs from 15 global climate models of CMIP6 under SSP2-4.5 and SSP5-8.5 scenarios. Bias correction was performed using Quantile Mapping (QM). The performance of bias-corrected data was evaluated using RMSE, RSR, mean bias, and pattern correlation coefficient (PCC).

Drought forecasting was conducted using machine-learning methods, including Gradient Boosting, Random Forest, and XGBoost, based on identified predictors. Model performance was evaluated using Accuracy, confusion matrix, and F1-score metrics.

#### **Scientific Novelty:**

1) For the first time for Northern Kazakhstan, a comprehensive comparative assessment of meteorological and satellite-based atmospheric drought indices (SPI, SPEI, HTC, MCZI, VHI, VCI, and TCI) was conducted, which made it possible to identify their seasonal sensitivity and to substantiate the selection of the most informative drought indicators; the MCZI index was calculated for the first time for the region.

2) For the first time, the dominant large-scale circulation factors governing the formation of atmospheric droughts in Northern Kazakhstan were identified, determining their spatio-temporal heterogeneity. This made it possible to reveal a statistically robust spatial structure of atmospheric droughts and to perform climatic regionalization of Northern Kazakhstan with the identification of homogeneous regions.

3) An assessment of the transformation of atmospheric droughts in Northern Kazakhstan under future climate conditions was carried out based on CMIP6 climate projections.

4) For the first time, an approach to forecasting atmospheric droughts in Northern Kazakhstan based on circulation predictors and machine learning methods was implemented, enabling the early detection of drought conditions.

**Scientific and practical significance of the research:** The scientific and practical significance of the study lies in advancing fundamental understanding of the mechanisms of formation and spatiotemporal variability of atmospheric droughts at the regional level under present-day and future climate conditions. The obtained results form a scientific basis for regional assessment of atmospheric drought severity. The practical significance of the research consists in the potential application of the findings in the development of regional drought monitoring and early warning systems, as well as in substantiating climate adaptation measures in the agricultural sector and in the rational management of land and water resources.

#### **Statements Submitted for Defense**

– It has been established that modern atmospheric drought indices exhibit different seasonal sensitivity and diagnostic informativeness under the conditions of Northern Kazakhstan, and that atmospheric droughts in the region are characterized by stable spatio-temporal patterns manifested through several dominant drought regimes. This substantiates the necessity of their comparative analysis when assessing drought conditions.

– It has been revealed that the formation of atmospheric droughts in Northern Kazakhstan is largely controlled by large-scale atmospheric circulation processes, with the East Atlantic (EA) index playing a leading role and the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) exerting a modifying influence, which determines the spatial heterogeneity of drought conditions across the region.

– It has been shown that under future climate conditions, a transformation of the seasonal structure of atmospheric droughts in Northern Kazakhstan is expected, most

pronounced during the spring–summer period and intensifying under scenarios with higher levels of anthropogenic forcing.

– A scientifically grounded approach to forecasting atmospheric droughts in Northern Kazakhstan has been developed and tested, based on the use of the identified climatic predictors and machine learning methods, providing the capability for early detection of drought conditions.

**The reliability and validity of the results** are ensured by the use of modern research methods. In addition, the credibility of the results is confirmed by publications in high–impact international scientific journals, as well as in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan (CQASHE MSHE RK), and in the proceedings of international scientific conferences.

**The personal contribution of the author.** The main results of the dissertation were obtained by the author. The task statement and discussion of the results were carried out jointly with scientific consultants.

**Approbation of the research.** Based on the materials of the dissertation, a total of seven publications have been produced, including one article in journals indexed in the Scopus and Web of Science databases, one article in journals recommended by the CQASHE MSHE RK, one article in a journal indexed in the Russian Science Citation Index (RSCI / Science Index), and four conference abstracts published in the proceedings of international scientific conferences.

The results obtained in the course of the dissertation research were presented and discussed at the following international scientific conferences:

1. «Статистический анализ засушливости на территории Северного Казахстана» // Материалы международной научной конференции студентов и молодых ученых «Фараби Әлемі». Алматы, Казахстан, 6-8 апреля 2021 года. – Алматы: Қазақ университеті, 2021. – 294 стр.

2. «Статистический анализ засушливости на территории Северного Казахстана» // Современные тенденции и перспективы развития гидрометеорологии: материалы IV Всероссийской научно-практической конференции, приуроченной к Году науки и технологий. Иркутск, 24-26 ноября 2021 г. / ФГБОУ ВО «ИГУ». – Иркутск: Издательство ИГУ, 2021. <https://doi.org/10.26516/978-5-9624-2009-7.2021.1-547>

3. «Анализ метеорологической засухи в регионе Северного Казахстана на основе расчетов стандартизированного индекса осадков SPI» // Материалы международной научной конференции студентов и молодых ученых «Фараби әлемі». Алматы, Казахстан, 6-8 апреля 2023 года. – Алматы: Қазақ университеті, 2023. – 446 стр.

4. «Оценка пространственно-временного распределения SPI на территории северного Казахстана» // Современные тенденции и перспективы развития гидрометеорологии в России : материалы V Всероссийской научно-практической конференции. Иркутск, 23–25 ноября 2022 г. / ФГБОУ ВО «ИГУ» ; отв. ред. Е. Н. Сутырина. – Иркутск : Издательство ИГУ, 2023. <https://doi.org/10.26516/978-5-9624-2119-3.2023.1-455>

**Publications.** The main results and conclusions of the dissertation have been published in three articles in national and international scientific journals, including:

5. One article in a journal indexed in the Scopus and Web of Science databases: Seasonal Sensitivity of Drought Indices in Northern Kazakhstan: A Comparative Evaluation and Selection of Optimal Indicators. Sustainability, 2025, 17, 9413. <https://doi.org/10.3390/su17219413>;

6. One article in a journal included in the List 1 recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan: Solar magnetic activity and its terrestrial impact through correlations with drought indices. *Physical Sciences and Technology*, 12(1–2), 38–44. <https://doi.org/10.26577/phst20251214>;

7. One article in a journal indexed in the Russian Science Citation Index (Science Index): Study of Atmospheric Drought in Central Asia. *Geographical Bulletin*, 2021, No. 2(57), pp. 110–120. <https://doi.org/10.17072/2079-7877-2021-2-110-120>

**Relation of the dissertation topic to research plans.** The dissertation research was carried out in accordance with the research plan of the scientific project No. AP25796409 “Assessment of Atmospheric Drought Risk and Development of an Early Warning System for Northern Kazakhstan Based on Machine Learning” (2025–2027).

**Structure of the dissertation.** The dissertation consists of an introduction, five chapters, a conclusion, a list of references, and appendices. The total length of the dissertation is 118 pages and includes 17 tables, 53 figures, 163 references, and 13 appendices.