

Editorial

Comprehensive Analysis Based on Observation, Remote Sensing, and Numerical Models to Understand the Meteorological Environment in Arid Areas and Their Surrounding Areas

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1. Introduction

Global arid and semi-arid regions cover approximately 40% of the land surface, and they play a decisive role in global carbon cycle variability (contributing, for example, 60% of interannual variability) and climate regulation through high carbon turnover rates and unique energy–water coupling mechanisms [1,2]. The socio-economic systems of these regions (e.g., areas with high population growth) face the risk of land degradation caused by climate change (e.g., 88% regional vulnerability), while their vegetation dynamics (e.g., extended growing seasons) and surface processes (e.g., changes in sensible heat flux) further influence regional precipitation and energy balance through boundary layer feedback [3–5]. However, under the combined effects of climate warming and intensified human activities, these regions are facing unprecedented environmental challenges, including an increased variability in precipitation, frequent extreme heat events, intensified surface evapotranspiration, desertification expansion, and heightened sandstorm activities, all of which continuously threaten regional ecological security and sustainable development [6]. These changes not only exacerbate water scarcity and land degradation in arid areas but also impact the stability of the global climate system through atmospheric circulation and cross-regional material transport [7]. For example, the long-range transport of dust aerosols from arid regions can alter cloud microphysical processes and radiative forcing, further influencing regional precipitation patterns [8]. Meanwhile, heat-driven local circulation anomalies may trigger cascading adjustments in weather systems, leading to extreme drought–flood events in surrounding, more humid regions [9]. Currently, research on the meteorological environment of arid regions faces several key bottlenecks: First, the complex topography (such as the interlacing of basins and mountains) and the strong heterogeneity of underlying surfaces (such as the coexistence of bare gravel plains, oases, and deserts) result in highly nonlinear local energy exchanges and boundary layer processes. Traditional observational networks are inadequate for capturing these multi-scale interactions [10]. Second, existing numerical models lack sufficient sensitivity to the specific surface parameterization schemes in arid regions (such as albedo, soil moisture, and aerosol–cloud feedback), which limits the ability to predict extreme weather and climate events [11]. Third, the water vapor transport mechanisms, land–atmosphere coupling effects, and climate impacts of human interventions (such as urbanization and irrigation expansion) between arid regions



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and their surrounding humid/semi-humid areas have not been systematically quantified, restricting the formulation of regional climate adaptation strategies [12].

In this context, integrating multi-source observational data (from ground stations, satellite remote sensing, and drones), developing high-resolution numerical models, and deepening the research on physical process mechanisms are key pathways to addressing the complexity of the meteorological environment in arid regions. Remote sensing technology can compensate for the sparse observational networks in arid areas by providing continuous spatial water and thermal parameters. Numerical models, through data assimilation and parameter optimization, can reveal the collaborative evolution of topographic forcing, surface radiative budgets, and large-scale circulation [13]. Moreover, interdisciplinary analysis can help to clarify the relative contributions of natural variability and human impact, providing scientific evidence for ecological restoration, disaster early warning, and climate resilience building in arid regions. Therefore, the launch of this Special Issue aims to drive paradigm innovation in the field; build a bridge between observation, modeling, and mechanism research; and promote the systematic and refined study of meteorological environments in global arid regions to address the increasingly severe challenges of regional sustainable development in the context of climate change. The 11 research papers collected in this issue cover various aspects, including observation and application, numerical simulation, and weather and climate change. They aim to reveal the complexity and diversity of meteorological environments in arid regions and their surrounding areas by conducting comprehensive studies from multiple perspectives and using various methods.

The evolution of meteorological environments in global arid and semi-arid regions has significant impacts on regional ecological security and global climate regulation. In recent years, research has shifted from single observation methods to multi-source data fusion, developing high-resolution numerical models and multi-scale physical mechanism analysis methods to achieve a detailed characterization of complex land-atmosphere coupling processes. This study integrates ground observations, satellite remote sensing, and numerical simulations, proposing a classification framework for meteorological environment research in arid regions, covering observation technology applications, model optimization, and climate change mechanism analysis. This study reveals the regulatory effects of plateau terrain on dust distribution, the multi-scale characteristics of desert surface heat sources, and the feedback mechanisms of dust radiation effects and emission processes, comparing the applicability of different methods in extreme weather forecasting. Future research should focus on multi-source data assimilation, AI-driven climate prediction models, and quantitative analyses of plateau–desert climate feedback mechanisms to address the urgent needs of ecological restoration and sustainable development in the context of climate change. This review provides theoretical support for the formulation of regional climate adaptation strategies and global climate system research.

2. Interplay of Topography, Surface Heating, and Dust Effects in Arid Climate Systems

- Observation and Application

In the field of observation and application, the studies in this issue explore the meteorological characteristics of arid regions and their change mechanisms using a variety of observational tools and remote sensing technologies. For example, Wang et al. (2024) used temperature profile products from the Fengyun-4B satellite (FY-4B), combined with radiosonde observations and ERA5 reanalysis data, to assess the representativeness of temperature profiles in the eastern Tibetan Plateau, providing new data support for meteorological observations in plateau regions [14]. Zeng et al. (2024) studied the kinetic energy of rainfall and quantitative precipitation estimates under different rainfall types in

the Tianshan region using dual-polarization radar and raindrop spectrum distribution data, offering a new approach to precipitation research in mountainous areas [15]. Additionally, Cheng et al. (2024) proposed an improved remote sensing retrieval method for studying waveguide phenomena in the South China Sea, further expanding the application of remote sensing technology in marine meteorology [16]. Yang et al. (2024) analyzed the height of the stable boundary layer in the summer and its influencing factors using observational data from the central Taklamakan Desert, providing new insights into the boundary layer characteristics of desert regions [17]. These studies not only enrich the data foundation for meteorological observation in arid regions but also offer new ideas for integrating remote sensing technology and ground-based observations, further advancing the research on meteorological environments in arid areas.

- Numerical Simulation

Numerical simulation, as an important tool in meteorological research, is also widely applied in this Special Issue. Abulimiti et al. (2024, 2025), through over a decade of WRF-UCM simulations, revealed how rapid urbanization has reshaped the summer climate in Urumqi. Their analysis indicates that nighttime warming is the primary driver of the reduced diurnal temperature range. Meanwhile, near-surface humidity has decreased, and precipitation patterns show spatial differences—precipitation has increased in the northern region, while it has decreased in the southern region. The team's follow-up research analyzed the changes in the thermal environment, revealing the connection between urban heat anomalies and changes in surface energy distribution, which are primarily dominated by shortwave radiation absorption and the dynamics of sensible heat flux during the day [18,19]. Wulayin et al. (2024) assessed the forecasting performance of the WRF-CUACE model in the Xinjiang region, providing important references for improving regional climate models [20]. These studies not only demonstrate the potential of numerical simulations in climate research in arid regions but also provide scientific foundations for developing climate adaptation strategies in the process of urbanization. The results of numerical simulation studies contribute to improving the accuracy of regional climate predictions and offer technical support for the early warning and response to extreme weather events, which is of significant practical importance.

- Weather and Climate Change

In the field of weather and climate change, scholars have revealed the complex interaction mechanisms of the climate system in arid regions through multi-scale analysis. Abulikemu et al. (2024) conducted a classification study of six types of atmospheric circulation patterns in northern Xinjiang, showing that the moisture transport driven by the westerlies and subtropical high, as well as the radiative effects in mountain-basin systems, is key to the formation of diurnal variations in precipitation and extreme events under specific circulation conditions [21]. This provides a new circulation-type diagnostic approach for precipitation forecasting in arid regions. Zeng et al. (2024) further contributed to the understanding of the water cycle in arid regions through cloud physics studies. Their multi-source validated cloud-phase seasonal transition characteristics provide a microphysical basis for understanding regional radiation balance changes [22]. Xu et al. (2024) fused significant wave height data from multiple satellites constrained by buoys to construct a new benchmark for the wave climate along the Chinese coast with minimized bias. The enhanced time consistency significantly improved the reliability of wave climate analysis in typhoon-prone areas [23]. In the field of extreme weather prediction, Zhang and Li (2024) developed a feature-aligned ensemble technique that effectively alleviated spatial displacement errors in tropical cyclone precipitation forecasts by enhancing the consistency of precipitation field structures [24]. This has opened new avenues for post-processing

techniques in ensemble forecasting. These systematic research findings not only deepen the understanding of climate evolution mechanisms in arid regions but also provide scientific support for regional ecological security in the context of global climate change.

In addition to the three main research categories covered in this issue (observation and application, numerical simulation, and weather and climate change), significant progress has also been made in recent years regarding the climate interactions between the Tibetan Plateau and desert regions. Not only have these studies deepened the understanding of the climate system in arid regions, but they have also provided new perspectives on regional climate response mechanisms in the context of global climate change.

- Impact of Vertical Distribution of Dust Aerosols

Zhou et al. (2024) revealed the significant impact of the Tibetan Plateau's topography on the vertical distribution of dust aerosols in the Tarim Basin (Figure 1). Their study found that, as the elevation of the Tibetan Plateau decreases, the vertical distribution of dust aerosols in the Tarim Basin exhibits a pattern of reduced concentrations at higher altitudes and increased concentrations at lower altitudes [25]. Specifically, when the surface elevation of the Tibetan Plateau drops to 3000 m, 2000 m, and 1000 m, the dust aerosol concentration increases by an average of 8.52%, 24.03%, and 43.05%, respectively, compared to the original topography. This change is primarily influenced by the increased concentration of dust aerosols in the lower layers of the Tarim Basin, with the variation in lower-layer concentrations dominating the overall vertical distribution of dust aerosols. Furthermore, the study pointed out that changes in the Tibetan Plateau's topography modulate the vertical distribution of dust aerosols by influencing meteorological conditions such as the convective boundary layer height, 10 m wind speed, near-surface temperature, atmospheric stability, and vertical circulation in the Tarim Basin. This finding not only provides new scientific evidence for understanding the impact of topography on dust transport but also offers important references for research on the climate effects of dust aerosols.

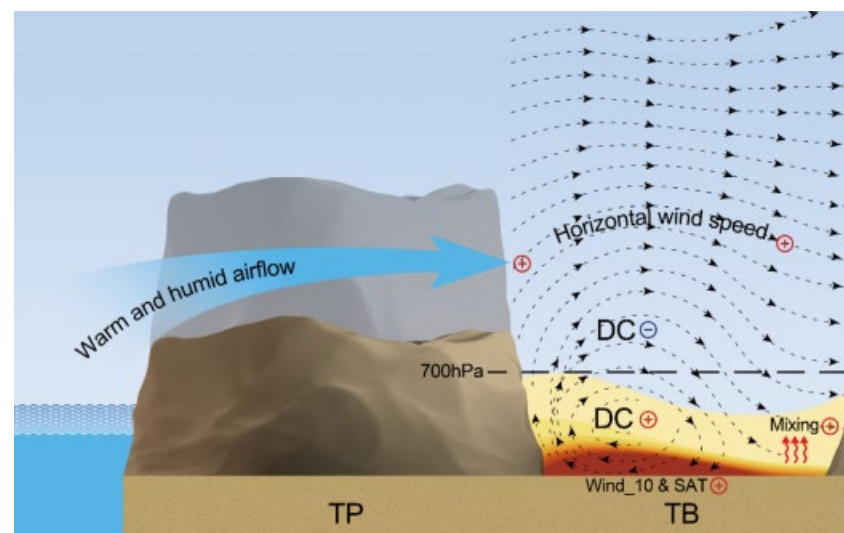


Figure 1. Schematic diagram illustrating the mechanism of the Tibetan Plateau's topography on the vertical distribution of dust aerosols in the Tarim Basin (source: Zhou et al., 2024 [25]).

- Surface Heating Anomalies and Climate Change in Desert Regions

Desert regions, as an important component of extreme environments, have significant impacts on regional climate change due to their unique surface conditions. Studies by Yang et al. (2011), Xie et al. (2021), and Yao et al. (2022) showed that, under the background of global warming, the thermal forcing and occurrence of climate events in desert regions

have undergone significant changes [26–28]. The high albedo and low thermal capacity of desert regions create distinct energy balance characteristics, making their response to climate change differ significantly from that of other types of surface environments. As the second-largest desert in China and the largest fixed/semi-fixed desert, the Gurbantunggut Desert plays a particularly important role in the study of surface heating anomalies.

Aihaiti et al. (2023) used observational data from the Gurbantunggut Desert land–atmosphere interaction station and ERA5-land reanalysis data to assess the applicability of ERA5 data in fixed/semi-fixed desert regions and investigate the long-term changes and spatial variations in desert surface heat sources [29]. The study found that, from 2013 to 2021, the hourly surface heat source in the northern Xinjiang desert region was weak or a cold source at night and a strong heat source during the day. The daily surface heat source showed significant seasonal variation, reaching its maximum in the summer and its minimum in the winter. Additionally, the trends in ERA5 data were found to be significantly consistent with the observational data, explaining 90% of the variability in the observations.

It was also discovered that the long-term average surface heat source of the Gurbantunggut Desert was less than 50 W/m^2 from January to March and from September to December, indicating a weak heat source, while it exceeded 50 W/m^2 between April and August, indicating a strong heat source. Geographically, the eastern and western regions of the desert exhibited strong heat sources, while the central region displayed weaker heat sources. These findings not only reveal the temporal and spatial distribution characteristics of surface heating anomalies in desert regions but also provide crucial data support for regional climate modeling and prediction.

- Impact of Dust Radiative Effect on Dust Emissions

Zhou et al. (2023) conducted a study that integrated ground observational data, such as air quality, temperature profiles, and meteorological factors, with reanalysis data to explore the impact of the dust radiation effect (DRE) on dust emissions from the Taklamakan Desert (TD) [30]. The study proposed a new method for calculating the DRE based on field observations and quantitatively estimated the contribution of the DRE to TD dust emissions. The results indicated that the dust radiation effect on dust lifting is significant, with a positive feedback mechanism between the DRE and TD dust emissions. The dust radiation effect influences dust emissions and transport by altering the surface energy balance and atmospheric stability. This finding not only provides a new perspective for understanding the climate effects of dust aerosols but also offers scientific support for improving dust lifting parameterization schemes. The results are of great practical significance for improving the accuracy of dust weather predictions and reducing the impact of dust disasters.

The study of climate interactions between the Tibetan Plateau and desert regions has expanded the depth and breadth of meteorological and environmental research in arid regions, providing new scientific evidence for regional climate response mechanisms under global climate change. These studies reveal the critical role of topography, surface heating anomalies, and dust radiation effects in regional climate systems, offering important theoretical support and practical guidance for addressing climate change and improving regional ecological environments.

3. Conclusions

This Special Issue delves into the meteorological environment characteristics and their changing mechanisms in arid regions through a combination of observation and application, numerical simulation, and studies on weather and climate change, achieving significant results. In terms of observation and application, it enriches the data foundation

for meteorological observation in arid regions by utilizing various observation methods and remote sensing technologies, providing new ideas for the integration of remote sensing technology and ground-based observations, and promoting the in-depth development of meteorological environment research in arid regions. In terms of numerical simulation, it demonstrates the potential of numerical simulation in climate research in arid regions, providing a scientific basis for formulating climate adaptation strategies in the process of urbanization, helping to improve the accuracy of regional climate prediction, and providing technical support for early warning and response to extreme weather events. In terms of weather and climate change, through multi-scale analysis, it reveals the complex interaction mechanisms of the climate system in arid regions, provides new ideas for circulation pattern diagnosis for precipitation prediction in arid regions, supplements the understanding of the water cycle in arid regions, and opens up new paths for technological innovation in the post-processing of ensemble forecasts. These research results not only deepen the understanding of the climate evolution mechanism in arid regions but also provide scientific support for regional ecological security in the context of global climate change.

4. Outlook

As global climate change intensifies, meteorological research in arid regions and their surrounding areas faces new challenges and opportunities. Future research should build on existing knowledge to deepen the understanding of climate systems in arid regions and explore more efficient research methods and technological approaches to address complex climate change issues. Emphasis should be placed on multi-source data integration and high-resolution observations. By combining ground-based observations, satellite remote sensing, and numerical simulation data, a more precise meteorological environment database can be constructed [31]. For example, the joint application of Fengyun satellites, ERA5 reanalysis data, and ground station data can provide comprehensive support for meteorological research in arid regions [32]. With the development of artificial intelligence and machine learning technologies, future research can utilize intelligent algorithms to efficiently process massive amounts of meteorological data, improving the accuracy and timeliness of climate predictions [33]. Additionally, the impact of urbanization on local climates, particularly the urban heat island effect, changes in precipitation patterns, and variations in the frequency and intensity of extreme weather events, has become a research hotspot [34]. High-resolution numerical simulations and long-term observational data can aid in understanding the interactions between urbanization and climate change, providing scientific evidence for urban planning and climate adaptation strategies.

5. Discussion

This Special Issue systematically reviews research on ground-based observations, satellite remote sensing, and numerical simulations in global arid and semi-arid regions. It highlights key topics, including the impact of aerosol vertical distribution, the relationship between surface heating anomalies in desert areas and climate change, and the feedback mechanisms of dust radiative effects and emission processes. Additionally, it evaluates the applicability of various approaches in extreme weather forecasting.

Ground-based observations, with their high-resolution time series data, provide a critical foundation for studying the meteorological characteristics of arid regions. For instance, observations in the Taklamakan Desert have revealed variations in the height of the stable boundary layer and its primary influencing factors during summer. These findings not only deepen the understanding of land–atmosphere interactions but also offer valuable references for calibrating numerical models [17,35]. However, the scarcity and

uneven spatial distribution of ground-based stations in arid regions result in a limited representativeness of observational data for certain areas.

Remote sensing technology compensates for the limitations of ground-based observations in spatial coverage, providing comprehensive data for arid regions and their surroundings. For example, the temperature profile products from the FY-4B satellite and dual-polarization radar have significantly enhanced research capabilities in regional water cycles and precipitation kinetic energy [36]. However, remote sensing observations are susceptible to interference from cloud cover and dust weather, and the accuracy of certain critical variables, such as boundary layer height, still requires validation using ground-based observational data.

Numerical simulations, such as the WRF and CUACE models, utilize high-resolution simulations to uncover the driving mechanisms of meteorological environments in arid regions. For instance, long-term studies using the WRF-UCM model have demonstrated how rapid urbanization profoundly influences regional climate patterns by altering diurnal temperature ranges and surface energy distribution [37,38]. However, these models are highly sensitive to the quality of input data, and optimizing parameterization schemes remains a significant challenge in the complex terrains of arid regions. Integrating the strengths of ground-based observations, remote sensing, and numerical simulations provides a robust data foundation for uncovering key mechanisms in arid region climate systems, such as boundary layer height and radiative effects. This integration also facilitates improvements in simulation schemes, enhancing predictive capabilities.

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