Wind, Temperature, and Humidity Profiles and Energy Exchange Characteristics in the Near-Surface Layer at the Southern Edge of the Taklamakan Desert (Postprint)

Authors: Fu Guangxiang

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Abstract

The southern margin of the Taklamakan Desert belongs to a desert-oasis ecological transition zone, with significant spatiotemporal variations in surface properties and particularly unique underlying surface characteristics and hydrothermal features. Therefore, conducting research on the characteristics of micro-meteorological elements in this region is of great significance for understanding future regional climate change. Using measured meteorological element data from 2022 at the Land-Atmosphere Interaction Observation Station on the northern side of the Tibetan Plateau, we analyzed the wind, temperature, and humidity profile structures, radiation fluxes, and energy exchange characteristics in the ecological transition zone at the southern margin of the Taklamakan Desert. The results show that: (1) Wind speed, temperature, and specific humidity at the southern margin of the Taklamakan Desert all exhibited significant variations with height across seasons, with temperature and specific humidity inversions occurring in the profiles. The heights of both the temperature inversion layer and humidity inversion layer reached 30 m. The maximum average wind speed occurred in spring at 6.23 m·s-1, while the maximum average temperature and specific humidity both occurred in summer at 28.93 ℃ and 6.36 g·kg-1, respectively. (2) The surface radiation balance was primarily positive across the four seasons, with differences in the peak magnitudes and occurrence times of each radiation component. Downward shortwave radiation was affected by dust weather, exhibiting a pattern of spring > autumn > summer > winter. Surface albedo was negatively correlated with solar elevation angle and soil moisture, with an annual mean value of 0.326. The maximum value occurred in December and the minimum in August, at 0.366 and 0.297, respectively. (3) Sensible heat, soil heat flux, and net radiation showed obvious seasonal variations, while latent heat varied smoothly, fluctuating around 0 W·m-2. Energy consumption was dominated by sensible heat. The seasonal energy closure rates were 76%, 82%, 53%, and 48%, respectively, showing a pattern of summer > spring > autumn > winter. (4) Effective energy showed clear seasonal variations, being positive during daytime when the surface acted as a heat source, indicating heat transfer from the surface to the atmosphere, and the opposite at night, following the pattern spring > summer > autumn > winter. The research results can provide a scientific basis for future land surface process parameterization at the southern margin of the Taklamakan Desert, thereby enhancing understanding of land surface processes in this region.

Full Text

Characteristics of Wind, Temperature, and Humidity Profiles and Energy Exchange in the Surface Layer at the Southern Edge of the Taklamakan Desert

FU Guangxiang[1,2], HE Qing[2], WANG Yonghui[1], MA Mingjie[1,2], YIN Lulu[1,2], ZHANG Qian[3]

[1]College of Geography and Tourism, Xinjiang Normal University / Xinjiang Key Laboratory of Lake Environment and Resources in Arid Region, Urumqi 830054, China

[2]Institute of Desert Meteorology, China Meteorological Administration / National Observation and Research Station of Desert Meteorology, Taklamakan Desert of Xinjiang / Taklamakan Desert Meteorology Field Experiment Station of China Meteorological Administration / Xinjiang Key Laboratory of Desert Meteorology and Sandstorm, Urumqi 830002, China

[3]Minfeng County Meteorological Bureau, Minfeng 848599, China

Abstract: The southern edge of the Taklamakan Desert constitutes a desert–oasis ecological transition zone characterized by significant spatiotemporal variations in land surface properties and distinctive underlying surface characteristics and hydrothermal features. Investigating the micrometeorological elements in this region is therefore crucial for understanding future climate change. Based on meteorological data measured in 2022 at the Land–Atmosphere Interaction Observatory on the northern side of the Tibetan Plateau, this study analyzes the wind, temperature, and humidity profile structures, radiation fluxes, and energy exchange characteristics of this ecological transition zone. The results show that: (1) Seasonal wind speed, temperature, and specific humidity at the southern edge of the Taklamakan Desert all vary significantly with height, with temperature and specific humidity profiles exhibiting inversion phenomena. Both the inversion layer and humidity inversion layer reach heights of 30 m. The maximum average wind speed occurs in spring ($6.23\ \mathrm{m \cdot s^{-1}}$), while the maximum average temperature ($28.93\,^{\circ}\mathrm{C}$) and specific humidity ($6.36\,\mathrm{g \cdot kg^{-1}}$) occur in summer. (2) The surface radiation balance remains positive across all seasons, with differences in peak magnitudes and timing among radiation components. Downward shortwave radiation is notably affected by dust weather, showing seasonal variation patterns of spring > autumn > summer > winter. Surface albedo is negatively correlated with solar elevation angle and soil moisture, with an annual mean of 0.326. (3) Energy consumption is dominated by sensible heat, with sensible heat flux, soil heat flux, and net radiation showing clear seasonal variations (spring > summer > winter), while latent heat flux remains stable, fluctuating around $0\,\mathrm{W\cdot m^{-2}}$. The energy closure rates for the four seasons are 76%, 82%, 53%, and 48%, respectively, showing a pattern of summer > spring > autumn > winter. (4) Effective energy varies significantly across seasons, being positive during daytime when the surface acts as a heat source, and negative at night. Seasonal patterns follow spring > summer > autumn > winter. These findings provide a scientific basis for parameterizing land surface processes at the southern edge of the Taklamakan Desert and enhance understanding of regional land–atmosphere interactions.

Keywords: ecological transition zone; wind–temperature–humidity profile; radiation balance; energy exchange

Introduction

As global warming intensifies and living environments deteriorate, Earth system science has gained widespread attention. Land surface processes, as a critical component of Earth system science, have become a key research focus. Since the 1990s, international organizations led by the World Climate Research Programme and the International Geosphere-Biosphere Programme have conducted numerous land surface process experiments focusing on climate and ecology, including the Heihe River Basin Field Experiment (HEIFE), the Inner Mongolia semi-arid grassland soil–vegetation–atmosphere interaction study (IMGRASS), and the Tibetan Plateau experiment (GAME/Tibet). China has also launched a series of scientific projects on land surface processes across different regions and underlying surfaces since the late 1980s, with the most representative being HEIFE, the Second Tibetan Plateau Atmospheric Scientific Experiment, the Northwest China Arid Region Land–Atmosphere Interaction Experiment (NWC_{ALIEX}), the Huai River Basin Energy and Water Cycle Experiment (HUBEX), and the Inner Mongolia semi-arid grassland study.

Deserts, as a typical underlying surface type, cover approximately one-third of the Earth's land area. Their unique environment and surface energy exchange play important roles in global climate change and respond sensitively to climatic variations. Therefore, studying land surface processes in desert regions is crucial for understanding climate change and formation mechanisms in arid zones. Research on land surface processes in Chinese deserts began in 1995 when the Institute of Desert Meteorology of the Xinjiang Meteorological Bureau established a series of gradient flux observation systems in the central Taklamakan Desert. Based on these observations, many scholars have analyzed radiation balance, energy balance, and wind–temperature–humidity profile structures in the desert interior, concluding that "energy consumption in the desert hinterland is dominated by sensible heat" and that "inversion phenomena are common in desert regions." Subsequent studies have examined land surface processes in the northern edge of the Taklamakan Desert, the Gurbantunggut Desert, the Badain Jaran Desert, and other areas. With increasingly mature theoretical frameworks, current desert land surface process research focuses on numerical simulation and satellite remote sensing inversion, providing important scientific foundations for understanding land–atmosphere interactions in arid regions.

However, few studies have investigated wind–temperature–humidity profiles and energy exchange at the southern edge of the Taklamakan Desert. This region represents a core area where the desert meets the Kunlun Mountains and serves as a typical zone of ecological degradation and deterioration. Characterized by low precipitation, high evaporation, and frequent wind–sand events, it belongs to a desert–oasis ecological transition zone with unique underlying surface properties and natural hydrothermal characteristics. Studying the near-surface land surface processes in this region can not only help predict extreme weather events such as strong winds, droughts, and sandstorms but also reveal special characteristics in land–atmosphere material and energy exchange. Therefore, this study utilizes gradient wind–temperature–humidity, radiation, and eddy covariance data from the Land–Atmosphere Interaction Observatory on the northern side of the Tibetan Plateau to analyze profile structures and energy exchange characteristics, thereby improving understanding of regional land surface processes.

1. Data and Methods

1.1 Study Area and Instrumentation

The Land–Atmosphere Interaction Observatory on the northern side of the Tibetan Plateau (36°44 21 N, 83°11 17 E, 2275 m above sea level) is located in Yeyike Township, Minfeng County, on the southern edge of the Taklamakan Desert, approximately 200 km south of the desert hinterland. The site experiences a temperate desert climate with extreme aridity, frequent dust events (approximately 280 days annually), long sunshine hours, large diurnal temperature ranges, scarce precipitation, high temperatures, and high potential evaporation. The annual mean temperature is 12.3 °C, annual precipitation is less than 40 mm, and evaporation reaches 3104.3 mm. The observation environment features sparse vegetation dominated by *Ceratoides latens* and *Gymnocarpos przewalskii*.

To enhance understanding of land surface processes at the southern edge of the Taklamakan Desert, the Institute of Desert Meteorology and Minfeng County Meteorological Bureau established a comprehensive observation system at Yeyike Station in March 2022, including gradient observations, soil temperature and moisture sensors, soil heat flux plates, eddy covariance systems, and radiation components. The observation instruments and models are listed in . Local time (UTC+6:32) is used in this study, which is 2 h 28 min behind Beijing time. Seasons are defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

1.2 Data Processing Methods

Raw data from wind speed, temperature, relative humidity, and radiation sensors were first converted using Loggernet software. Sensible and latent heat flux data were processed using EddyPro software, including quality control procedures such as validity testing, outlier removal, and time lag correction, ultimately producing 30-minute averaged sensible and latent heat fluxes.

Specific humidity (q, in $\mathrm{g \cdot kg^{-1}}$) was calculated as follows:

$$q = 622 \times \frac{e}{p - 0.378e}$$

where e is water vapor pressure (hPa), p is atmospheric pressure (hPa), and e is calculated using the saturation vapor pressure formula:

$$e = \frac{RH}{100} \times 6.122 \times \exp\left(\frac{17.62T}{243.12 + T}\right)$$

where RH is relative humidity (%) and T is temperature (°C).

Net radiation (R_n, $\mathrm{W \cdot m^{-2}}$) and surface albedo (α) were calculated as:

$$R_n = SW_{\downarrow} - SW_{\uparrow} + LW_{\downarrow} - LW_{\uparrow}$$

$$\alpha = \frac{SW_{\uparrow}}{SW_{\downarrow}}$$

where $SW_{\downarrow}$, $SW_{\uparrow}$, $LW_{\downarrow}$, and $LW_{\uparrow}$ represent downward shortwave, upward shortwave, downward longwave, and upward longwave radiation, respectively.

The surface energy balance equation is:

$$R_n = H + LE + G_0$$

where H is sensible heat flux, LE is latent heat flux, and G_0 is soil heat flux at the surface.

Soil heat flux was corrected to the surface using a one-dimensional heat conduction equation:

$$G_0 = G_z + \int_0^z \rho_s c_s \frac{\partial T_s}{\partial t} dz$$

where G_0 is the corrected surface soil heat flux ($\mathrm{W \cdot m^{-2}}$), G_z is soil heat flux at depth z ($\mathrm{W \cdot m^{-2}}$), ρ_s is soil bulk density ($1.08 \times 10^3\,\mathrm{kg \cdot m^{-3}}$), c_s is soil specific heat capacity ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), T_s is soil temperature (K), z is soil depth (10 cm and 20 cm), and t is time (s). The time interval Δt was set to 3600 s.

Surface temperature (T_0) was calculated from upward longwave radiation:

$$T_0 = \sqrt[4]{\frac{LW_{\uparrow} - (1-\varepsilon_g)LW_{\downarrow}}{\varepsilon_g \sigma}}$$

where ε_g is emissivity (0.95) and σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{W \cdot m^{-2} \cdot K^{-4}}$).

Sensible heat flux (H) and latent heat flux (LE) were obtained directly from the eddy covariance system:

$$H = \rho c_p \overline{\omega' \theta'}$$

$$LE = \lambda \rho \overline{\omega' q'}$$

where ρ is air density ($\mathrm{kg \cdot m^{-3}}$), c_p is specific heat at constant pressure ($1004.67\,\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), λ is latent heat of vaporization ($2.5 \times 10^6\,\mathrm{J \cdot kg^{-1}}$), ω' is vertical wind speed fluctuation, θ' is potential temperature fluctuation, and q' is specific humidity fluctuation.

2. Results and Analysis

2.1 Wind, Temperature, and Humidity Profiles from the 32 m Tower

2.1.1 Wind Speed Profile Characteristics Wind speed profiles across the four seasons [Figure 1: see original paper] show that wind speed generally increases with height, though from night to morning, wind speed may decrease with height due to nighttime cooling creating a temperature inversion (higher temperatures aloft, lower temperatures near the surface), causing winds to flow from high to low pressure and resulting in weakened wind speeds.

The annual average wind speed across all levels is $3.59\,\mathrm{m \cdot s^{-1}}$, with seasonal averages of $3.20\,\mathrm{m \cdot s^{-1}}$ (spring), $3.24\,\mathrm{m \cdot s^{-1}}$ (summer), $2.54\,\mathrm{m \cdot s^{-1}}$ (autumn), and $3.05\,\mathrm{m \cdot s^{-1}}$ (winter). The highest seasonal average occurs in spring, likely due to rapid temperature recovery creating large diurnal temperature and pressure differences and strong winds. Maximum wind speed gradients are $5.69\,\mathrm{m \cdot s^{-1}}$ (spring), $3.83\,\mathrm{m \cdot s^{-1}}$ (summer), $6.23\,\mathrm{m \cdot s^{-1}}$ (autumn), and $5.88\,\mathrm{m \cdot s^{-1}}$ (winter), while minimum gradients are $1.37\,\mathrm{m \cdot s^{-1}}$, $1.40\,\mathrm{m \cdot s^{-1}}$, $0.74\,\mathrm{m \cdot s^{-1}}$, and $1.44\,\mathrm{m \cdot s^{-1}}$, respectively.

2.1.2 Temperature Profile Characteristics Temperature profiles [Figure 2: see original paper] exhibit clear diurnal and seasonal patterns. During daytime, temperature decreases with height, while nighttime temperature inversions occur, reaching thicknesses of 30 m. Seasonal mean temperatures are 13.69 °C (spring), 23.64 °C (summer), 9.16 °C (autumn), and -5.44 °C (winter), primarily controlled by solar elevation angle. Maximum temperature gradients are 28.93 °C (spring), 15.06 °C (summer), 0.48 °C (autumn), and 7.91 °C (winter), while minimum gradients are 19.11 °C, -10.35 °C, 3.59 °C, and 19.9 °C, respectively.

The temperature profiles can be classified into four types, similar to other arid regions: morning transition, daytime radiation, evening transition, and nighttime radiation. Spring and summer morning transitions occur earlier (06:00–08:00) than in autumn and winter (08:00–10:00). Daytime radiation types appear at 08:00–18:00, evening transitions at 18:00–20:00, and nighttime radiation types at 20:00–06:00.

2.1.3 Specific Humidity Profile Characteristics Specific humidity profiles [Figure 3: see original paper] show distinct seasonal differences. Spring and summer profiles are similar, while autumn and winter exhibit different patterns. Seasonal mean specific humidity values are $5.91\,\mathrm{g \cdot kg^{-1}}$ (spring), $6.36\,\mathrm{g \cdot kg^{-1}}$ (summer), $2.34\,\mathrm{g \cdot kg^{-1}}$ (autumn), and $1.13\,\mathrm{g \cdot kg^{-1}}$ (winter). The summer maximum results from concentrated precipitation , which increases atmospheric moisture.

Inversion humidity occurs at night in autumn (above 8 m) and winter (above 2 m), with maximum inversion thickness reaching 30 m. Maximum specific humidity gradients are $2.51\,\mathrm{g \cdot kg^{-1}}$ (spring), $5.48\,\mathrm{g \cdot kg^{-1}}$ (summer), $2.20\,\mathrm{g \cdot kg^{-1}}$ (autumn), and $1.27\,\mathrm{g \cdot kg^{-1}}$ (winter), while minimum gradients are $2.52\,\mathrm{g \cdot kg^{-1}}$, $2.35\,\mathrm{g \cdot kg^{-1}}$, $1.01\,\mathrm{g \cdot kg^{-1}}$, and $1.27\,\mathrm{g \cdot kg^{-1}}$, respectively. Notably, specific humidity shows an inflection point at 1.5 m at all times.

2.2 Radiation Balance

The seasonal mean diurnal variation of radiation balance [Figure 4: see original paper] shows that surface radiation balance is predominantly positive across all seasons. All radiation components except downward longwave radiation exhibit single-peak diurnal patterns, though peak magnitudes and timing vary seasonally.

Downward shortwave radiation is significantly affected by dust weather, with seasonal means of $325.9\,\mathrm{W \cdot m^{-2}}$ (spring), $271.9\,\mathrm{W \cdot m^{-2}}$ (summer), $174.5\,\mathrm{W \cdot m^{-2}}$ (autumn), and $159.8\,\mathrm{W \cdot m^{-2}}$ (winter). Daily peaks are $846.3\,\mathrm{W \cdot m^{-2}}$ (spring), $759.8\,\mathrm{W \cdot m^{-2}}$ (summer), $543.2\,\mathrm{W \cdot m^{-2}}$ (autumn), and $459.8\,\mathrm{W \cdot m^{-2}}$ (winter), occurring at solar noon (12:00–13:00). Upward shortwave radiation follows similar seasonal trends, with means of $44.1\,\mathrm{W \cdot m^{-2}}$ (spring), $38.1\,\mathrm{W \cdot m^{-2}}$ (summer), $29.8\,\mathrm{W \cdot m^{-2}}$ (autumn), and $28.3\,\mathrm{W \cdot m^{-2}}$ (winter). Daily peaks are 87.5 W · m^{-2} (spring), 71.9 W · m^{-2} (summer), 61.2 W · m^{-2} (autumn), and 235.3 W · m^{-2} (winter). The anomalously high winter peak likely results from snow cover.

Downward longwave radiation shows significant seasonal variation due to atmospheric temperature and weather conditions, with means of 302.6 W · m^{-2} (spring), 381.9 W · m^{-2} (summer), 221.1 W · m^{-2} (autumn), and 202.6 W · m^{-2} (winter). Daily peaks occur at 12:00–15:00, with values of 374.7 W · m^{-2}, 463.2 W · m^{-2}, 370.1 W · m^{-2}, and 230.9 W · m^{-2}, respectively. The summer maximum results from increased cloud cover and dust particles enhancing atmospheric scattering.

Upward longwave radiation shows large seasonal amplitude due to the large diurnal temperature range of sandy soils, with means of 401.4 W · m^{-2} (spring), 463.1 W · m^{-2} (summer), 286.5 W · m^{-2} (autumn), and 286.5 W · m^{-2} (winter). Daily peaks at 13:00 are 524.8 W · m^{-2}, 568.7 W · m^{-2}, 463.1 W · m^{-2}, and 463.1 W · m^{-2}, respectively, coinciding with the times of maximum surface temperature.

Surface albedo is a critical parameter affecting radiation balance, influenced by underlying surface properties, weather conditions, and solar elevation angle [Figure 5: see original paper]. Monthly mean albedo ranges from 0.297 (August) to 0.366 (December), with an annual mean of 0.326. Seasonally, albedo shows winter > autumn > spring > summer, primarily because winter snow cover increases albedo, while summer's high solar elevation angle and soil moisture reduce it. Albedo exhibits an irregular "U-shaped" diurnal pattern (high in morning/evening, low at noon) and is negatively correlated with both solar elevation angle and soil moisture [Figure 6: see original paper].

2.3 Energy Exchange

2.3.1 Seasonal Variation of Energy Fluxes Energy flux variations [Figure 7: see original paper] show that energy consumption at the southern edge of the Taklamakan Desert is dominated by sensible heat. Sensible heat flux, soil heat flux, and net radiation exhibit clear seasonal patterns (spring > summer > winter), while latent heat flux remains stable, fluctuating around 0 W · m^{-2}. This pattern aligns with observations from the desert hinterland. Net radiation is negative and relatively constant at night, increasing rapidly after sunrise to reach maximum values at solar noon. Sensible heat flux follows similar diurnal patterns to downward shortwave radiation, with daily peaks of 200.1 W · m^{-2} (spring), 158.1 W · m^{-2} (summer), 120.4 W · m^{-2} (autumn), and 89.2 W · m^{-2} (winter). Soil heat flux peaks are 91.4 W · m^{-2}, 81.7 W · m^{-2}, 26.2 W · m^{-2}, and 26.2 W · m^{-2}, respectively.

Although summer has the highest solar elevation angle, spring shows greater net radiation, sensible heat, and soil heat flux due to frequent summer dust events that reduce solar radiation. Winter values are lowest due to weak solar radiation and low surface temperatures. Summer daytime latent heat flux shows more variation than other seasons, correlating with summer precipitation. According to meteorological data from Minfeng County, total precipitation in 2022 was 21.2 mm, with summer accounting for the maximum, increasing near-surface moisture and evapotranspiration, thereby altering energy partitioning while maintaining sensible heat dominance.

2.3.2 Seasonal Energy Closure Status

Energy imbalance is a common issue in surface flux observations. Energy closure status is typically evaluated through linear regression between available energy and turbulent fluxes, where the regression slope represents the closure rate. Linear regression results [Figure 8: see original paper] show that energy closure at the southern edge of the Taklamakan Desert is significant at the 0.05% level, with slopes of 0.76 (spring), 0.82 (summer), 0.53 (autumn), and 0.48 (winter). Corresponding coefficients of determination (R^2) are 0.84, 0.88, 0.75, and 0.73, respectively. Energy closure rates are 76% (spring), 82% (summer), 53% (autumn), and 48% (winter), showing a pattern of summer > spring > autumn > winter. These closure rates are consistent with the desert hinterland, with overall energy imbalance ranging from 18% to 59%. Except for autumn and winter, spring and summer closure rates fall within the typical range of 10–30% observed in most ecosystems.

2.4 Effective Energy Variation

Studying effective energy over desert surfaces is important for understanding climate change in northwest China, as turbulent and radiative processes determine atmospheric heating. Effective energy is defined as net radiation minus soil heat flux. When effective energy > 0, the surface transfers heat to the atmosphere (heat source); when effective energy < 0, the surface acts as a heat sink.

Seasonal mean diurnal variation of effective energy [Figure 9: see original paper] shows clear seasonal patterns (spring > summer > autumn > winter), consistent with the desert hinterland. Daily peaks are $218.5\,\mathrm{W \cdot m^{-2}}$ (spring), $213.9\,\mathrm{W \cdot m^{-2}}$ (summer), $96.2\,\mathrm{W \cdot m^{-2}}$ (autumn), and $89.2\,\mathrm{W \cdot m^{-2}}$ (winter), occurring at 12:00–13:00 (spring, summer, autumn) and 12:00 (winter). The maximum daily peak ($218.5\,\mathrm{W \cdot m^{-2}}$ in spring) is lower than that in the desert hinterland ($274\,\mathrm{W \cdot m^{-2}}$). Effective energy is positive during daytime, making the surface a strong heat source, while at night it becomes negative, transforming the surface into a weak heat sink.

3. Discussion

Temperature and humidity inversions are unique phenomena in the near-surface layer of arid and semi-arid regions. The southern edge of the Taklamakan Desert experiences nighttime temperature inversions in all seasons, consistent with most arid areas. While temperature inversions positively suppress dust storms, they inhibit vertical air convection, hindering the dispersion of smoke, pollutants, and water vapor condensates, potentially aggravating atmospheric pollution. The humidity inversion in this region is distinctive, occurring primarily at night in autumn and winter, whereas humidity inversion within oases at the southern edge occurs during daytime due to the “oasis cold island effect.” Differences in inversion occurrence times and heights among the desert hinterland, northern edge, southern edge, Badain Jaran Desert, and Dingxin Gobi are attributable to variations in geographic location, altitude, and observation height.

Solar radiation is the primary driver maintaining surface temperature, atmospheric motion, and energy balance. Like other regions, the maximum instantaneous value of downward shortwave radiation at the southern edge ($1374\,\mathrm{W\cdot m^{-2}}$) exceeds the solar constant ($1367\,\mathrm{W\cdot m^{-2}}$). Compared with other areas, seasonal variation in downward shortwave radiation shows spring > summer, similar to the Shenzha wetland on the Qiangtang Plateau, but for different reasons: dust weather in the desert versus precipitation effects in the plateau. Downward shortwave radiation is also influenced by solar elevation angle, altitude, latitude, and topography. As shown in , daily peaks of downward shortwave radiation at the southern edge exceed those in the desert hinterland and Dingxin Gobi in all seasons except summer, but are lower than those in Gaize and Shiquanhe on the Tibetan Plateau during spring, summer, and winter. These differences arise because frequent summer dust events at the southern edge reduce surface solar radiation absorption, while the higher altitude of the Tibetan Plateau locations increases radiation receipt.

Under the background of recent intensified warming and humidification in northwest China, temperature and relative humidity in the region may have increased significantly compared with historical values, potentially increasing downward shortwave radiation, sensible heat, and latent heat, while surface albedo may show greater fluctuations. However, this trend exhibits significant variability and uncertainty, and extreme weather events still occur despite the overall warming and humidification. The duration and spatial extent of these impacts remain uncertain and require further investigation.

4. Conclusions

1. Seasonal wind speed, temperature, and specific humidity at the southern edge of the Taklamakan Desert vary significantly with height. Temperature and specific humidity profiles exhibit inversion phenomena, with both inversion layers reaching 30 m. Maximum average wind speed occurs in spring ($6.23\,\mathrm{m\cdot s^{-1}}$), while maximum average temperature (28.93 °C) and specific humidity ($6.36\,\mathrm{g\cdot kg^{-1}}$) occur in summer.
2. The surface radiation balance is predominantly positive across all seasons. All radiation components except downward longwave radiation show single-peak diurnal patterns, with seasonal differences in mean values, peak magnitudes, and timing. Downward shortwave radiation is significantly affected by dust weather (spring > autumn > summer > winter).

Surface albedo, with an annual mean of 0.326, is negatively correlated with solar elevation angle and soil moisture.

3. Energy consumption is dominated by sensible heat. Sensible heat flux, soil heat flux, and net radiation show clear seasonal variations (spring > summer > winter), while latent heat flux remains stable around $0\,\mathrm{W} \cdot \mathrm{m}^{-2}$. Energy closure rates are 76% (spring), 82% (summer), 53% (autumn), and 48% (winter), showing a pattern of summer > spring > autumn > winter.
4. Effective energy varies significantly across seasons, being positive during daytime when the surface acts as a heat source, and negative at night. Seasonal patterns follow spring > summer > autumn > winter.

These results provide a scientific basis for parameterizing land surface processes at the southern edge of the Taklamakan Desert and improve understanding of regional land–atmosphere interactions.

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Note: Figure translations are in progress. See original paper for figures.