The user wants me to translate a Chinese academic paper title and a note about it being a postprint. The title is: “Characteristics of summer turbulence and analysis of ozone sounding in the hinterland of the Taklimakan Desert, Northwest China” The note is: “后印本” which means “postprint” in academ…

Authors: The user has provided a name “WANG Minzhong” which appears to be a Chinese name. This is not a paragraph with tags, LaTeX commands, or any of the structural elements described in the instructions. It’ s simply a name.

According to the instructions: - I should preserve ALL LaTeX commands and placeholders exactly - I should preserve ALL citation commands exactly - I should **PRESERVE ALL …paragraph wrapper tags EXACTLY** - I should translate from Simplified Chinese to English with the highest accuracy and academic tone

However, this input is just a name, not a paragraph with tags. The instructions say “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).”

For Chinese names, the standard academic translation convention is: 1. Keep the surname first (WANG) 2. Capitalize the surname 3. Translate the given name using Pinyin with proper capitalization

“WANG Minzhong” is already in Pinyin format. The surname is WANG (王) and the given name is Minzhong (敏忠 or similar characters).

In academic contexts, Chinese names are typically presented as: - WANG Minzhong (with surname in all caps) - Or sometimes: Wang, Minzhong - Or in Western order: Minzhong Wang

Given that the input is already in Pinyin with the surname capitalized, the most appropriate translation would be to keep it as is, since it’ s already in the standard academic format for Chinese names in English publications.

The instructions emphasize preserving structural elements like tags, but there are none here. So I should just provide the name in the appropriate English academic format.

Since the name is already in proper Pinyin format with surname capitalized (WANG Minzhong), which is the standard for Chinese names in English academic papers, I should return it unchanged.

Let me double-check the requirements: - "Translate from Simplified Chinese to English" - but this is already transliterated - "Preserve ALL LaTeX commands" - none present - "Preserve ALL …tags" - none present - "Return ONLY the translated text" - so just the name

The most faithful approach is to keep the name as "WANG Minzhong" since it' s already in the correct format for English academic, The user wants me to translate a scientific paper from Simplified Chinese to English. The input is just "MING Hu" which seems like a name. This is likely the author name or part of a title. Let me check the requirements again.

The user provided: - CRITICAL REQUIREMENTS about preserving LaTeX, citations, and tags - OUTPUT RULES about format - GLOSSARY: 机器学习 => machine learning, 深度学习 => deep learning

But the actual content to translate is just "MING Hu" . This is a name, likely "胡明" in Chinese. In academic papers, Chinese names are typically written with the surname first, then given name. "MING Hu" would be the English representation, but if it' s originally Chinese, it should probably be "Hu Ming" or kept as "MING Hu" if that' s the author' s preferred romanization.

Wait, let me re-read the instructions. The user says "Translate from Simplified Chinese to English" . The input is "MING Hu" . This could be: 1. Already in English (a romanized name) 2. A Chinese name written in pinyin but with incorrect capitalization

Given the context of academic translation, and that the user wants me to translate from Chinese to English, I should consider if this is meant to be Chinese characters that got lost or if it' s a test case.

Actually, looking at the format, the user expects me to work with content wrapped in …tags. The input "MING Hu" doesn' t have these tags. This might be: - A fragment of a larger document - A test to see if I follow instructions - An error in the input

The instructions are very specific: "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."and "Maintain exact count and IDs of …tags" .

Since there are no tags in the input, and no Chinese text to translate, I should just return the input as is, because: 1. There' s nothing to translate (it' s already English/romanized) 2. There are no tags to preserve 3. The instructions say to return ONLY the translated text

But wait, “MING Hu” could be the romanization of “胡明”. In Chinese academic contexts, names are often written as “Hu Ming” (surname first in pinyin, but with proper capitalization)., The user has provided a name “WANG Yinjun” which appears to be a Chinese name. This is likely a fragment or a test input. Let me analyze what needs to be done:

1. The name “WANG Yinjun” is a Chinese name that should be transliterated to English
2. According to standard academic conventions, Chinese names are typically written with the surname first, followed by the given name
3. “WANG” is the surname (王) and “Yinjun” is the given name (寅君 or similar)
4. In academic contexts, this would typically be written as “Wang Yinjun” or “Yinjun Wang” depending on the convention

However, looking at the instructions more carefully: - The system prompt is about translating scientific papers from Simplified Chinese to English - It mentions preserving LaTeX commands, citation commands, and tags - The user has only provided a name, not a full paragraph with tags

This seems like either: 1. A test to see if I follow instructions 2. A fragment of a larger document 3. An error in the input

Given the strict requirements: - I must preserve …tags - I must translate Chinese content to English - I must maintain academic tone

The input “WANG Yinjun” is already in a form that could be considered English transliteration. It’ s written in all caps for the surname, which is a common convention. However, it’ s not wrapped in tags.

Since the instructions are very specific about preserving tags, and the input doesn’ t contain any, I have a few options: 1. Return the name as is (since it’ s already transliterated) 2. Wrap it in a tag with a default ID 3. Ask for clarification

But the instructions say “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).” This suggests I should not add tags if they weren’ t present.

The name “WANG Yinjun” is already in English letters. The surname is capitalized. In academic contexts, Chinese names are often written this way. I could convert it to “Wang Yinjun” (with only first letter capitalized) which is more standard in English academic writing, but that would be modifying the input.

Let me reconsider: The input, The user wants me to translate a Chinese academic text to English. The text appears to be just “ALI Mamtimin” which is a name. Let me check the requirements:

1. Preserve ALL LaTeX commands and placeholders - there are none here
2. Preserve ALL citation commands - none here

3. **PRESERVE ALL ···paragraph wrapper tags EXACTLY** - there are none here
4. Maintain academic tone and formal scientific writing style - for a name, this means proper transliteration
5. Use precise technical terminology - not applicable for a name
6. Preserve section structure and paragraph organization - not applicable
7. Translate all content completely - the content is just a name

The name “ALI Mamtimin” appears to be already in a Latin script form. It’ s likely a Uyghur name (as Mamtimin is a common Uyghur surname). The user might be asking me to confirm or format this name.

Looking at the requirements again, I need to check if there are any tags. The input is just “ALI Mamtimin” without any tags. But the instructions say I must preserve these tags. Let me re-read the input carefully.

The input is: “ALI Mamtimin”

That’ s it. No paragraph tags, no LaTeX, no citations. So I should just return the name as is. But wait, the instructions say “Return ONLY the translated text for the given input” and “Keep one output paragraph per input paragraph; do not merge or split paragraphs.”

Since there’ s no paragraph tag in the input, should I add one? The instructions say “PRESERVE ALL ···paragraph wrapper tags EXACTLY” and “Maintain exact count and IDs of ···tags” . This suggests that if there are no tags in the input, there should be none in the output.

But the user might have forgotten to include the tags. Let me think about the typical structure. Usually, the input would be something like: Some Chinese text

And the output would be: Translated English text

In this case, the input is just “ALI Mamtimin” . This could be: 1. A test to see if I handle names correctly 2. A fragment where the, The user wants me to translate a scientific paper from Simplified Chinese to English. The input is just “ZHANG Jiantao” which appears to be an author’ s name. Let me check the requirements:

1. Preserve ALL LaTeX commands and placeholders
2. Preserve ALL citation commands
3. **PRESERVE ALL ···paragraph wrapper tags EXACTLY**
4. Maintain academic tone
5. Use precise technical terminology from glossary
6. Preserve section structure
7. Translate all content completely

The input is just a name: “ZHANG Jiantao”. This doesn’t contain any: - LaTeX commands - placeholders - Citation commands - tags - Technical terminology from the glossary - Section structure

It’ s just a name. According to the instructions, I should: - Return ONLY the translated text - Keep one output paragraph per input paragraph - Maintain exact count and IDs of tags - Not add Markdown formatting unless present - Preserve original line breaks

Since the input is just a name, the translation would be the same name, but perhaps formatted according to academic conventions. In Chinese academic papers, names are typically written in Chinese characters, but when translated to English, they often remain as “ZHANG Jiantao” or “Jiantao Zhang” .

Looking at the glossary: - 机器学习 => machine learning - 深度学习 => deep learning

These don’ t apply here.

The name “ZHANG Jiantao” is already in Pinyin format. In English academic papers, Chinese names are typically written either as: 1. ZHANG Jiantao (surname in all caps) 2. Jiantao Zhang (Western order)

Since the input is already in the format “ZHANG Jiantao”, I should preserve this format as it’ s likely the author’ s preferred romanization. The instruction says to translate from Simplified Chinese to English, but this is already a romanized name.

Wait, let me reconsider. The user might be providing just a snippet to test my understanding. The name “ZHANG Jiantao” in Chinese would be “张健涛” or similar. But they’ ve provided the Pinyin.

The most faithful translation would be to keep it as “ZHANG Jiantao” since that’ s the standard academic representation. However, if the original Chinese was actually “张健涛” , the translation to, The user wants me to translate a scientific paper from Simplified Chinese to English. The input is just “ZHU Congzhen” which appears to be a name. Let me check the critical requirements:

1. Preserve ALL LaTeX commands and placeholders - there are none here
2. Preserve ALL citation commands - none here
3. **PRESERVE ALL ···paragraph wrapper tags EXACTLY** - none here
4. Maintain academic tone and formal scientific writing style - this is just a name
5. Use precise technical terminology - obey the glossary strictly - not applicable
6. Preserve section structure and paragraph organization - not applicable
7. Translate all content completely - do not omit any information - it’ s just a name

The output rules say: - Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent). - Keep one output paragraph per input paragraph; do not merge or split paragraphs. - **Maintain exact count and IDs of ···tags** - not applicable here - Do NOT add Markdown formatting unless it is present in the source. - Preserve original line breaks within the paragraph when meaningful; otherwise use standard English sentence spacing.

The formatting guidelines: - Keep mathematical expressions in their original LaTeX format - not applicable - Preserve equation numbers and references - not applicable - Maintain proper academic paragraph structure - not applicable - Use formal scientific language appropriate for research papers - not applicable - Never remove or modify ⋯tags - not applicable

The glossary: - 机器学习 => machine learning - 深度学习 => deep learning

The input is just "ZHU Congzhen" which is a Chinese name. In academic contexts, Chinese names are typically transliterated. The surname is ZHU and the given name is Congzhen. The standard format for English academic papers would be "Congzhen Zhu" (given name first, surname last) or sometimes "ZHU, Congzhen" depending on the style guide.

However, looking at the requirements more carefully, this seems to be a test case or a fragment. The user might be checking if I understand that names should be transliterated but not translated. "ZHU Congzhen" should become "Congzhen Zhu" in English academic writing.

But wait, let me reconsider. The name "ZHU Congzhen" could be: 1. A person's name, The user wants me to translate a scientific paper from Simplified Chinese to English. The key requirements are:

1. Preserve ALL LaTeX commands and placeholders exactly
2. Preserve ALL citation commands ([?], ??, (??), etc.) exactly
3. **PRESERVE ALL ⋯paragraph wrapper tags EXACTLY**
4. Maintain academic tone and formal scientific writing style
5. Use precise technical terminology - obey the glossary strictly
6. Preserve section structure and paragraph organization
7. Translate all content completely - do not omit any information

The glossary provided is: - 机器学习 => machine learning - 深度学习 => deep learning

The user has provided "MING Hu" which seems to be the name of the author or a reference. However, I need to wait for the actual content to translate.

Let me prepare for the translation task. I need to be careful about: - Not modifying any LaTeX commands - Not modifying any citation commands - Not modifying any tags - Only translating the Chinese text within these tags - Maintaining academic tone - Using the glossary terms exactly as specified

Since no actual content has been provided yet, I should wait for the user to provide the text they want translated. The "MING Hu" appears to be just a name, not the actual content to translate.

I should respond by indicating I' m ready to translate, but I need the actual content. However, looking at the instructions again, the user might be providing the author name as context, and the actual content might follow in subsequent messages. Let me check if there' s any content to translate.

Actually, the user just wrote “MING Hu” . This could be: 1. The author name that should be preserved as is 2. A test to see if I understand the instructions 3. The beginning of the content that got cut off

Given the instructions are very specific about preserving tags and not modifying certain elements, and “MING Hu” doesn' t contain any Chinese characters that need translation, I should probably just return it as is, or ask for clarification.

But wait - the user might be providing the author name as part of the document structure. In academic papers, author names are typically not translated but kept as is. So “MING Hu” should remain “MING Hu” .

However, without the actual content wrapped in tags, I don' t have anything to translate. The user might

Date: 2025-12-15T18:09:14+00:00

Abstract

The user wants me to translate a scientific abstract from Chinese to English. Let me analyze the requirements:

1. **Critical Requirements**:
   - Preserve ALL LaTeX commands and placeholders exactly
   - Preserve ALL citation commands ([?], **??**, (**??**), etc.) exactly
   - **PRESERVE ALL ···paragraph wrapper tags EXACTLY**
   - Maintain academic tone and formal scientific writing style
   - Use precise technical terminology - obey the glossary strictly
   - Preserve section structure and paragraph organization
   - Translate all content completely - do not omit any information
2. **Output Rules**:
   - Return ONLY the translated text (no explanations, no quotes, no headings)
   - Keep one output paragraph per input paragraph
   - **Maintain exact count and IDs of ···tags**
   - Do NOT add Markdown formatting unless present in source
   - Preserve original line breaks within the paragraph when meaningful
3. **Formatting Guidelines**:
   - Keep mathematical expressions in original LaTeX format
   - Preserve equation numbers and references
   - Maintain proper academic paragraph structure
   - Use formal scientific language
   - Never remove or modify ···tags
4. **Glossary**:
   - 机器学习 => machine learning

- 深度学习 => deep learning

Looking at the input text, I notice: - There are no tags in the input - There are no LaTeX commands or math placeholders - There are no citation commands - The text is a single paragraph (an abstract)

Since there are no tags in the input, I should NOT add them. The instruction says "PRESERVE ALL ···paragraph wrapper tags EXACTLY" - if there are none, I should not create any. The output should be just the translated text.

Let me translate the text carefully, maintaining academic tone:

Original Chinese text: "Due to the arid and sandy surface of the Taklimakan Desert (TD) in China, the turbulence structure and vertical distribution of ozone exhibit unique and complex characteristics. However, few studies have focused on these issues. To reveal the variation characteristics of summertime atmospheric turbulence and ozone concentration over the TD, we conducted joint detection experiments in July 2016 and July 2021 at Tazhong in the hinterland of the TD using an eddy covariance detection system, a GPS (Global Positioning System) sounding system, and a meteorological gradient tower. Using methods such as statistical analysis, nonlinear fitting, and Fast Fourier Transform, this study analyzed and processed parameters including temperature, relative humidity, wind speed, turbulence parameters, turbulence spectra, and ozone concentration. The high average temperature is accompanied by low relative humidity over the TD, showing a negative correlation between the two. The temperature of the 10.0-cm-deep sand layer lags the near-surface air temperature by nearly 4 h. From 09:30 to 21:00 (Beijing Time), under conditions where the sensible heat flux is positive but stability parameter (z/L, where z is the height and L is the Obukhov length) is negative, the atmosphere is heated by the land surface, with the occurrence of unstable stratification; however, the conditions are the opposite (sensible heat flux is negative and z/L is positive) after 22:00, which are accompanied with the cooling of the surface radiation, occurrence of temperature inversion in the lower atmosphere, and stable stratification. A positive correlation is identified between the diurnal variation of turbulent kinetic energy (TKE) and the atmospheric boundary layer (ABL) height, with significant contributions from both the buoyancy and shear terms during the daytime. Under unstable stratification, the normalized standard deviations of the three-dimensional wind speed, temperature, and humidity conform to the Monin-Obukhov Similarity Theory (MOST). As the stability parameter z/L transitions from strongly unstable to strongly stable, the energy of the dimensionless turbulent velocity spectra gradually decreases and conforms to the -2/3 power law within the inertial subrange. In the hinterland of the TD, the summertime tropospheric ozone concentration remains below approximately 0.70\$$\times 10–6(volumeconcentration).Abovethetroposphere,withintherangeof16,500.0–30,000.0m,asignifican$
6. The research findings provide both theoretical and data foundations for future in-depth studies of turbulent motion and ozone concentration distribution in the TD, as well as in the similar areas around the world."

Wait, the user provided English text already. Let me re-read the prompt. The user says "Translate from Simplified Chinese to English" but then provides English text. Let me check if this is Chinese text that looks like English···

Actually, looking more carefully, the user has provided what appears to be an English abstract. But the instruction says "Translate from Simplified Chinese to English" . This is confusing. Let me check the text again:

"Due to the arid and sandy surface of the Taklimakan Desert (TD) in China, the turbulence structure and vertical distribution of ozone exhibit unique and complex characteristics. However, few studies have focused on these issues. To reveal the variation characteristics of summertime atmospheric turbulence and ozone concentration over the TD, we conducted joint detection experiments in July 2016 and July 2021 at Tazhong in the hinterland of the TD using an eddy covariance detection system, a GPS (Global Positioning System) sounding system, and a meteorological gradient tower. Using methods such as statistical analysis, nonlinear fitting, and Fast Fourier Transform, this study analyzed and processed parameters including temperature, relative humidity, wind speed, turbulence parameters, turbulence spectra, and ozone concentration. The high average temperature is accompanied by low relative humidity over the TD, showing a negative correlation between the two. The temperature of the 10.0-cm-deep sand layer lags the near-surface air temperature by nearly 4 h. From 09:30 to 21:00 (Beijing Time), under conditions where the sensible heat flux is positive but stability parameter (z/L, where z is the height and L is the Obukhov length) is negative, the atmosphere is heated by the land surface, with the occurrence of unstable stratification; however, the conditions are the opposite (sensible heat flux is negative and z/L is positive) after 22:00, which are accompanied with the cooling of the surface radiation, occurrence of temperature inversion in the lower atmosphere, and stable stratification. A positive correlation is identified between the diurnal

Full Text

Preamble

Characteristics of Summer Turbulence and Analysis of Ozone Sounding in the Hinterland of the Taklimakan Desert, Northwest China

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Abstract: Due to the arid and sandy surface of the Taklimakan Desert (TD) in China, the turbulence structure and vertical distribution of ozone exhibit unique and complex characteristics. However, few studies have focused on these issues. To reveal the variation characteristics of summertime atmospheric turbulence and ozone concentration over the TD, we conducted joint detection experiments in July 2016 and July 2021 at Tazhong in the hinterland of the TD using an eddy covariance detection system, a GPS (Global Positioning System) sounding system, and a meteorological gradient tower. Using methods such as statistical analysis, nonlinear fitting, and Fast Fourier Transform, this study analyzed and processed parameters including temperature, relative humidity, wind speed, turbulence parameters, turbulence spectra, and ozone concentration. The high average temperature is accompanied by low relative humidity over the TD, showing a negative correlation between the two. The temperature of the 10.0-cm-deep sand layer lags the near-surface air temperature by nearly 4 h. From 09:30 to 21:00 (Beijing Time), under conditions where the sensible heat flux is positive but stability parameter (z/L, where z is the height and L is the Obukhov length) is negative, the atmosphere is heated by the land surface, with the occurrence of unstable stratification; however, the conditions are the opposite (sensible heat flux is negative and z/L is positive) after 22:00, which are accompanied with the cooling of the surface radiation, occurrence of temperature inversion in the lower atmosphere, and stable stratification. A positive correlation is identified between the diurnal variation of turbulent kinetic energy (TKE) and the atmospheric boundary layer (ABL) height, with significant contributions from both the buoyancy and shear terms during the daytime.

Under unstable stratification, the normalized standard deviations of the three-dimensional wind speed, temperature, and humidity conform to the Monin-Obukhov Similarity Theory (MOST). As the stability parameter z/L transitions from strongly unstable to strongly stable, the energy of the dimensionless turbulent velocity spectra gradually decreases and conforms to the -2/3 power law within the inertial subrange. In the hinterland of the TD, the summertime tropospheric ozone concentration remains below approximately 0.70$\times10^{-6}$ (volume concentration). Above the troposphere, within the range of 16,500.0-30,000.0 m, a significant increasing trend is identified in the ozone concentration with altitude. At an altitude of 30,000.0 m, the maximum ozone concentration can reach up to 7.50$\times10^{-6}$. The research findings provide both theoretical and data foundations for future in-depth studies of turbulent motion and ozone concentration distribution in the TD, as well as in similar areas around the world.

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Keywords: Monin-Obukhov Similarity Theory (MOST); turbulence energy spectrum; turbulent kinetic energy (TKE); atmospheric boundary layer height; ozone concentration profile; Taklimakan Desert

Citation: WANG Minzhong, MING Hu, WANG Yinjun, ALI Mamtimin, ZHANG Jiantao, ZHU Congzhen. 2025. Characteristics of summer turbulence and analysis of ozone sounding in the hinterland of the Taklimakan Desert, Northwest China. Journal of Arid Land, 17(12): 1719–1740. https://doi.org/10.1007/s40333-025-0060-4; https://cstr.cn/32276.14.JAL.02500604

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1 Introduction

The Taklimakan Desert (TD) in Northwest China is the second-largest shifting desert in the world and contributes significantly to global dust emissions (Mehta et al., 2018; Ming et al., 2022; Sun et al., 2024; Zhou et al., 2024). Moreover, dust aerosols from the TD play an important role in weather and climate conditions at the regional scale (Huang et al., 2023; Zhang et al., 2024). As the Qinghai-Xizang Plateau in China and its surrounding mountainous areas block the transport of oceanic water vapour, the TD region is extremely arid, with minimal precipitation (Wang et al., 2019; Ming et al., 2021). Due to the arid and sandy surface of the TD, the turbulence structure within the boundary layer and the vertical distribution of ozone exhibit typical, unique, and complex characteristics. The physical processes of the atmospheric boundary layer (ABL) over the TD exert a significant influence on the regional and even global climate and environment. Therefore, investigating the turbulence characteristics and vertical ozone structure over the TD holds significant scientific importance and research value.

Turbulence in the ABL is a key physical process linking the land surface and the atmosphere, dominating the exchange of heat, moisture, momentum, and pollutants between the Earth' s surface and the atmosphere (Garratt, 1994; Oke et al., 2017; Kim et al., 2023; Sun et al., 2025). The mechanisms of turbulence production are associated with terrain, circulations around it, and spatial variations in surface roughness, which are typically characterized by the aerodynamic roughness length and zero-plane displacement height (Huang et al., 2010; Liang et al., 2014; Wei et al., 2021). Additionally, turbulence leads to the formation of the thermal and mechanical structures of the ABL, and factors such as turbulent flux, velocity, turbulent kinetic energy (TKE), and dissipation rate can all show intermittency characteristics (Coulter and Doran, 2002; Muschinski et al., 2004; Acevedo et al., 2006; Mahrt, 2010). Turbulence intermittency is driven by the nonstationarity of the mean flow imposed by motions on different time scales, sometimes referred to as sub-mesoscale motions (Sun et al., 2015; Rakesh et al., 2017; Cava et al., 2019). In previous research, TKE and turbulence spectra were widely used to analyze turbulence characteristics, and the ratio of the buoyancy term to the shear term can substantially affect the depth of the ABL and turbulence statistics (Fedorovich et al., 2001a, b; Sorbjan and Czerwinska, 2013). Moreover, the differing contributions of the buoyancy and shear terms were applied to classify free convection dominated by buoyancy, and forced convection dominated by shear (Oldroyd et al., 2016).

Land surface processes and the vertical structures of the ABL have been investigated along with the construction of the atmospheric environment observation network in the TD (Yang et al., 2013). Unlike the typical ABL height of 1000.0–2000.0 m over land, the ABL height in the TD can exceed 5000.0 m, and this deep ABL has become a key component of the climate system in East Asia (Wang et al., 2016a). Wei et al. (2019) used the arbitrary-order Hilbert method to analyze the behaviour of turbulent intermittency in the TD. Zhang et al. (2022) explained the turbulent mechanisms of the deep ABL in the TD based on observational experiments and large-eddy simulations. Additionally, Su et al. (2024) showed that the deep ABL is mainly driven by the low-level jet, which provides the necessary momentum, energy, and material for its formation. However, few studies have revealed the statistical characteristics of turbulence quantities as a function of stability parameter (z/L, where z is the height and L is the Obukhov length) over the TD in summer.

Ozone is a critical atmospheric trace species in both the stratosphere and troposphere, playing a significant role in atmospheric heating rates and adversely affecting human health and plant growth (Monks et al., 2015; Mills et al., 2018; Zeng et al., 2023). With rapid industrial development over the past 20 a, China has been increasingly affected by tropospheric ozone pollution (Dufour et al., 2021). For example, Ding et al. (2008) revealed the climatology of tropospheric ozone over Beijing and the North China Plain. Using a vertical ozone profile dataset from March 2001 to February 2019 over the North China Plain, Zhang et al. (2021) analyzed the vertical ozone structure on different time scales and preliminarily discussed the effect of stratospheric intrusion on ozone variation. Sun et al. (2022) analyzed the characteristics and mechanisms of tropospheric ozone variation over the Qinghai-Xizang Plateau. However, due to the lack of observational data, few studies have focused on the vertical characteristics of ozone over the TD.

This study analyzed data from eddy covariance detection system and GPS (Global Positioning System) sounding system in the hinterland of the TD, aiming to reveal the statistical characteristics of turbulent physical quantities over the TD in summer as they vary with z/L, verify the applicability of the Monin-Obukhov Similarity Theory (MOST) in the TD, and preliminarily determine the vertical distribution characteristics of ozone concentration in the troposphere-lower stratosphere over the TD. First, the diurnal variation characteristics of land surface parameters and turbulent energy over the TD were studied. Second, the statistical characteristics of turbulence quantities as a function of z/L were obtained. Third, the impact of turbulent motion on the ABL was investigated. Finally, the ozone concentration profile in the troposphere–lower stratosphere over the TD in summer was presented. These research results provide both data foundation and scientific basis for future studies on the physical processes of the ABL, the dynamics of atmospheric turbulent motion, and the distribution of tropospheric ozone concentration in the arid regions of Northwest China.

2 Study Area and Data Collection

The study area (center coordinates of 39°00′N and 83°40′E; elevation of 1009.3 m) is located at Tazhong Town in the hinterland of the TD, Northwest China. The region has an annual mean temperature of 12.1°C, with extreme maximums ranging from 40.0°C to 46.0°C. Although annual precipitation is low, at approximately 30.0 mm, potential evaporation is much higher, reaching 3812.3 mm. The area is characterized by prevailing easterly winds with an average speed of 2.30 m/s. Blowing sand and dust storms also occur frequently. The test site for this study has a mobile desert surface with sparse surrounding vegetation, which is representative of the geomorphology of the TD. To reveal the variation characteristics of summertime atmospheric turbulence and ozone concentration in the region, we used an eddy covariance detection system (R3-50; Gill Instruments Ltd., Lymington, UK) [Figure 1: see original paper], a 10-m meteorological gradient tower [Figure 1: see original paper], a GPS sounding system (CFL-GNSS-JS; The 23rd Research Institute under the Second Academy of China Aerospace Science and Industry Corporation, Beijing, China), and ozone sondes (CF-18-AO; The 23rd Research Institute under the Second Academy of China Aerospace Science and Industry Corporation, Beijing, China) for detection experiments conducted at Tazhong in July 2016 and July 2021, respectively.

The meteorological gradient tower is equipped with observation instruments installed at heights of 0.5, 2.0, 4.0, and 10.0 m, which monitor temperature, relative humidity (RH), wind speed, and wind direction at each height level. A 3D ultrasonic anemometer (R3-50; Gill Instruments Ltd., Lymington, UK) is used in the eddy covariance detection system. It is installed at 3.0 m above the mobile sand surface, with a detection frequency of 20 Hz, a wind speed measurement range of 0.00–45.00 m/s, a wind speed measurement error of less than 0.01 m/s, and a wind direction error of less than 1°. The observation data were mainly used to analyze the characteristics of the turbulence energy spectrum in the TD. The main parameter specifications of the GPS sounding system are shown in Table 1 .

To understand the vertical distribution characteristics of summertime ozone concentration over the TD, we conducted ozone sounding experiments five times at Tazhong, from 2 July to 8 July in 2016. Further, we conducted intensive sounding experiments every 3 h in July 2021 to obtain vertical profiles of temperature, RH, wind speed, wind direction, and air pressure for analyzing the impact of turbulence changes on the ABL height over the TD. The specific detection times and corresponding frequencies are shown in Table 2 .

Overall, to reveal the characteristics of turbulent physical quantities over the TD, we used the data comprising observations from the meteorological gradient tower, eddy covariance measurements, land surface flux data, and GPS sounding data collected during 1-31 July in 2021. Additionally, GPS radiosonde data from 2 July to 8 July in 2016 were utilized to analyze the distribution characteristics of ozone. All times in this study are given in Beijing Time (UTC+8).

Fig. 1 Main observational equipment related to this study. (a), an eddy covariance detection system; (b), a meteorological gradient tower.

Table 1 Main parameter indices of the GPS (Global Positioning System) sounding system

Parameter	Range	Precision	Deviation
Air temperature (°C)			
Relative humidity (%)			
Air pressure (hPa)			
Wind speed (m/s)			
Wind direction (°)			
Ozone partial pressure (hPa)	0.0–30.0$×10^{-5}$	0.1$×10^{-5}$	<0.15 (Troposphere: pressure>10.0 hPa) and $±10 $10.0 hPa) Stratosphere:

Table 2 Specific times and detection frequencies of the GPS sounding experiments conducted in July 2021

Detection time	Detection frequency	Detection time	Detection frequency
02:00		14:00	
05:00		17:00	
08:00		20:00	
11:00		23:00	

Note: All times are given in Beijing Time (UTC+8).

3 Methods

This study employed EDDYPRO software (version 7.0.9) for data quality control and preprocessing, including methods such as outlier removal and secondary coordinate rotation correction. Additionally, statistical analysis of turbulence parameters, including mean values, fluctuations, variances, and covariances, was conducted. The following descriptions are the main turbulence parameters and the retrieval algorithm for the ABL height used in this study.

3.1 Turbulence Characteristic Parameters

To reveal the atmospheric turbulent characteristics of the TD, this study primarily calculated the following relevant atmospheric turbulence parameters: friction velocity (u_*; m/s), stability, heat flux, and turbulent energy. The specific calculation formulas for each parameter are provided below.

The friction velocity is calculated as:

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$$

where u', v', and w' denote the three-dimensional wind fluctuations (m/s), respectively; $\overline{u'}$, $\overline{v'}$, and $\overline{w'}$ stand for the average three-dimensional wind fluctuations (m/s), respectively.

The stability parameter is:

$$\zeta = \frac{z}{L}$$

where z is the height (m) and L is the Obukhov length (m).

The Obukhov length is calculated as:

$$L = -\frac{\bar{T}u_*^3}{kg\overline{w'T'}}$$

where k is the von Kármán constant (0.4); $\overline{w'T'}$ is the average kinematic heat flux (K · m/s); g is the acceleration due to gravity (9.8 m/s^2); and $\bar{T}$ is the mean temperature (K).

The sensible heat flux is:

$$H = \rho c_p \overline{w'T'}$$

where ρ is the air density (1.194 kg/m^3) and c_p is the specific heat capacity at constant pressure (J/(kg · K)).

The latent heat flux is:

$$Q = \rho L_v \overline{w'q'}$$

where L_v is the latent heat of vaporization of water vapor (J/kg) and $\overline{w'q'}$ is the average kinematic moisture flux (g/(kg · m/s)).

The Bowen ratio is:

$$\beta = \frac{H}{Q}$$

The characteristic temperature is:

$$T_* = \frac{\overline{w'T'}}{u_*}$$

The characteristic humidity is:

$$q_* = \frac{\overline{w'q'}}{u_*}$$

The turbulent kinetic energy (TKE) is:

$$e = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$$

where σ_u, σ_v, and σ_w denote the three-dimensional wind standard deviations (m/s), respectively.

Using a coordinate system aligned with the average wind direction, the transport equation for TKE is expressed in Equation 9:

$$\frac{\partial e}{\partial t} = -\frac{g}{\bar{T}}\overline{w'T'} - \overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \frac{\partial}{\partial z}\left[\overline{w'\left(e + \frac{p'}{\rho_0}\right)}\right] - \varepsilon$$

where t is the time (s); $\bar{u}$ is the average wind speed in the u-direction (m/s); ρ_0 is the reference density (kg/m^3); p' is the pressure fluctuation (Pa); and ε is the turbulent dissipation rate (m^2/s^3).

In Equation 9, the left-hand side represents the local storage or rate of change of TKE (m^2/s^3), whereas the right-hand side includes the buoyancy term (1st term), shear term (2nd term), turbulent transport of kinetic energy (3rd term), pressure correlation term (4th term), and turbulent dissipation term (5th term).

3.2 ABL Height

The ABL is the most intense and complex part of the lower atmosphere, where the Earth' s surface interacts with the atmosphere, and the diurnal variation of turbulent energy has a significant impact on the development of the ABL height (Miao et al., 2015; Ren et al., 2023). Vogelezang and Holtslag (1996) proposed that the ABL height can be determined from the vertical gradients of potential temperature, wind speed, and specific humidity using the bulk Richardson number (Ri). In this study, temperature, RH, and air pressure data detected using the GPS sounding system were used to determine the ABL height with the maximum gradient method, following the steps outlined below.

First, we selected temperature, RH, and air pressure to calculate the potential temperature and specific humidity according to Equations 10 and 11.

The potential temperature is calculated as:

$$\theta = T \left(\frac{p_0}{p_a} \right)^{R/c_p}$$

where θ is the potential temperature (K); p_0 is the standard reference pressure (hPa), equal to 1000.0 hPa; p_a is the actual pressure (hPa); R is the gas constant for dry air; and c_p is the specific heat capacity at constant pressure.

The specific humidity is:

$$q = \frac{\xi e}{p_a - e}$$

where q is the specific humidity (g/kg); ξ is the ratio of the molar mass of water vapor to that of dry air, equal to 0.622; and e represents the water vapor pressure (hPa), which can be calculated from the RH and saturation water vapor pressure (e_s; hPa) using Equation 12.

The water vapor pressure is:

$$e = \frac{RH}{100} \times e_s$$

Then, the potential temperature and specific humidity data at heights h_1 and h_2 were utilized to calculate the gradient difference (Δg) over a 100.0 m interval ($h_1 - h_2 = 100.0$ m) using Equation 13:

$$\Delta g = \frac{\theta_2 - \theta_1}{h_2 - h_1} + \frac{q_2 - q_1}{h_2 - h_1}$$

In this equation, θ_1 and θ_2 represent the potential temperature at heights h_1 and h_2 (K), respectively; and q_1 and q_2 represent the specific humidity at heights h_1 and h_2 (g/kg), respectively.

Finally, by comparing Δg at different heights, the maximum gradient difference (Δg_{max}) can be identified. The height corresponding to the Δg_{max} was determined to be the boundary layer height (BLH).

Taking the clear day of 11 July in 2021 as an example, the ABL height was determined using the method described above, and the results are shown in Figure 2 [Figure 2: see original paper]. In Figure 2a, as the surface potential temperature was lower than the air potential temperature at 08:00, a temperature inversion occurred within the boundary layer, and the specific humidity noticeably decreased, with the BLH being around 200.0 m. In Figure 2b, intense solar radiation and significant surface heating of the atmosphere led to convective mixing in the lower atmosphere at 14:00. The potential temperature and specific humidity changed little with height within the boundary layer, and a clear gradient change was identified near the top of the boundary layer. At this time, the ABL height was approximately 2500.0 m. In Figure 2c, with convective mixing reaching its maximum, the ABL height peaked at approximately 4000.0 m. In Figure 2d, radiational cooling occurred at the surface after sunset, followed by an inversion in the near-surface atmosphere, causing the BLH to decrease to less than 300.0 m.

4 Results

4.1 Diurnal Variation Characteristics of Land Surface Parameters and Turbulent Energy

Using land surface and atmospheric observation data while excluding rainfall days, we categorized the data by hour, and conducted statistical analysis to determine the diurnal variation characteristics of the following elements: air temperature, RH, temperature and humidity of the sand surface, and temperature and humidity of sand layers at different depths (Fig. 3 [Figure 3: see original paper]); surface, sensible, and latent heat fluxes (Fig. 4 [Figure 4: see original paper]); and u_* and z/L (Fig. 5 [Figure 5: see original paper]).

4.1.1 Diurnal Variation Characteristics of Temperature and Humidity

In Figure 3a and b, air temperature and RH at different heights within the 10-m near-surface layer do not differ significantly and follow a consistent trend. At 08:00, as the sun rises and radiational heating begins at the ground, the air temperature gradually increases, reaching a maximum of approximately 38.0°C around 18:00. Subsequently, as solar radiation weakens, the air temperature gradually decreases. After 20:00, both sunset and the cessation of radiational heating lead to a further temperature reduction, with the lowest temperature reaching around 25.0°C by 06:00. The variation trend of RH is opposite to that of air temperature. As air temperature rises, evaporation increases, resulting in a gradual decrease in RH, which reaches its minimum of 10% around 18:00. After 20:00, evaporation weakens while condensation becomes more pronounced, leading to an increase in air moisture and a gradual rise in RH, which peaks at approximately 35% by 06:00.

Comparing Figure 3a and c, it can be seen that due to surface dust particles, the surface sand temperature (black line in Fig. 3c) is more strongly affected by solar radiation than the air temperatures at heights of 0.5, 2.0, 4.0, and 10.0 m (Fig. 3a). The temperature trends of subsurface sand (10.0 and 20.0

cm) lag the surface sand temperature by approximately 4 h. At 08:00, as the sun rises and its radiative effect increases, the surface sand temperature rises rapidly, reaching a maximum of 56.0°C around 16:00, which is 2 h earlier than the peak air temperature. Subsequently, as solar radiation weakens, the surface sand temperature begins to decrease, exhibiting a larger drop than the air temperature. After 20:00, the surface sand temperature becomes lower than the air temperature, leading to an inversion in the lower atmosphere. From the diurnal variation of subsurface sand temperatures (10.0 and 20.0 cm), it can be inferred that the deeper the sand layer, the less pronounced the temperature variation and the smaller the impact of solar radiation. Figure 3d exhibits the low soil moisture content of the sand layer. As the water absorption capacity of sand particles is very poor, the soil moisture contents of the subsurface sand (10.0 and 20.0 cm) are small (approximately 0.03% and 0.06%, respectively) and change little over time.

Fig. 2 Distribution of potential temperature (θ) and specific humidity (q) profiles, and atmospheric boundary layer (ABL) heights at 08:00 (a1 and a2), 14:00 (b1 and b2), 20:00 (c1 and c2), and 23:00 (d1 and d2) on 11 July 2021. All times are given in Beijing Time (UTC+8).

Fig. 3 Statistical characteristics of temporal variations of air temperature (a) and relative humidity (RH; b) at heights of 0.5, 2.0, 4.0, and 10.0 m, as well as soil temperature (c) at sand layer depths of 0.0, 10.0, and 20.0 cm, and soil moisture content (d) at depths of 5.0, 10.0, and 20.0 cm in July 2021. The reddish-brown vertical line at 20:00 marks the dividing line between daytime and nighttime.

4.1.2 Diurnal Variation Characteristics of Soil Heat Flux, Surface Sensible Heat, and Surface Latent Heat

Figure 4a shows that the variation amplitude of soil heat flux at a sand layer depth of 10.0 cm is greater than that at 20.0 cm depth. At 09:00, the soil heat flux at 10.0 cm depth gradually increases, indicating heat conduction from top to bottom. It reaches a maximum of approximately 120 W/m^2 at 14:00, representing the peak heat conduction. Afterwards, the soil heat flux at 10.0 cm depth gradually decreases, and by 19:00, it falls below zero, signifying heat conduction from bottom to top. It reaches a minimum of approximately -60 W/m^2 at 21:00, corresponding to the maximum heat conduction in the reverse direction. Overall, during the daytime, the soil heat flux at a sand layer depth of 10.0 cm is generally greater than zero, indicating downward heat conduction. During the nighttime, the subsurface heat flux at 10.0 cm depth is generally less than zero, indicating upward heat conduction. In comparison, changes in the deeper soil layer at 20.0 cm depth lag those at 10.0 cm depth. From 12:00 to 00:00, the soil heat flux at 20.0 cm depth is greater than zero, indicating downward heat conduction, whereas from 00:00 to 12:00, it is less than zero, indicating upward heat conduction.

Figure 4b indicates that at 09:30, immediately after sunrise, the sensible heat flux is greater than zero and gradually increases, indicating that the desert surface heats the atmosphere during this period. By 16:00, this heating reaches a maximum of approximately 230 W/m^2; afterwards, the sensible heat flux begins to decrease, reflecting a weakening of the ground' s heating effect on the atmosphere. From 21:00 to 08:00, the sensible heat flux is less than zero and remains very small, indicating a minor heating effect of the lower atmosphere on the sand surface. During this period, temperature inversion occurs. As shown in Figure 4c, the latent heat flux is greater than zero during the daytime, indicating significant evaporation and relatively low water vapor content in the atmosphere. At nighttime, particularly from 00:00 to 07:00, the latent heat flux is small, even approaching zero, indicating minimal evaporation. In Figure 4d, the Bowen ratio during the daytime shows that sensible heat transport exceeds latent heat transport, whereas the small Bowen ratio at nighttime reflects the minimal contributions of both sensible heat and latent heat.

Fig. 4 Diurnal variations of soil heat flux at sand layer depths of 10.0 and 20.0 cm (a), sensible heat flux (b), latent heat flux (c), and Bowen ratio (d) in July 2021. The reddish-brown vertical line at 20:00 marks the dividing line between daytime and nighttime.

4.1.3 Diurnal Variation Characteristics of u_* and z/L In Figure 5a, it can be observed that from 09:00 to 20:00, after sunrise, z/L is less than zero, indicating intense low-level turbulence and an unstable atmospheric stratification during this period. At 13:00, the minimum value of $z/L \approx -0.70$ indicates the most intense turbulence and the most unstable stratification. After sunset, from 23:00 to 03:00 and from 05:00 to 07:00, z/L exceeds 0.10, signifying strong stratification stability. Whereas from 03:00 to 04:00, the absolute z/L is less than 0.10, indicating weak stratification stability during this period.

The comparison between Figure 5a and b shows that the temporal variation pattern of u_* is opposite to that of z/L. Smaller z/L values correspond to larger u_*, and larger z/L values correspond to smaller u_*, indicating that greater instability in the near-surface atmosphere leads to higher u_*. After sunrise at 09:00, u_* gradually increases, reflecting a strengthening of turbulence. By 17:00-18:00, u_* reaches the value of approximately 0.35 m/s, representing the maximum turbulence, after which u_* begins to decrease. From 22:00 to 09:00, u_* is approximately at 0.15 m/s, indicating relatively weak and stable turbulence.

Fig. 5 Statistical characteristics of temporal variations of stability parameter (z/L, where z is the height and L is the Obukhov length; a) and friction velocity (u_*; b) in July 2021. The reddish-brown vertical line at 20:00 marks the dividing line between daytime and nighttime.

4.1.4 Diurnal Variation Characteristics of TKE, Buoyancy Term, and Shear Term This study utilizes the eddy covariance method to statistically analyze the measured data in July 2021. Figure 6 [Figure 6: see original paper] illustrates significant diurnal variations in TKE, buoyancy term, and shear term, with all peaks occurring between 15:00 and 17:00. After sunrise at 09:00, these three quantities gradually increase, indicating that both the buoyancy and shear terms grow with the strengthening of solar radiation. Moreover, the ABL height progressively rises due to the combined enhancement of these two terms during this period. However, after 18:00, as solar radiation weakens, these quantities also decrease gradually. By 22:00, all three quantities are relatively small and remain stable. As the buoyancy term mainly depends on changes in near-surface heat flux, which is manifested as downward heat transfer from the atmosphere to the sand surface, it exhibits a small negative value at nighttime, indicating a weak negative contribution of the buoyancy term during this period. Consequently, the shear term is the primary contributor to turbulent energy in the nocturnal stable boundary layer.

Fig. 6 Diurnal variation characteristics of turbulent kinetic energy (TKE; a), buoyancy term (b), and shear term (c) in July 2021. The reddish-brown vertical line at 20:00 marks the dividing line between daytime and nighttime.

4.2 Statistical Characteristics of Turbulence Quantities as a Function of z/L

4.2.1 Statistical Characteristics of Normalized Wind Speed as a Function of z/L According to the MOST, when the near-surface atmosphere is unstable, the normalized wind speeds follow a 1/3 power law with respect to z/L. Using the normalized wind speeds in July 2021, we performed statistical fitting under unstable stratification ($z/L < 0.00$) and stable stratification ($z/L > 0.00$) conditions, as shown in Figure 7 [Figure 7: see original paper]. Figure 7a, c, and e show that under unstable conditions, when $-z/L < 0.10$, the variations in the normalized three-dimensional wind speeds are small; whereas when $-z/L > 0.10$, the normalized three-dimensional wind speeds increase with $-z/L$. A 1/3 power law fit was applied to the normalized three-dimensional wind speeds and $-z/L$, as shown in the corresponding formula (Equation 14), where the normalized three-dimensional wind speeds are respectively expressed by σ_u/u_*, σ_v/u_*, and σ_w/u_* (in which σ_u, σ_v, and σ_w denote the standard deviations of three-dimensional wind speeds, respectively). The correlation coefficient (r) for the normalized three-dimensional wind speeds after fitting are all greater than 0.70, indicating that the normalized three-dimensional wind speeds in the TD satisfy the 1/3 power law. Additionally, for the normalized vertical wind speed and $-z/L$, the r between the fitted and measured values is 0.81, showing the strongest correlation.

$$\frac{\sigma_u}{u_*} = 3.4873\left(1 - 9.3\frac{z}{L}\right)^{1/3}$$

$$\frac{\sigma_v}{u_*} = 4.0519\left(1 - 5.2\frac{z}{L}\right)^{1/3}$$

$$\frac{\sigma_w}{u_*} = 1.0415\left(1 - 3.6\frac{z}{L}\right)^{1/3}$$

Under stable conditions (Fig. 7b, d, and f), the variations of the normalized three-dimensional wind speeds also follow the 1/3 power law, as shown in the corresponding fitting equation (Eq. 15). Compared to unstable conditions, the fitted coefficients under stable conditions are smaller, and the normalized wind speeds generally remain below 10.00, rarely exceeding large values, indicating lower TKE under stable conditions. This is because nocturnal stable stratification partially suppresses large-scale turbulence, whereas intermittent turbulence and gravity waves become dominant. Furthermore, the coefficient for σ_w/u_* is significantly smaller than those for σ_u/u_* and σ_v/u_*, which is consistent with previous study by Wang et al. (2016b). This discrepancy arises primarily because the scatter in the horizontal direction is greater than that in the vertical direction.

$$\frac{\sigma_u}{u_*} = 3.0046\left(1 + 4.5\frac{z}{L}\right)^{1/3}$$

$$\frac{\sigma_v}{u_*} = 2.6843\left(1 + 4.2\frac{z}{L}\right)^{1/3}$$

$$\frac{\sigma_w}{u_*} = 1.0325\left(1 + 2.7\frac{z}{L}\right)^{1/3}$$

Fig. 7 Distribution characteristics of normalized wind speeds in the u-direction (σ_u/u_*; a and b), v-direction (σ_v/u_*; c and d), and w-direction (σ_w/u_*; e and f) under unstable ($-z/L$) and stable (z/L) stratifications. σ_u, σ_v, and σ_w denote the standard deviations of three-dimensional wind speeds, respectively.

4.2.2 Statistical Characteristics of Normalized Turbulent Energy as a Function of z/L By dividing the TKE by the square of the friction velocity, we obtained the dimensionless normalized TKE, denoted as e/u_*^2, under both unstable and stable stratifications. Figure 8 [Figure 8: see original paper] shows the variations of normalized TKE under unstable ($-z/L$) and stable (z/L) stratifications. In the case of unstable stratification (Fig. 8a), e/u_*^2 increases with $-z/L$, and the value distribution is relatively concentrated. A 1/3 power law fit was applied to e/u_*^2 and $-z/L$, as shown in the corresponding formula (Equation 16). The r between the fitted and measured values is 0.66, showing a relatively satisfactory correlation between e/u_*^2 and $-z/L$.

$$\frac{e}{u_*^2} = 1.45\left(1 - 52622.72\frac{z}{L}\right)^{1/3}$$

Under stable stratification (Fig. 8b), e/u_*^2 shows a scattered distribution with respect to z/L, and the relationship between the two does not follow the 1/3 power law. During nocturnal stable stratification, the turbulent energy is small and exhibits significant intermittency, with uncertain change patterns. This intermittency also leads to an unpredictable variation of e/u_*^2 with z/L, resulting in no significant correlation between the two.

Fig. 8 Variation characteristics of normalized TKE (e/u_*^2, where e is the TKE) under unstable ($-z/L$; a) and stable (z/L; b) stratifications.

4.2.3 Statistical Characteristics of Normalized Temperature and Humidity with z/L Using the standard deviation of temperature, expressed as σ_T, and the standard deviation of specific humidity, expressed as σ_q (which is divided by the characteristic temperature T_* and characteristic humidity q_*), respectively, we obtained the dimensionless normalized temperature (σ_T/T_*) and dimensionless normalized specific humidity (σ_q/q_*). Moreover, Figure 9 [Figure 9: see original paper] shows the distributions of σ_T/T_* and σ_q/q_* with z/L. Under unstable stratification (Fig. 9a and c), σ_T/T_* and σ_q/q_* decrease with increasing $-z/L$. When the near surface is under free convection conditions (Choi et al., 2004), the relationship of σ_T/T_* and σ_q/q_* with $-z/L$ can be expressed by Equation 17, in which σ_x is defined as the standard deviation of the turbulent statistics, X_* is the characteristic value, and C is the fitting constant. Subsequently, the relationships of σ_T/T_* and σ_q/q_* with $-z/L$ are fitted and expressed in Equation 18, showing that both σ_T/T_* and σ_q/q_* have good correlations with $-z/L$. Compared to the fitted r value (0.41) for σ_q/q_* and $-z/L$, the higher r value (0.61) for σ_T/T_* and $-z/L$ indicates a stronger correlation between the latter two variables, which also conforms more closely to the 1/3 power law.

$$\frac{\sigma_x}{X_*} = C\left(-\frac{z}{L}\right)^{-1/3}$$

$$\frac{\sigma_T}{T_*} = 1.85\left(-\frac{z}{L}\right)^{-1/3}$$

$$\frac{\sigma_q}{q_*} = 2.12\left(-\frac{z}{L}\right)^{-1/3}$$

Under stable stratification (Fig. 9b and d), the scattered distributions of σ_T/T_* and σ_q/q_* with z/L do not conform to the 1/3 power law. As z/L decreases, σ_T/T_* and σ_q/q_* tend to increase. An integrated analysis of Figures 5 and 9 illustrates that the observed state of $|z/L| < 0.10$ mainly occurs from 21:30 to 22:30. During this period, the stable boundary layer forms. The temperature of the sand layer on the surface cools rapidly, whereas the air temperature decreases more slowly. The ground-to-atmosphere heat transfer is reversed. Meanwhile, the mode of water vapor transition shifts from evaporation to condensation. These pattern changes lead to considerable fluctuations in temperature and humidity, resulting in higher σ_T/T_* and σ_q/q_*.

Fig. 9 Distribution characteristics of normalized temperature (σ_T/T_*, where σ_T is the standard deviation of temperature and T_* is the characteristic temperature) under unstable ($-z/L$; a) and stable (z/L; b) stratifications, as well as normalized humidity (σ_q/q_*, where σ_q is the standard deviation of specific humidity and q_* is the characteristic humidity) under unstable ($-z/L$; c) and stable (z/L; d) stratifications.

4.2.4 Statistical Characteristics of Turbulence Spectra Under Different Stability Conditions The data from the 3D ultrasonic anemometer, sampled at 20 Hz, were used to analyze turbulence spectral distributions under varying stability conditions. The dataset was segmented into 30-min intervals, yielding 36,000 data points per segment and 48 segments per day. Moreover, the power spectral densities (S_u, S_v, and S_w, denoting the wind speed components of u, v, and w, respectively) were nondimensionalized across frequencies to derive normalized spectra nS_u/u_*^2, nS_v/u_*^2, and nS_w/u_*^2, where n denotes frequency. Subsequently, the turbulence spectra were obtained through Fast Fourier Transform processing of each segment.

Figure 10 [Figure 10: see original paper] shows the u-component spectral distributions with dimensionless frequency for three distinct periods (07:30, 16:00, and 20:00) on 5 July 2021 under clear-sky conditions. At 07:30 (red curve in Fig. 10), the spectral frequencies are mainly above $10^{-3.5}$, with minimal spectral power, indicating the absence of large convective eddies. At 16:00 (blue curve in Fig. 10), the prominent low-frequency signal ($< 10^{-3.5}$) exhibits maximum spectral power, confirming the presence of large convective eddies that drive BLH development. However, at 20:00 (green curve in Fig. 10), residual large-scale convection persists, with spectral power lower than that at 16:00, accompanied by a reduced mixed-layer height.

Based on the classifications of strong instability ($-2.00 \leq z/L < -0.50$), weak instability ($-0.50 \leq z/L < -0.10$), near-neutral stability ($-0.10 \leq z/L < 0.00$), neutral stability ($0.00 \leq z/L < 0.10$), weak stability ($0.10 \leq z/L < 0.50$), and strong stability ($0.50 \leq z/L < 1.00$), we categorized z/L accordingly. Subsequently, turbulence spectra with dimensionless frequency were calculated to obtain Figure 11 [Figure 11: see original paper]. According to Kolmogorov theory (Stull, 1988), the energy of turbulence is primarily distributed in the low-frequency region near the spectral peak. The energy contained in low-frequency turbulence is progressively transferred to vortices of higher frequencies until it is completely dissipated by molecular thermal effects. When the transfer process conforms to isotropy, an inertial subrange is formed in the high-frequency region, and its spectral density follows the -2/3 power law. Figure 11 shows that the inertial subranges in the three wind speed spectra match very well with the -2/3 power law (as shown by the blue line), indicating that the transfer of turbulent energy satisfies isotropy.

As the atmospheric structure transitions from strong stability to strong instability, normalized spectra nS_u/u_*^2 increase gradually (Fig. 11), indicating that the more unstable the atmospheric structure, the greater the turbulent energy. Compared to the power spectral values of nS_u/u_*^2 and nS_v/u_*^2, the power of nS_w/u_*^2 is relatively small at low frequencies ($nz/U < 10^{-1}$). This suggests that in low-frequency turbulent motion, horizontal motion predominates while vertical motion is relatively weak. When $nz/U > 10^{-1}$, the power spectral values of the three components (u, v, and w) are essentially the same, indicating that in high-frequency turbulence, the contributions of horizontal and vertical motions are roughly equal. The peak values of nS_u/u_*^2 and nS_v/u_*^2, located near the low frequency of 0.001, are greater than 10.0. In contrast, the peak value of nS_w/u_*^2, located near the high frequency of 0.700, is less than 1.0. This further confirms the intensified vertical motion of turbulence at high frequencies and the dominant horizontal motion at low frequencies. In the strong stability spectrum (black line in Fig. 11), a relatively narrow power peak appears at low frequencies, which may be the main dynamic source of intermittent turbulence at nighttime.

Fig. 10 Normalized spectrum (nS_u/u_*^2) distributions with dimensionless frequency (nz/U) for three distinct periods (07:30, 16:00, and 20:00) on 5 July 2021. n denotes frequency; S_u denotes power spectral density for the wind speed component of u; nz/U denotes the dimensionless frequency; U denotes the mean wind speed.

Fig. 11 Variation characteristics of normalized spectrum (nS_u/u_*^2, nS_v/u_*^2, and nS_w/u_*^2) for wind speed components of u (a), v (b), and w (c) with dimensionless frequencies (nz/U) under different z/L conditions.

4.3 Impact of Turbulent Motion on the ABL Height

Using GPS sounding data, we retrieved the ABL height according to Section 3.2 and then obtained Figure 12 [Figure 12: see original paper]. By combining the daily variation characteristics of z/L and TKE (Figs. 5 and 6), the following findings can be drawn: before sunrise (08:00), atmospheric turbulence energy is low and z/L is greater than 0.00, indicating a stable boundary layer at low altitudes with a height of approximately 250.0 m. After sunrise (after 09:00), solar radiation gradually increases, turbulence energy rises, and z/L becomes less than 0.00, leading to a transition from a stable boundary layer to a convective boundary layer with progressively increasing height. Both the turbulence energy and the height of the convective boundary layer reach their maximum values (average ≈ 4500.0 m) around 16:00. Due to the dry conditions and low moisture content in the TD, solar radiation reaching the surface is substantially high, which heats the atmosphere through sensible heat transfer, triggering intense turbulent development and resulting in an ABL height significantly higher than that in other regions. Moreover, after 18:00, weakened solar radiation and decreased turbulence energy result in a gradual decline of the ABL height. After 22:00, solar radiation disappears, turbulence energy drops to low values, z/L changes from negative to positive, and the low-altitude boundary layer transitions from a convective to a stable state. Between 23:00 and 07:00, the formation of an inversion layer maintains strong stability at low altitudes, with the ABL height remaining below 300.0 m.

Fig. 12 ABL heights at different times and the temporal variation of the average ABL height.

TKE serves as a key physical quantity characterizing turbulence intensity and significantly influences the development of the ABL height. Figure 13 [Figure 13: see original paper] presents the distributions of the ABL heights derived from GPS sounding data and the corresponding TKE during the daytime (08:00-20:00), demonstrating a strong correlation. Moreover, the relationship between the two parameters is established using nonlinear fitting, as shown in Equation 19, where H_{ABL} denotes the ABL height. The r between the fitted and measured values is 0.82.

$$H_{ABL} = 0.15e^{1.2} + 1200$$

Fig. 13 Distribution characteristics of the ABL height with TKE during the daytime (08:00-20:00).

4.4 Characteristics of Ozone Concentration Profiles at Tazhong

Air temperature and ozone concentration profiles from five experiments conducted at Tazhong from 2 July to 8 July in 2016 are shown in Figure 14 [Figure 14: see original paper]. Starting from the ground, air temperature decreases with increasing altitude, reaching a minimum at approximately 16,500.0 m (Fig. 14a). Above this altitude, air temperature increases with height. Based on the characteristics of the air temperature profile, we determined the average height of the summer troposphere at Tazhong to be approximately 16,500.0 m. This indicates that the altitude at which the air temperature trend shifts from decreasing to increasing corresponds to the tropopause. According to Figure 14b, below 16,500.0 m, ozone concentration is relatively low, varying below approximately 0.70\$×10^{-6}\$ (volume concentration). In contrast, above 16,500.0 m, ozone concentration increases significantly with altitude, reaching a maximum of 7.50\$×10^{-6}\$ at 30,000.0 m. Combining Figure 14c and d, it is evident that ozone concentration exhibits diurnal variations. Below 15,000.0 m, the maximum difference of ozone concentrations between nighttime and daytime reaches 0.15\$×10$^{\{-6\}, whereasabove15,000.0m, thisdifferencecanreachupto0.90×10}${-6}\$. These observations indicate that, in the hinterland of the TD, summertime ozone concentration exhibits limited variation within the troposphere, whereas in the stratosphere, ozone concentration increases significantly with altitude.

Fig. 14 Vertical profiles of (a) air temperature, (b) ozone concentration, (c) ozone concentration difference between 01:35 and 16:15 on 6 July 2016 (height range of 0.0-15,000.0 m), and (d) ozone concentration difference between 01:35 and 16:15 on 6 July 2016 (height range of 15,000.0-30,000.0 m).

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5 Discussion

5.1 MOST in the TD

Previous studies on turbulence over the TD have mainly focused on the interaction characteristics of momentum, heat, and water vapor between the atmosphere and ground surface, the variation characteristics of TKE, and the impact of dust on radiation (Zhao et al., 2010; Chen et al., 2013; Meng et al., 2020; Chang et al., 2021; Chen et al., 2023, 2025; Zhang et al., 2023). Moreover, most studies employed Fourier and Hilbert transforms to investigate the turbulence spectrum of the TD (Jin et al., 2019; Wei et al., 2019). However, few studies have established the fitting relationships between the turbulent parameters and z/L in the TD. In this study, data from eddy covariance observation system were analyzed not only to explore the diurnal variation characteristics of summertime land surface parameters and turbulence energy over the TD but also to construct fitting equations (Eqs. 14-18) relating turbulence characteristics to z/L. These equations further confirm that the MOST remains valid within the TD and advance predictive capabilities for desert turbulence modelling, providing a mechanistic framework for future studies on dust-atmosphere interactions in the TD.

5.2 Validity of the ABL Height Retrieved Using the TKE

Investigations into the ABL height of the TD have principally concentrated on the spatial characteristics of temperature and humidity within the boundary layer, the turbulent mechanisms governing boundary layer development, and the impact of the desert surface on the ABL height (Wang et al., 2016a, 2019; Xu et al., 2018; Xu and Lin, 2021; Zhang et al., 2022). Nevertheless, the intricate relationship between the ABL height and TKE remains underexplored. This study develops a novel retrieval formula (Eq. 19), establishing a functional interdependence between TKE and the ABL height, with empirical validation through rigorous analysis under multiple meteorological scenarios.

To further evaluate the accuracy of Equation 19, we selected three different weather scenarios: sunny day (4 July 2021), precipitation day (14 July 2021), and blowing sand day (12 July 2021). The ABL heights were then calculated using Equation 19 and compared with the ABL heights retrieved from GPS sounding data (Fig. 15 [Figure 15: see original paper]). Overall, the TKE-inverted ABL heights align well with the development characteristics of the convective boundary layer, showing small deviations from the GPS sounding measurements (all less than 500.0 m). On the sunny day (Fig. 15a), the development of the ABL height and TKE exhibits strong consistency, with the maximum ABL height reaching 5000.0 m. However, as Figure 15b shows, episodic precipitation occurs between 12:00 and 14:00. During this period, the ABL height is influenced not only by TKE but also by large-scale advection. In this study, only TKE is considered as an influencing factor, whereas large-scale advection is excluded, resulting in considerable discrepancies between TKE-derived and GPS-derived ABL heights. In comparison with the sunny day (Fig. 15a), the ABL height decreases as dust particle concentration increases during blowing sand (Fig. 15c). This is primarily because higher dust concentrations significantly reduce the net solar radiation reaching the surface, lowering sensible heat and consequently reducing the ABL height.

The ABL height of the TD is primarily influenced by thermal and dynamic factors of the underlying surface, the residual mixed layer, and large-scale advection. While TKE effectively reflects the thermal and dynamic variations of the underlying surface, it cannot adequately represent the effects of the residual mixed layer or large-scale advection. As a result, Equation 19 exhibits certain deviations in retrieval under some convective weather conditions. In future studies, it is recommended to further explore methods to determine the ABL height by incorporating multiple factors, including atmospheric advection, TKE, and the residual mixed layer.

Fig. 15 ABL heights retrieved by GPS and TKE on sunny day (4 July 2021; a), precipitation day (14 July 2021; b), and blowing sand day (12 July 2021; c) in the hinterland of the TD.

5.3 Peculiarity of the TD Ozone Structure

Although many previous studies have analyzed the vertical structure of ozone in different regions (e.g., Bian et al., 2007; Li et al., 2015), few of them have examined ozone concentration profiles over the TD. This study presents, for the first time, the summertime ozone concentration distribution over the hinterland of the TD based on sounding observations. Liang et al. (2024) previously studied the summertime ozone concentration distribution over Lhasa on the Qinghai-Xizang Plateau. Their results indicate that tropospheric ozone concentrations over the Qinghai-Xizang Plateau remain below approximately 0.20$\times10^{\{-6\}, whereasabovethetropopause, ozoneconcentrationsincreaserapidlywithaltitude, reachingnearly 9.00\times10}${-6}$ at 30,000.0 m.

Observations in the hinterland of the TD show that within the troposphere, the maximum ozone concentration can reach nearly 0.70$×10^{-6}$, significantly higher than that over Lhasa. This is mainly because during summertime, the TD is characterized by clear skies, fewer clouds, intense solar ultraviolet radiation, high temperatures, and dry air, all of which favour ozone formation. However, in the stratosphere at altitudes between 16,500.0 and 30,000.0 m, ozone concentrations over the TD are lower than those over Lhasa.

Due to the limited number of observation times, research on the large-sample statistical characteristics of ozone concentrations over the TD remains insufficient and preliminary. Further observations and studies will be conducted in the future.

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6 Conclusions

This study, based on eddy covariance observation data, meteorological tower measurements, and GPS sounding data, analyzed the diurnal variation characteristics of summertime land surface parameters and turbulent energy over the TD, the variation of normalized turbulent quantities with z/L, the impact of turbulent motion on the ABL height, and the characteristics of ozone concentration profiles at Tazhong.

Temperature variations in the 10.0- and 20.0-cm deep sand layers are significantly smaller than those at the sand surface, with the changes in the former lagging the latter by approximately 4 h. The dimensionless three-dimensional wind speed components, temperature, and humidity of the TD all follow the 1/3 power law under the unstable condition, confirming that the MOST remains valid within the TD.

During the daytime, the $z/L < 0.00$ state is accompanied by enlarged buoyancy and shear terms, indicating an unstable atmospheric structure with intense turbulent motion and subsequent heat transfer from the sand layer to the atmosphere. At nighttime, the $z/L > 0.00$ state is associated with low TKE and a negative sensible heat flux, resulting in heat transfer from the atmosphere back to the sand layer. As the sand layer of the TD is highly susceptible to solar radiation, its temperature rises sharply during the daytime, contributing to the high-level development of the ABL height (>5000.0 m). At nighttime, the sand layer temperature drops rapidly, leading to the formation of a temperature inversion and creating a very stable atmospheric structure. The height of this stable boundary layer is typically less than 800.0 m.

In the hinterland of the TD, the height of the summertime tropopause is approximately 16,500.0 m. Within the troposphere, ozone concentrations exhibit limited variation, generally remaining below 0.70\$$\times 10^{\{-6\}.Abovethetropopause,ozoneconcentrationincreasessignificantlywith}$
6}\$ at 30,000.0 m.

Due to constraints in temporal coverage and data volume, the findings of this study are applicable to the turbulence characteristics of the TD region during summertime. In future research, intensive sounding experiments across different seasons will be conducted to further elucidate seasonal variations in turbulence and the vertical distribution of ozone throughout the TD region.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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References

Acevedo O C, Moraes O L L, Degrazia G A, et al. 2006. Intermittency and the exchange of scalars in the nocturnal surface layer. Boundary-Layer Meteorology, 119(1): 41–55.

Bian J C, Gettelman A, Chen H B, et al. 2007. Validation of satellite ozone profile retrievals using Beijing ozonesonde data. Journal of Geophysical Research: Atmospheres, 112(D6): D06305, doi: 10.1029/2006JD007502.

Cava D, Mortarini L, Giostra U, et al. 2019. Submeso motions and intermittent turbulence across a nocturnal low-level jet: A self-organized criticality analogy. Boundary-Layer Meteorology, 172: 17–43.

Chang W Y, Zhang Y, Li Z Q, et al. 2021. Improving the sectional Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) aerosols of the Weather Research and Forecasting-Chemistry (WRF-Chem) model with the revised Gridpoint Statistical Interpolation system and multi-wavelength aerosol optical measurements: the dust aerosol observation campaign at Kashi, near the Taklimakan Desert, northwestern China. Atmospheric Chemistry and Physics, 21(6): 4403–4430.

Chen S Y, Huang J P, Zhao C, et al. 2013. Modeling the transport and radiative forcing of Taklimakan dust over the Tibetan Plateau: a case study in the summer of 2006. Journal of Geophysical Research: Atmospheres, 118(2): 797–812.

Chen Y, An J L, Qu Y, et al. 2023. Dust radiation effect on the weather and dust transport over the Taklimakan Desert, China. Atmospheric Research, 284: 106600, doi: 10.1016/j.atmosres.2022.106600.

Chen Y, An J L, Qu Y, et al. 2025. Dust- versus cloud-radiation impacts on the diurnal temperature range for long-lasting dust weather over the Taklimakan Desert. Atmospheric Environment, 342: 120946, doi: 10.1016/j.atmosenv.2024.120946.

Choi T, Hong J, Kim J, et al. 2004. Turbulent exchange of heat, water vapor, and momentum over a Tibetan prairie by eddy covariance and flux variance measurements. Journal of Geophysical Research: Atmospheres, 109(D21): D21106, doi: 10.1029/2004JD004767.

Coulter R L, Doran J C. 2002. Spatial and temporal occurrences of intermittent turbulence during CASES-99. Boundary-Layer Meteorology, 105: 329–349.

Ding A J, Wang T, Thouret V, et al. 2008. Tropospheric ozone climatology over Beijing: analysis of aircraft data from the MOZAIC program. Atmospheric Chemistry and Physics, 8(1): 1–13.

Dufour G, Hauglustaine D, Zhang Y J, et al. 2021. Recent ozone trends in the Chinese free troposphere: role of the local emission reductions and meteorology. Atmospheric Chemistry and Physics, 21(20): 16001–16025.

Fedorovich E, Nieuwstadt F T M, Kaiser R. 2001a. Numerical and laboratory study of a horizontally evolving convective boundary layer. Part I: Transition regimes and development of the mixed layer. Journal of the Atmospheric Sciences, 58(1): 45–60.

Fedorovich E, Nieuwstadt F T M, Kaiser R. 2001b. Numerical and laboratory study of horizontally evolving convective boundary layer. Part II: Effects of elevated wind shear and surface roughness. Journal of the Atmospheric Sciences, 58(6): 820–835.

Garratt J R. 1994. Review: The atmospheric boundary layer. Earth-Science Reviews, 37(1–2): 89–134.

Huang J, Minnis P, Yan H, et al. 2010. Dust aerosol effect on semi-arid climate over Northwest China detected from A-Train satellite measurements. Atmospheric Chemistry and Physics, 10(14): 6863–6872.

Huang J P, Zhou X J, Wu G X, et al. 2023. Global climate impacts of land-surface and atmospheric processes over the Tibetan Plateau. Reviews of Geophysics, 61(3): e2022RG000771, doi: 10.1029/2022RG000771.

Jin L L, Li Z J, He Q, et al. 2019. Characteristic of surface-layer turbulence spectra on typical sunny days over the northern marginal zone of the Taklimakan Desert. Journal of Desert Research, 39(6): 1–12. (in Chinese)

Kim E R, Choi K C, Park S, et al. 2023. Turbulent characteristics in complex coastal areas assessed using BSWO observations and WRF-LES simulation results. Atmospheric Research, 289: 106756, doi: 10.1016/j.atmosres.2023.106756.

Li D, Bian J C. 2015. Observation of a summer tropopause fold by ozonesonde at Changchun, China: Comparison with reanalysis and model simulation. Advances in Atmospheric Sciences, 32(10): 1354–1364.

Liang J N, Zhang L, Wang Y, et al. 2014. Turbulence regimes and the validity of similarity theory in the stable boundary layer over complex terrain of the Loess Plateau, China. Journal of Geophysical Research: Atmospheres, 119(10): 6009–6021.

Liang T, Luo J L, Zhang C Y, et al. 2024. The impact of tropopause fold event on surface ozone concentration over Tibetan Plateau in July. Atmospheric Research, 298: 10715, doi: 10.1016/j.atmosres.2023.107156.

Mahrt L. 2010. Variability and maintenance of turbulence in the very stable boundary layer. Boundary-Layer Meteorology, 135: 1–18.

Mehta M, Singh N, Anshumali. 2018. Global trends of columnar and vertically distributed properties of aerosols with emphasis on dust, polluted dust and smoke-inferences from 10-year long CALIOP observations. Remote Sensing of Environment, 208: 21–37.

Meng L, Yang X H, Zhao T L, et al. 2020. Simulated regional transport structures and budgets of dust aerosols during a typical springtime dust storm in the Tarim Basin, Northwest China. Atmospheric Research, 238: 104892, doi: 10.1016/j.atmosres.2020.104892.

Miao Y C, Hu X M, Liu S H, et al. 2015. Seasonal variation of local atmospheric circulations and boundary layer structure in the Beijing-Tianjin-Hebei region and implications for air quality. Journal of Advances in Modeling Earth Systems, 7(4): 1763–1773.

Mills G, Sabine S, Olga L, et al. 2018. Tropospheric ozone assessment report: present-day tro

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