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Recent advances and future research directions in the study of land-atmosphere interaction in northern China since the beginning of the 21st century

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Abstract The northern region of China is not only a sensitive area for global climate change and a key region with prominent monsoon climate, but also a “hotspot” for global land-atmosphere coupling. Terrain and geomorphology in this area are complex with a large spatiotemporal variation in land surface characteristics, and the climate dynamics of land-atmosphere interaction is relatively significant. In addition, affected by interactions between circulation systems in the mid-to high latitudes and low latitudes, atmospheric circulations in this area are relatively active, which makes it easy to induce extreme meteorological events such as droughts, sand storms, rainstorms, and hail. In view of this, from the perspective of scientific innovation, the main research works in the field of land-air interaction in northern China since this century are systematically summarized. Seven new research advancements have been outlined, including the comprehensive observational and experimental system of land-atmosphere interaction in northern China, the spatiotemporal changes in physical quantities involved in land surface processes and their responses to summer monsoon, the response characteristics of land surface evapotranspiration to climate warming, land surface process parameters and parameterization schemes, the mechanism of land surface energy and water imbalance, the spatiotemporal changes and influence mechanisms of atmospheric boundary layer, and the relationship of land-atmosphere interaction with weather and climate. Based on the research progress summarized in this paper and the cutting-edge international study trend, we propose six key breakthroughs in the future for the study in this field: (1) the study should be based on the implementation and development of a new meteorologically integrated operational observation system that can observe and test conventional land-atmosphere interaction, (2) we need to improve our understanding of multi-interface exchange processes involved in land-atmosphere interaction, (3) mechanism study in the multi-scale land-atmosphere coupling process will be strengthened, (4) we need to deepen our understanding of the characteristics of land-atmosphere interaction in the specific environment of northern China, (5) the impact of land-atmosphere interaction on extreme weather and climate will be revealed,

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(6) multiple complicated feedback mechanisms between land-atmosphere interaction and climate warming will be explored. The information given in this paper will provide a scientific reference as well as a roadmap to promote land-atmosphere interaction study in northern China in the future.

Keywords Northern China, Monsoon climate, Land-atmosphere interaction, Several new developments, Future research directions

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1. Introduction

Land-atmosphere interaction mainly refers to the mutual influences between the land surface and the atmosphere through important processes such as land surface processes, atmospheric boundary layer transport, and interface exchanges between the boundary layer top and the free atmosphere. It is not only the primary method of mass and energy exchange between the land surface and the atmosphere, but also an important pathway for the transfer, exchange, transformation, and redistribution of energy, water, and greenhouse gases between various spheres of the Earth system (Jia, 2020; Zhou et al., 2024). In fact, in addition to the effects of atmospheric circulations and sea surface temperature anomalies, the evolution of and spatial pattern changes in global climate largely depend on the contribution of land-atmosphere interaction (Zellner et al., 2000; Dirmeyer et al., 2014), and the formation and development of many extreme meteorological events are also closely related to land-atmosphere interaction (Zhang et al., 2011; Orth and Seneviratne, 2017; Yang and Wang, 2019). Currently, many uncertainties in weather forecasts and climate predictions can largely be attributed to insufficient scientific understanding of land-atmosphere interaction (Wang et al., 2017; Zhong et al., 2018).

The northern region of China covers a broad area that extends from west to east, including Northwest China, North China, Northeast China, and the northern central region of China. It accounts for more than half of China's total area (Hu and Zhang, 2001; Yang et al., 2021). Atmospheric circulation background in this region is complicated. The eastern part of this region is located in the East Asian monsoon zone, which is jointly influenced by monsoon circulation and westerly circulation. The central and western parts are mainly located in the temperate climate zone and the plateau slope climate zone, which are under the control of westerly circulation and plateau monsoon (Liu Y Z et al., 2018). Moreover, the northern region of China is also one of the areas in the world that have the most active summer monsoon, and monsoon precipitation makes a decisive contribution to total annual precipitation in this region (Zhang et al., 2021; Zhang et al., 2020). The climate in this region is highly sensitive to changes in the strength, spatial advance and retreat, annual cycle, interannual fluctuation, and decadal oscillation of the East Asian summer monsoon (Li et al., 2013; Zhang et al., 2017b). Climatic variability of precipitation is significant in this region (Wang and Zhang, 2011), and natural vegetation and crop growth are highly dependent on changes in summer monsoon precipitation (Zhang Q et al., 2019e). Precipitation variability results in significant spatiotemporal variabilities in land surface water and heat characteristics as well as vegetation coverage in this region. In fact, several previous studies have shown that under the background of global warming, the semi-arid region in northern China has been expanding significantly (Huang et al., 2019), and the spatial pattern of land cover types is undergoing significant changes.

At the same time, the northern region of China is also highly sensitive to global climate change, and the warming in the semi-arid area of northern China is more than twice that in other regions (Huang et al., 2012). Moreover, the terrain and geomorphology in this region are complex, while the spatiotemporal distributions of underlying surface characteristics such as soil and vegetation are extremely uneven. Significant spatiotemporal variabilities of surface energy budget and radiative processes can be found in this region. Meanwhile, the atmospheric boundary layer structure shows a large spatial gradient and a drastic temporal variability (Zhang Q et al., 2019e), which can lead to feedback loops in mass and energy exchanges between the land surface and the boundary layer as well as between the boundary layer and the free atmosphere. As a result, atypical mesoscale circulations (Segal and Arritt, 1992) and boundary layer coherent structures could be induced, forming certain physical factors that are conducive to the initiation of atmospheric convection. Thereby, the northern region of China is not only a "hotspot" for global land-atmosphere coupling, but also has prominent climate dynamic characteristics of land-atmosphere interaction. In addition, atmospheric activities in this region are influenced by the interaction between circulation systems in the mid-to high latitudes such as cold fronts and low troughs from the northwest, and circulation systems in the low latitudes such as subtropical highs and warm and humid air flows from the southeast. As a result, this region is one of the active areas in the world with significant variability of global atmospheric circulations (Bai and Xu, 1991). The unique land-atmosphere interaction processes superimposed on the special atmospheric circulation characteristics in northern China often led to droughts, sandstorms, local rainstorms, hailstorms, and other extreme meteorological events in this region (Zeng and Zhang, 2012). A previous study also reveals that the frequency of extreme drought and flood events in northern China has significantly increased (Huang et al., 2016, 2017).

In recent decades, many research institutes and programs have conducted extensive studies on the interaction between land and atmosphere in northern China, and many meaningful research results have been achieved (Lv et al., 2002; Chen and Sun, 2002; Hu et al., 2004; Lv, 2004; Xu and Chen, 2006; Huang et al., 2008; Li X et al., 2012; Liu et al., 2013; Zhao et al., 2018; Ma et al., 2020). Dozens of national level research projects have been conducted under the sponsorship of the National Natural Science Foundation of China, and the key projects "Observation and Experimental Study of Land Surface Processes on the Loess Plateau" and "Research on Land-atmosphere Interaction and Its Response to the Summer Monsoon in the Transitional zone of Typical Summer Monsoon in China" are just two examples of such research projects. Based on the results of these research projects mentioned above, the Land-Atmosphere Interaction Research Team in the Key Laboratory of Drought Climate Change and Disaster Reduction of the China Meteorological Administration has conducted planned and continuous research on relevant scientific issues involved in land-atmosphere interaction in northern China since the beginning of the 21st century, and a series of innovative progresses have been achieved. These research results have been recognized to a certain extent by the international scientific community. However, the research results of these different projects have been sporadically published over a long period of time. Without a systematic review and summary, it is hard for the scientific community to get a systematic understanding of the research results in this area. It is even more difficult for the scientific community to have a full picture of scientific breakthroughs shown in these results, which to some extent limits continuous in-depth research on the interaction between land and atmosphere in northern China. In view of this, the present paper intends to comprehensively summarize the achievements in the field of land-atmosphere interaction study in northern China over the past two decades from the perspective of scientific innovation. The purpose of this paper is to systematically understand the important progress of dozens of research projects and more than 200 related scientific papers published in the field of land-atmosphere land-gas interaction in northern China since the beginning of this century. Based on the results, future research directions that need to be focused on are proposed for the purpose to provide a solid and reliable scientific reference for further exploration of the mechanism for land-atmosphere interaction in northern China and its impact on weather and climate. It is worth noting that there have been a large number of papers in China that summarize and generalize important progresses made by other research teams in the study of land-atmosphere interaction in northern China, and information included in these papers will not be repeated here.

2. Recent progresses in the study of land-atmosphere interaction in northern China

2.1 Comprehensive observational and experimental system for land-atmosphere interaction in northern China

2.1.1 The establishment of a comprehensive observational and experimental system for land-atmosphere interaction study that crosses the longitudinal and latitudinal directions in northern China

Field scientific observation experiments are an important approach for the study of land-atmosphere interaction (Andre et al., 1989). Since the beginning of the 21st century, on the basis of the observation and experiment resources accumulated in the previous observational and experimental projects (Lv et al., 2002; Hu et al., 2004; Lv, 2004; Xu and Chen, 2006; Huang et al., 2008; Li X et al., 2012; Liu et al., 2013; Zhao et al., 2018; Ma et al., 2020). A series of national scientific research projects focusing on various observational and experimental tasks, including "The Northwest Arid Zone Land-atmosphere Interaction Experimental Study (NWC-ALIEX)" (Huang et al., 2013), "The Loess Plateau Land Surface Process Observation Experimental Study (LOPEX)" (Zhang et al., 2009a), and "Study on the Land-Atmosphere Interaction and Its Response to Summer Monsoon over Typical Summer Monsoon Transition Zone in China" (Zhang Q et al., 2019e). Six stations for land surface process observation, i.e., Dingxi, Pingliang, Qingyang, Yuzhong, Zhangye, and Wuwei, as well as four stations for intensive spatiotemporal observation of atmospheric boundary layer, i.e., Dingxi, Pingliang, Qingyang, and Wuwei, have been added in the study region, forming a comprehensive observational and experimental system for the study of land-atmosphere interaction in northern China that crosses the meridional and latitudinal directions. This system consists of 329 meteorological observation stations, 30 land surface flux observation stations, 12 intensive spatiotemporal observation stations for atmospheric boundary layer, and 10 experimental stations for agricultural ecology and meteorology observation (as shown in Figure 1). This observational and experimental system not only fully re-

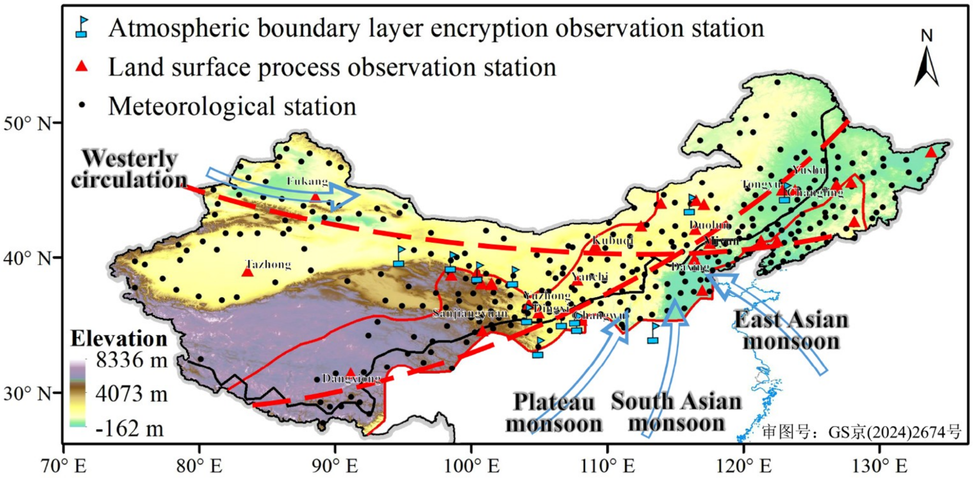

Figure 1 Distribution of 329 meteorological stations (black dots), 30 land surface process observation stations (red triangle), and 12 atmospheric boundary layer intensive observation stations (blue flag) in arid and semi-arid areas of northern China. Among them, the solid red line is the northern boundary of East Asian summer monsoon activities, the dotted red line is the layout of experimental observation that is meridionally and zonally crossing, and the blue arrows indicate the locations of the westerly circulation, plateau monsoon, South Asian monsoon and East Asian monsoon respectively.

flects the obvious spatial changes in the land-atmosphere interaction process in northern China, but also reflects its significant response characteristics to the advance and retreat of the Asian monsoon. Thereby, it can basically meet the scientific requirements of comprehensive observational and experimental research on land-atmosphere interaction in this region.

2.1.2 Construction of a refined and long-term time series land surface flux dataset in the northern region

A refined and long-term time series land surface flux dataset is an important foundation for understanding the dynamic processes of and fundamental principles governing land-atmosphere interaction. By combining multi-source land surface data such as NCEP, JRA, ERA, MERRA and GLDAS with long-term time series land surface flux data obtained from observations over different underlying surfaces in northern China, Li et al. (2021) has constructed a refined and long-term time series land surface energy flux dataset, which is a gridded dataset that is constrained by actual flux observation data and covers a large spatial range in northern China. The cross validation results with multi-source reanalysis data and model flux data show that this dataset not only effectively reduces the systematic bias shown in gridded data, but also improves the spatiotemporal refinement level. It addresses the need for high-precision and long sequence flux data in the region (1979–2020, 0.5°×0.5°) (Li et al., 2020). Moreover, this dataset, along with other related datasets, forms the scientific database for the study of land-atmosphere interaction in northern China (as shown in Table 1). It can provide reliable scientific data support for the research of land-atmosphere interaction in northern China.

2.1.3 A new method for observing and identifying non-precipitation water components on the land surface has been proposed

Although non-precipitation surface water (NRW) is a special and important component of land surface water processes in northern regions, the issue of quantitative observations of NRW has not been well addressed internationally (Zhang et al., 2012b). Zhang Q et al. (2019c) have established a new method that can objectively and quantitatively identify and observe various components of NRW (QINRW) based on the physical principles of atmospheric water phase transition using the evapotranspiration meter and micrometeorological observation instruments deployed in the Northern Land-Atmosphere Interaction Comprehensive Observational and Experimental System. The observation and identification systems of this method include observational systems such as hygrometers, rain gauges, dust collectors, air temperature and humidity sensors, and surface temperature sensors. The identification system consists of five physical judgment and separation processes that rely on the input of the observation data (as shown in Figure 2). This method not only solves the problem of the inability to directly quantify NRW, but also provides an important foundation for in-depth research on land surface moisture processes in northern regions of China.

2.2 Temporal and spatial variations of physical quantities in land surface processes and their responses to summer monsoon

2.2.1 Some spatial distribution characteristics of land surface energy have been newly found

Due to the combined influence of summer monsoon activities and geographical location, the spatial distribution of

Table 1 Scientific database on land-atmosphere interaction in northern China

Observation content	Data type	Spatial resolution	Time resolution	Time length
Land surface flux grid dataset	Sensible heat flux, latent heat flux, net radiation	0.5°×0.5°	30 min	1979–2020
Conventional meteorological station observations	wind, temperature, pressure, humidity, precipitation, as well as sunshine hours, visibility, weather phenomena, visual obstacles, cloud and wire icing, evapotranspiration, snow cover, etc	329 sites	1 min	Since 1950
Land Surface observation (North China Land Surface Process Observation Experiment)	Gradient observation (wind speed, temperature, humidity, latent heat flux, sensible heat flux, carbon dioxide flux, soil heat flux, etc.), radiation observation, soil temperature and humidity observation, precipitation	30 sites	30 min	Since 2003
Boundary layer observation dataset	GPS and L-band sounding radar obtain wind, temperature, humidity, and pressure	12 encrypted observation stations	6 h	Since 2003 (4–9 months)
Physiological and ecological observation data set	Crop leaf area index, leaf moisture content, chlorophyll, net photosynthetic rate, transpiration rate, leaf stomatal conductance, leaf area index and more than 20 physiological and ecological indicators	12 stations	5–7 d	Since 2003 (4–8 months)

land surface energy in northern China is relatively unique. Our research reveals that the spatial distribution of total radiation in northern China is mainly influenced by latitude and cloud condition, with the highest value in the Loess Plateau, followed by that in the arid northwestern region, and the lowest value is found in the cold northeastern region. Reflected radiation is closely related to vegetation coverage, and increases progressively from the cold regions of Northeast China, through the semi-arid regions of the Loess Plateau, to the arid regions of Northwest China. Atmospheric longwave radiation is mainly regulated by atmospheric water vapor condition with the highest longwave radiation occurring in the cold region of Northeast China and the lowest in the semi-arid region of the Loess Plateau. The changes in surface longwave radiation and surface sensible heat flux (SHF) are consistent and they mainly reflect the effect of surface heating, which gradually weakens from northwest to southeast. The latent heat flux (LHF) is largely influenced by the distribution of East Asian summer monsoon precipitation (Zeng et al., 2011; Zeng and Zhang, 2012). Especially in summer, the land surface SHF rapidly decreases from 60 W m^{-2} in the arid northwestern region to around 40 W m^{-2} in the semi-arid Loess Plateau region, and even reaches 30 W m^{-2} in the cold northeastern region (Figure 3a). The spatial variation of LHF is more severe than that of SHF with a range of nearly 100 W m^{-2} from the arid northwestern region through the semi-arid Loess Plateau region and then to the cold northeastern region (Figure 3c). This pattern is mainly related to the characteristics of summer monsoon activities. Meanwhile, influenced by the drastic interannual and decadal variations of the summer monsoon, climate variabilities of SHF and LHF in the semi-arid region of the Loess Plateau are more pronounced than in other areas with an annual average standard deviation exceeding 8 W m^{-2} (Figure 3b and 3d) (Li H Y et al., 2021). It can be seen that many of these characteristics are significantly different to those in other regions of the world.

2.2.2 *A new pattern of land surface energy response to summer monsoon changes has been discovered*

The surface heat flux in northern China is highly sensitive to the advance and retreat of the summer monsoon as well as changes in its intensity. Research has shown that SHF and LHF in the region have a non-linear relationship with the duration of the monsoon, and the annual variation of the heat flux is more pronounced in weak monsoon years (Li H Y et al., 2021). Moreover, seasonal fluctuations in monsoon precipitation can also lead to significant conversion characteristics of land surface energy on a short time scale (Yue et al., 2020) (Figure 4). Moreover, due to the limited range of the summer monsoon influence, there exist significant regional differences in the distribution of land surface energy between the western and eastern subregions of northern China. The heat stored in the western region is significantly higher than that in the eastern region. As the soil heat flux (G) decreases significantly, the soil will gradually shift from releasing heat to absorbing heat. Therefore, compared to the effects of solar radiation and vegetation, the non-uniform spatiotemporal distribution of summer monsoon precipitation has a more significant impact on distributions of land surface water and heat, and the degree to which water stress affects land-atmosphere interactions is more closely related to monsoon changes (Ren et al., 2022).

2.2.3 *Differences in land surface fluxes between the northern China monsoon region and other global monsoon regions have been explored*

Due to the varying patterns of global monsoon activity, land

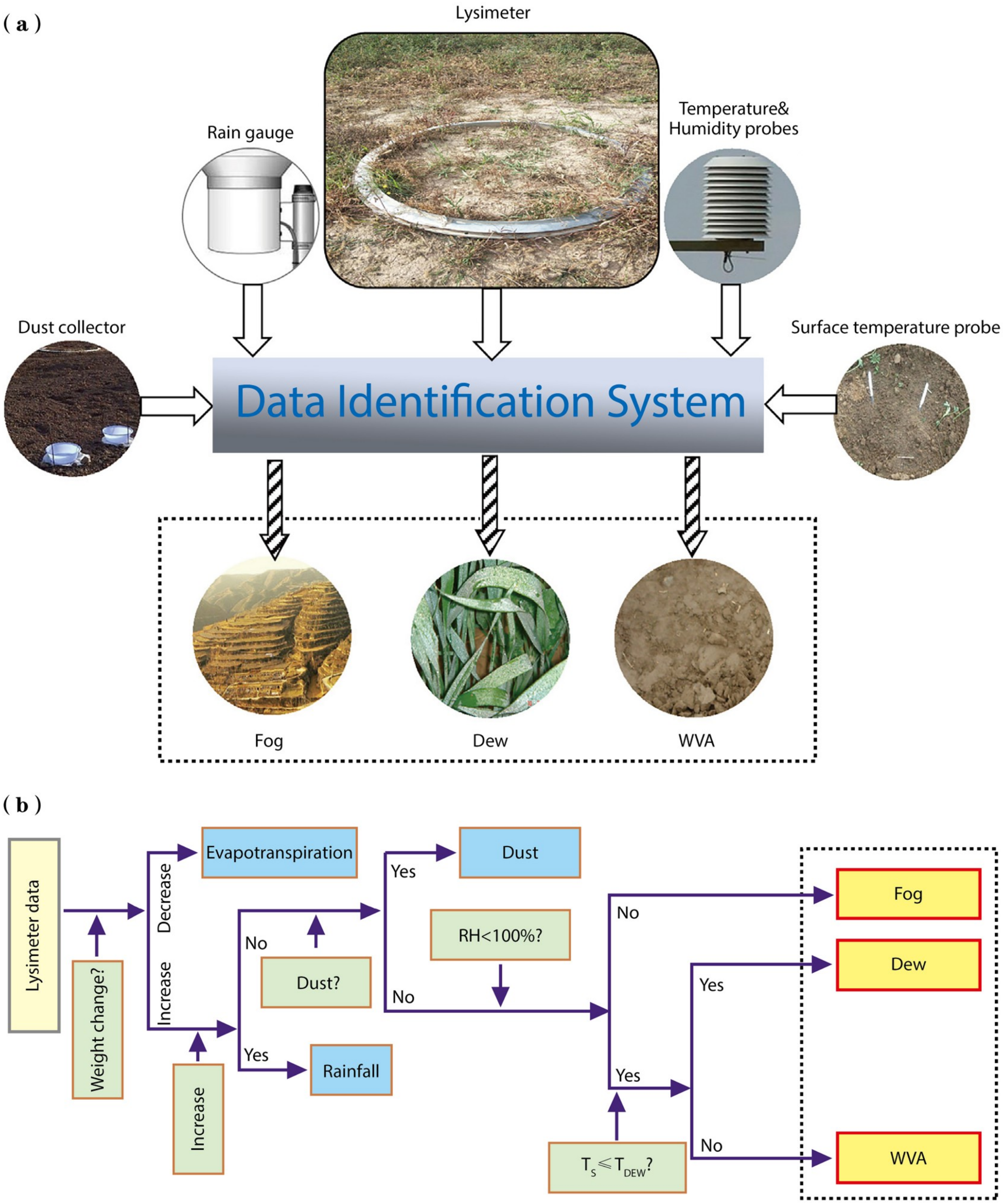

Figure 2 Identification system (a) and quantitative calculation system (b) for various components of land surface non-precipitation water (NRW) (adapted from Zhang Q et al., 2019c).

surface fluxes and their response characteristics to monsoon precipitation may also differ in different monsoon regions. Studies on the trends of land surface energy change in different monsoon regions around the world have revealed that the northern monsoon region of China (ASN) is similar to the monsoon regions of Australia (AUS), North Africa (NAF), and North America (NAM), where an increasing trend in LHF and a decreasing trend in SHF are obvious. However, the trends of LHF and SHF mentioned above are significantly different from the synchronous trends of LHF and SHF in the monsoon regions of South America (SAM) and South Africa (SAF) (Figure 5). At the regional scale, when precipitation is low (such as in regions like AUS, NAF, SAF, and ASN), LHF has a stronger dependence on precipitation. When precipitation is high (such as in the eastern part of ASN, SAM, and NAM), the correlation between LHF and precipitation is weak, and most of the precipitation is transformed into river runoff. In addition, compared to LHF, SHF is more sensitive to changes in monsoon precipitation, and there is a significant linear relationship between SHF and precipitation (Zeng and Zhang, 2020).

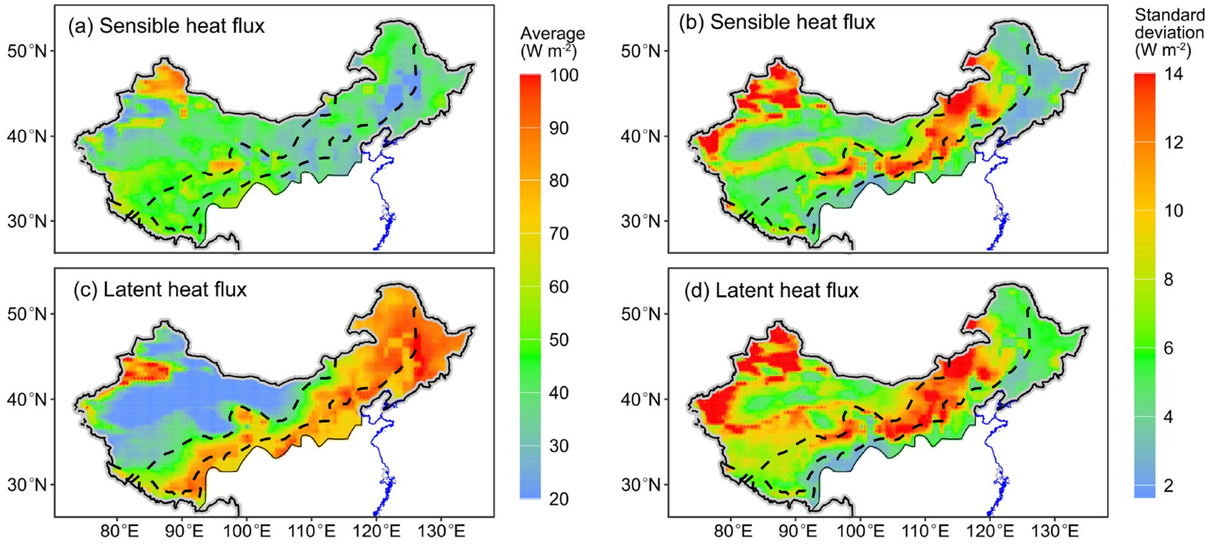

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Figure 3 Spatial patterns of mean sensible heat flux (SHF) and latent heat flux (LHF) (a and c) and their corresponding standard deviations (b and d) over northern China during the summers of 1979–2015. The two black dashed lines represent the range of the northern margin of East Asian summer monsoon activities (adapted from Li H Y et al. (2021)).

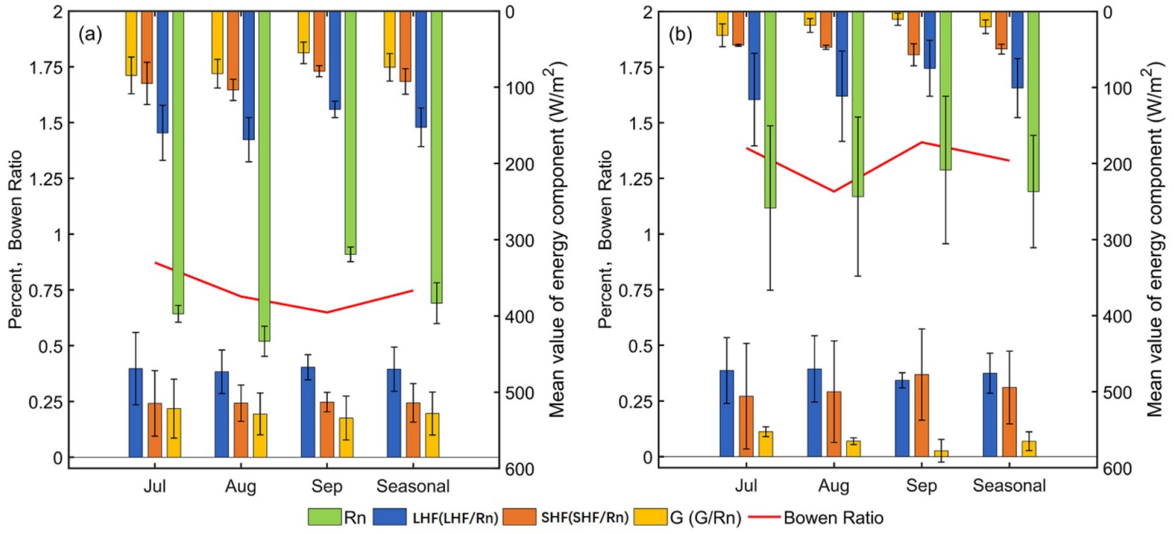

Figure 4 Monthly and seasonal averages of mean net radiation, ratio of latent heat flux (LHF) to net radiation (*Rn*), ratio of sensible heat flux (SHF) to net radiation, ratio of soil heat flux (*G*) to net radiation, and Bowen ratio in the arid and semi-arid transitional zone of northern China from July to September 2008 (adapted from Ren et al., 2022).

2.2.4 The coupling characteristics of land surface energy and ecological processes, as well as their relationship with the efficiency of precipitation utilization has been revealed

The ecosystems in northern China are complex and diverse, where the coupling effect between land surface energy and ecological processes is prominent (Kang et al., 2015; Du et al., 2012). Yue et al. (2019) research shows that the typical grassland ecosystem in the northern region of China often exhibit significant seasonal and interannual differences in land surface energy fluxes, particularly in SHF and LHF, both of which are significantly regulated by the effects of precipitation on soil moisture content (SWC) and vegetation growth. Compared to SHF, LHF has a greater interannual variability, which is related to the joint regulation of climate and ecosystem (i.e., *Rn*, SWC, VPD (water vapor pressure difference) and *Gs* (stomatal conductance)) (Yue et al., 2018). The analysis of evapotranspiration (ET) based on the Priestley Taylor relationship also indicates that the biophysical control of ET is mainly achieved through the response of SWC to the interannual variation of effective precipita-

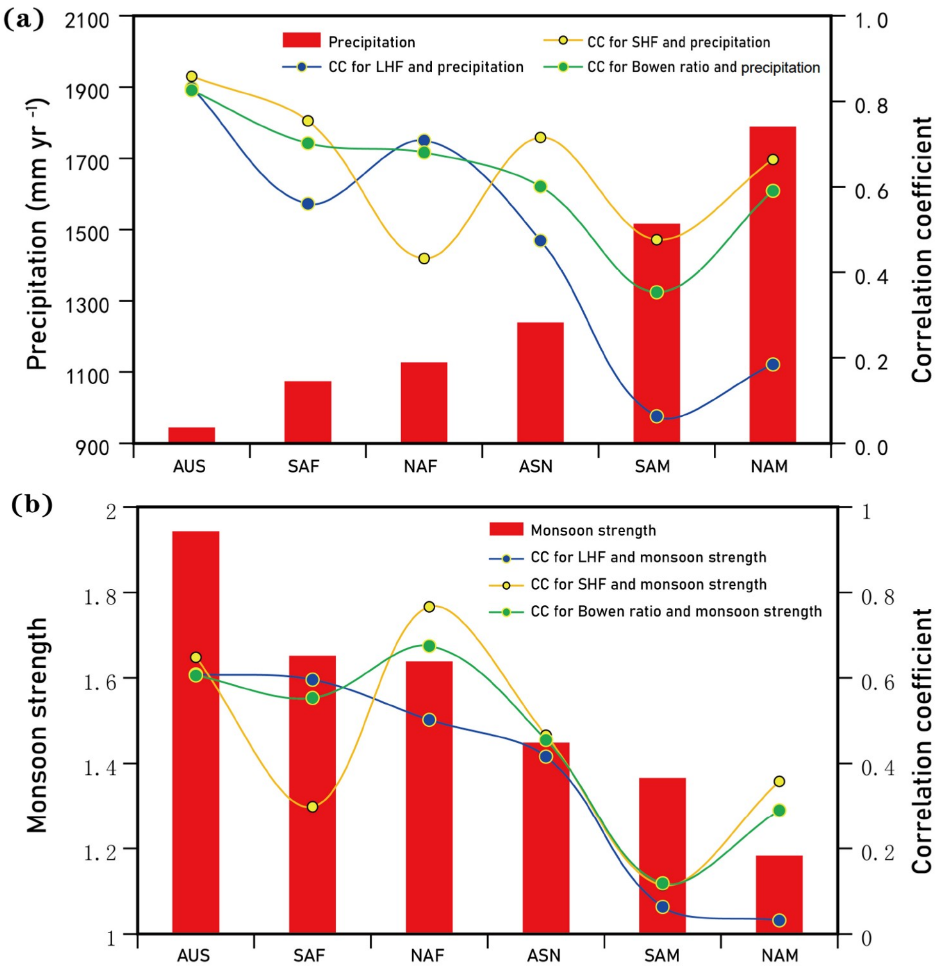

Figure 5 Correlation coefficients of latent heat flux (LHF, blue), sensible heat flux (SHF, yellow) and Bowen ratio (green) with precipitation (a) and monsoon intensity (b) in six global monsoon regions during 1982–2011 (adapted from Zeng and Zhang, 2020).

tion. This is different from the research results in other regions, which suggest that the biophysical control of ET is regulated by annual total precipitation (Jia et al., 2016). The peak of maximum precipitation utilization efficiency (PUE) in northern China occurs in the transitional zone between arid and semi-arid regions, where precipitation is limited. From west to east, the controlling factors of PUE show a characteristic conversion from water to energy. In the northwestern arid region, the increase of PUE is mainly controlled by the decrease in potential evaporation (ET_0) and the increase in soil moisture (SM) (Figure 6), while the impact mechanism of PUE in the semi-arid region is more complex (Wang et al., 2022).

2.2.5 The response characteristics of land surface moisture processes to drought stress have been presented

The response characteristics of land surface moisture processes in northern China to soil drought stress are closely related to summer monsoon activities and are greatly influenced by monsoon precipitation (Yue et al., 2020). In humid areas affected by the summer monsoon and arid areas not affected by the summer monsoon, water use efficiency (WUE) decreases with increasing drought stress index (DSI). In the transitional zone affected by the summer monsoon, i.e., the semi-arid zone, WUE increases with increasing DSI (Figure 7). This is related to the threshold of ET response to DSI (Yue et al., 2020). Moreover, compared to arid regions that are not affected by the summer monsoon, the transitional zone affected by the summer monsoon, i.e., the semi-arid zone, is more sensitive to seasonal and interannual variations of the summer monsoon because the water use efficiency is limited by both water and energy (Zhang et al., 2020). This further confirms the result obtained by Eichelmann et al. (2016) in other similar regions around the world.

2.3 Characteristics of land surface evapotranspiration and its response to climate change

2.3.1 The phenomenon of “anti-evaporation paradox” of pan evaporation has been discovered

Evapotranspiration (emission) is a key physical quantity in the interaction between terrestrial soil and vegetation in the

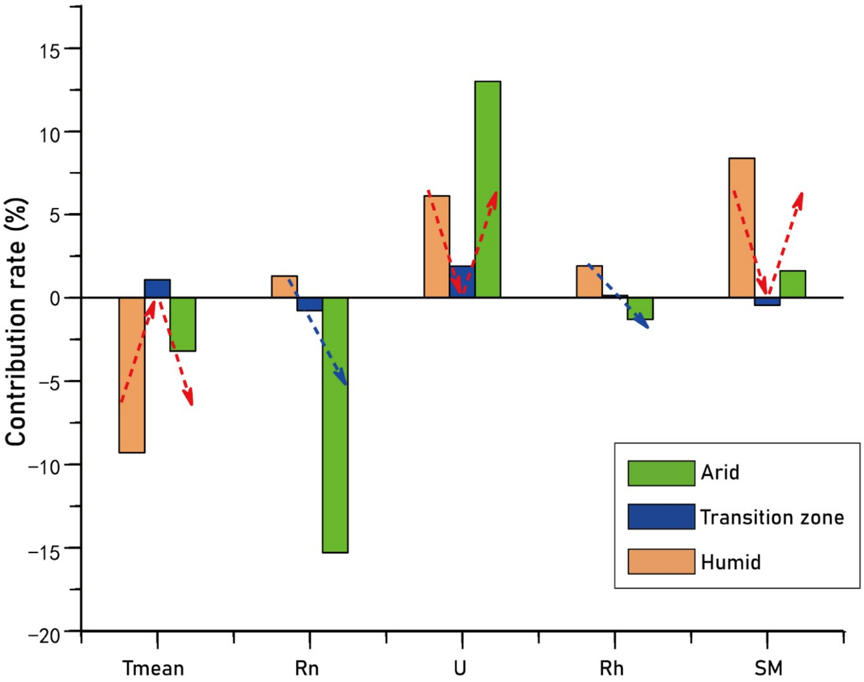

Figure 6 Contributions of environmental factors to PUE in different climate zones. *T*mean、*Rn*、*U*、*Rh* and SM represent average temperature, net radiation, 10 m wind speed, relative humidity, and soil moisture, respectively (revised based on Wang et al., 2022).

Earth system and the atmosphere (Koster et al., 2004; Trenberth et al., 2009), and it is also highly sensitive to climate change. Research has found that the changes in surface evapotranspiration (evaporation) in northern China are quite unique, and these changes are significantly different from the "evaporation paradox" phenomenon that occurred in most parts of the world (Padmakumari et al., 2013; Breña-Naranjo et al., 2017). Especially in semi-arid areas, the evaporation capacity of evaporating dishes does not show a decreasing trend with increasing temperature, but shows a completely opposite and significant upward trend, known as the "anti-evaporation paradox" phenomenon (Figure 8) (Zhang Q et al., 2016a), This is mainly due to changes in multiple meteorological factors that affect evaporation in the region, such as temperature, sunshine hours, relative humidity, precipitation, low cloud cover, and wind speed etc., all of which contribute to an increase in evaporation from the evaporating dish. Among them, the increase in temperature and the decrease in low cloud cover make the greatest contributions (Yang S Q et al., 2019).

2.3.2 Spatial transformation characteristics of actual evapotranspiration in response to climate warming trends have been revealed

Currently, there is no consensus on the response trend of land surface ET to climate warming (Koster et al., 2004; Liu et al., 2010). Recent research has found that the response of land surface ET to temperature increase shows an increasing trend in the eastern portion of northern China, where the climate is relatively humid. However, a decreasing trend is found in the drier western portion of northern China. The trend shows a clear transitional feature from decreasing to increasing in the transitional area from humid to dry (Zhang et al., 2020). This is related to direct and indirect impacts of temperature increase on ET. Research has shown that temperature can have a direct impact on ET by affecting potential evapotranspiration (PET) as well as an indirect impact on ET by affecting SM, while the two feedback mechanisms are completely opposite. In regions with relatively humid climate, temperature increases play a dominant role through the mechanism of directly increasing potential evapotranspiration. However, in regions with relatively dry climate, temperature increase indirectly suppresses land evapotranspiration through soil moisture stress, which is the dominant mechanism behind ET response to climate warming. In the semi-arid region, both mechanisms work simultaneously (as shown in Figure 9).

2.3.3 The multi-factorial impact mechanism for land surface evapotranspiration change has been understood

The impact mechanism for ET changes on the northern land surface of China is relatively complex with many environmental factors involved. Zhang et al. (2022b) research shows that the significant seasonal and interannual fluctuations of various environmental factors in northern China result in unique characteristics of ET response to climate change. Among them, *Rn* and SM are the two dominant factors in ET changes, followed by normalized difference vegetation index

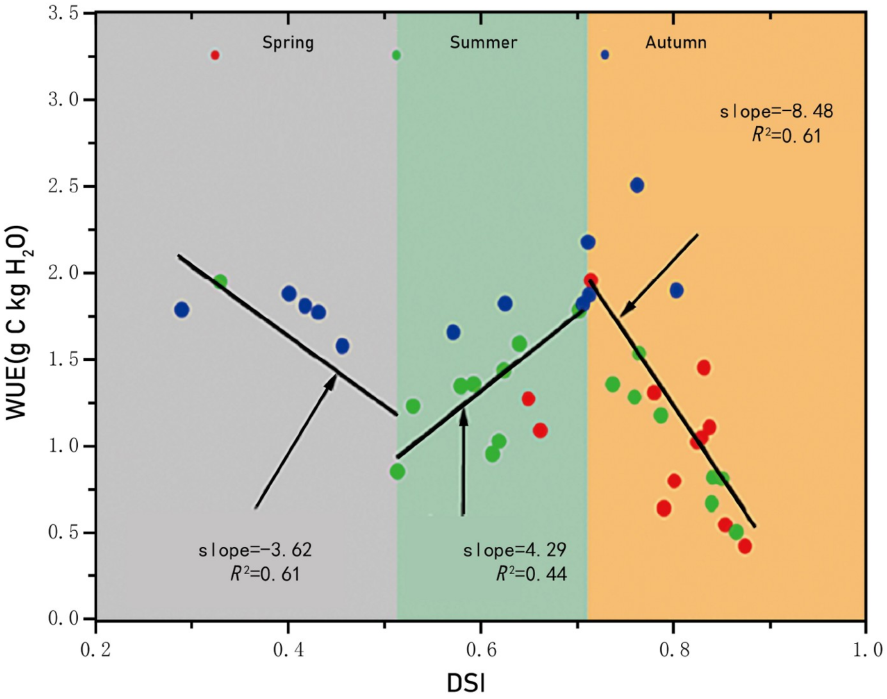

Figure 7 The relationship between drought stress index (DSI) and water use efficiency (WUE) during the growing seasons (April October) from 2007 to 2012. Gray represents moist condition (DSI<0.53), light green represents drought stress (0.53<DSI<0.72), and yellow represents severe drought stress (0.72<DSI) (modified based on Yue et al., 2020).

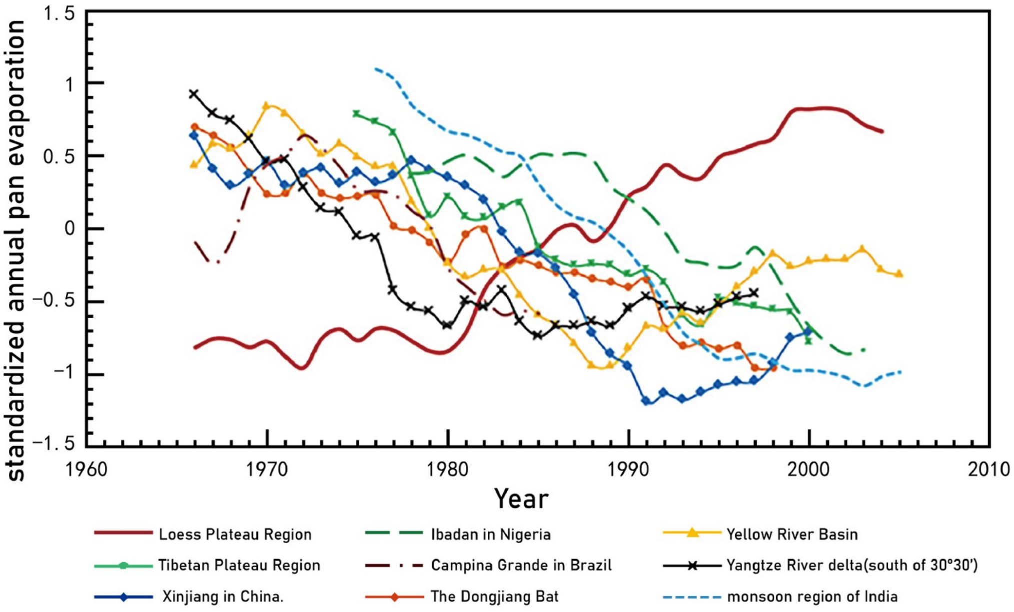

Figure 8 Comparison of standardized pan evaporation trends between the semi-arid Loess Plateau in northern China and the rest of the world during 1961–2010 (10-year sliding average) (adapted from Zhang Q et al., 2016a).

(NDVI). The role of VPD is more significant in wet season than in dry season (Figure 10). There are certain mutual constraints between some environmental factors and ET: when SM<0.2 $m^3\ m^{-3}$, ET increases with increasing vapor pressure (Evap); in contrast, when SM⩾0.2 $m^3\ m^{-3}$, ET decreases with increasing vapor pressure. When the wind speed (WS) <2 $m\ s^{-1}$, ET increases with increasing VPD. However, when WS⩾2 $m\ s^{-1}$, ET decreases with increasing VPD. When Rn<100 W m^{-2}, ET increases with the increase of Ta; when Rn⩾100 W m^{-2}, ET decreases with the increase of Ta.

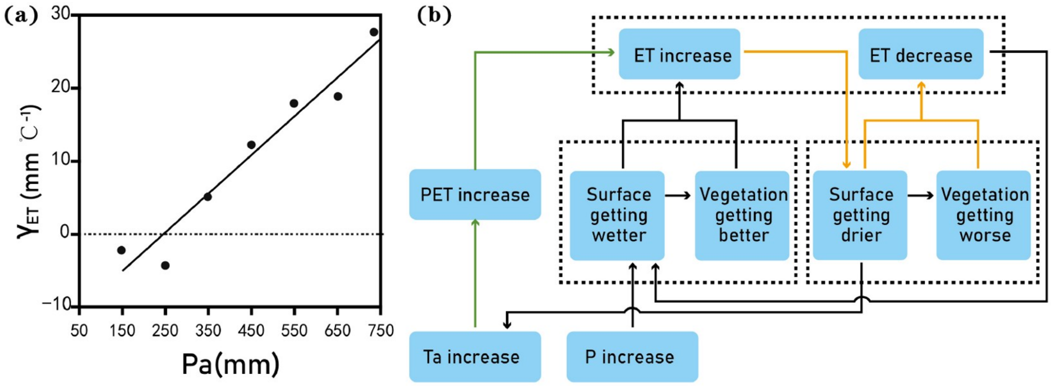

Figure 9 Response of annual mean surface evapotranspiration (ET) to climate warming in arid and semi-arid areas of northern China, (a) The change of warming tendency rate of annual mean surface evapotranspiration (ET) with precipitation (mm) climate type; (b) A simple mechanism diagram of the influence of precipitation (*P*) and temperature (*Ta*) on ET, where the green line represents the direct impact of climate warming on ET, the yellow line represents the indirect impact of climate warming on ET, and *P*ET represents the potential evapotranspiration. (adapted from Zhang et al., 2020).

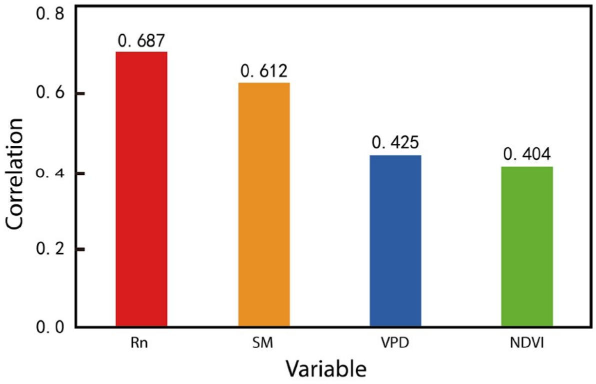

Figure 10 Correlations between ET and its influencing factors in northern China (adapted from Zhang et al., 2022b).

When NDVI<0.2, ET increases with the increase of *Ta*; when NDVI⩾0.2, ET decreases with the increase of *Ta*. It can be seen that the relationships between ET and certain environmental factors are always based on the thresholds of some other environmental factors, and this complicated interaction has not been recognized in previous research.

2.3.4 The characteristics of potential evapotranspiration influence on dry and wet climate changes have been revealed

Although climate change is mainly determined by precipitation trend (Zhai et al., 2017; Chen and Sun, 2015), in the northern region of China where global warming is significant, the role of ET in the changes of climate dryness and wetness cannot be ignored. Wang S P et al. (2020) have analyzed the differences between sensitivities of the dry and wet climate changes in northern China to potential evaporation (ET_0) and precipitation (*P*). Results indicate that sometimes ET_0 plays a dominant role in the dry and wet climate changes of the northern arid region and its contribution is about 7% more than that of *P* (Figure 11a). It is exactly due to the combined effects of decreased ET_0 and increased *P* that the climate in this arid region has become wetter (Figure 11b). In the semi-arid region of northern China, ET_0 is the dominant factor that leads to climate drying, especially in spring when the increase in ET_0 has a significant impact on the trend of aridification in this region, and its contribution is about 21% greater than that of *P* (Figure 11a). It is also because of the combined effects of increased ET_0 and decreased P (Figure 11b) that the climate in the semi-arid region has become drier.

2.3.5 The characteristic of water cycle slowdown in the semi-arid regions of northern China have been revealed

In the context of global warming, water cycle is accelerating in most parts of the world (Zhang K et al., 2015). However, Yang et al. (2016) research found that ET in the semi-arid region of northern China has shown a significant downward trend, and other components of the water cycle such as precipitation and atmospheric humidity have also shown a decreasing trend. The regional water cycle exhibits a clear characteristic of slowing down (Figure 12a). Looking at the contributions of various environmental variables to ET in the region (Figure 12b), it is found that, in addition to surface temperature, changes in relative humidity (RH), *Rn*, and NDVI all lead to a decrease in ET. Among them, the decrease in RH contributes the most, which is related to the drying of the air caused by the increase in saturation specific humidity in a warmer atmosphere (Yang Z S et al., 2019). Marshall et al. (2012) also found a similar phenomenon in their study of semi-arid regions in Africa. However, compared with characteristics of water cycle over other semi-arid regions of the world in the same latitude, the ET in the semi-arid region of northern China has been decreasing faster with a rate of 4.61 mm yr^{-1}, and the water cycle slowdown feature is more prominent.

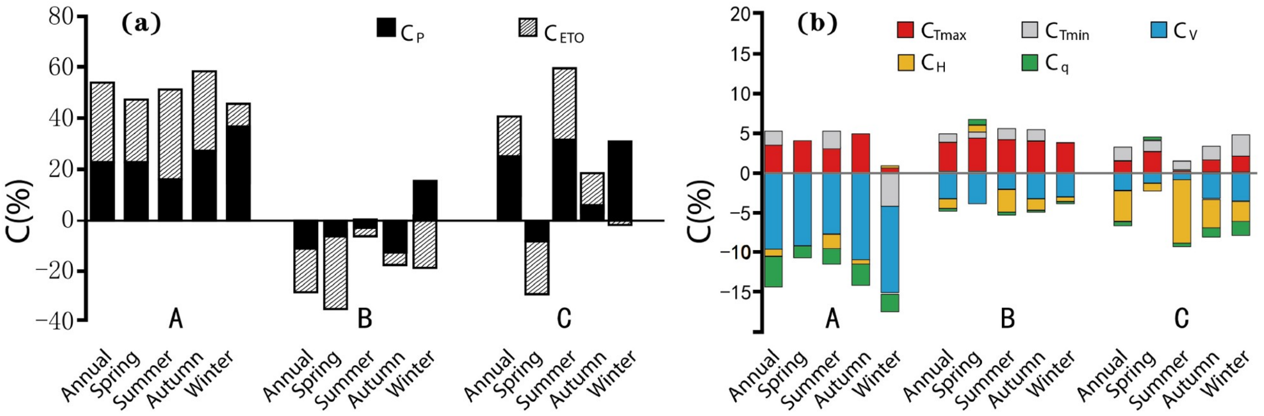

Figure 11 1960–2017 (a) Relative contributions of evapotranspiration (hash) and precipitation (black) to arid (A) and semi-arid, semi-humid (B) regions in northern China and humid (C) regions in southern China, 1960–2017. Positive and negative values indicate increases and decreases in the drought index (SPEI) (i.e., wetting and drying), respectively. (b) Contributions of maximum temperature (*T*max), minimum temperature (*T*min), wind speed (*V*), sunshine duration (*H*) and relative humidity (*q*) to evapotranspiration in different regions (adapted from Wang S P et al., 2020).

2.4 Parameters in land surface process and land surface parameterization schemes

2.4.1 A parameterized relationship between surface albedo and soil thermal parameters has been established

Currently, significant uncertainties related to many important physical parameters involved in land-atmosphere interaction in northern China can be found in various atmospheric numerical models. Surface physical parameters such as albedo, roughness, overall transport coefficient, and soil thermal characteristics, etc. have great impacts on the simulation capability of numerical models (Wang and Zhang, 2011). Through experimental research, Zeng (2011) has determined the major parameters in land surface process such as the overall transport coefficient, roughness, albedo, soil thermal conductivity, and soil thermal diffusivity for 12 representative underlying surfaces in northern China. Results are shown in Tables 1–4 in the attachment. Zhang Q et al. (2016b) have also proposed the climate dynamics relationship between dynamic roughness length and climate factors such as precipitation. Moreover, our research has found that the albedo corresponding to high solar zenith angle is strongly controlled by soil moisture and solar zenith angle, with soil moisture is the dominant factor that affects soil thermal conductivity in the region. Based on the aforementioned results, various parameterized relationships have been established between albedo (α_{mod}), soil thermal conductivity (λ_s), and thermal diffusivity (v). These relationships are expressed by eqs. (1), (2), and (3):

$$\alpha_{\text{mod}}\left(h_\theta,\omega_s\right)\begin{cases} 2.311\times10^{-5}h_\theta^2-0.003449h_\theta-1.5584\omega_s^2 \\ +0.2117\omega_s+0.3022, \\ 0.2056\times e^{-0.002h_\theta}-0.6608\omega_s^2 \\ +0.0441\omega_s+0.0048, \end{cases} \tag{1}$$

In the above equation,h_θ and ω_s represent the solar altitude angle and soil moisture, respectively.

$$\lambda_s=0.5191\ln\omega_s+2.047, \tag{2}$$

$$v=\lambda_s/\left[c_{s-p}(1-\theta)+c_w\theta_w\right], \tag{3}$$

In the above equations, c_{s-p} is the average volumetric heat capacity of soil particles, which is set to 2.3×10^6 J m^{-3} K^{-1}; θ is the soil particle size, which is 0.53 in this area; c_w (4.18×10^6 J m^{-3} K^{-1};) is the volumetric heat capacity of water; θ_w is the volumetric moisture content of the soil near the surface layer (Li H Y et al., 2012). These land surface parameters or parameterized relationships are significantly different from previous studies.

2.4.2 A parameterized relationship for the overall transport coefficient has been proposed

The overall transport coefficient is one of the most important parameters in land surface process in large-scale numerical models and obtaining accurate overall transport coefficient is a key step in improving the simulation capability of numerical models (Qiao et al., 2008). Through analyzed the relationship of the overall transport coefficient with atmospheric stability and near surface wind speed over desert and typical grassland underlying surfaces in northern China, and constructed parameterized relationships of the dynamic overall transport coefficient (C_D) and sensible overall transport coefficient (C_H) with near surface air temperature and overall Richardson number (R_i) over desert and Gobi underlying surface (eqs. (4) and (5)) and over typical grassland underlying surface (eqs. (6) and (7)) (Zhang et al., 2001; Yue et al., 2013).

$$C_D=\begin{cases}\left[k/In\left(z/z_0\right)-\psi_m\right]^2, \\ \tau/\left(\rho V_a^2\right), \end{cases} \tag{4}$$

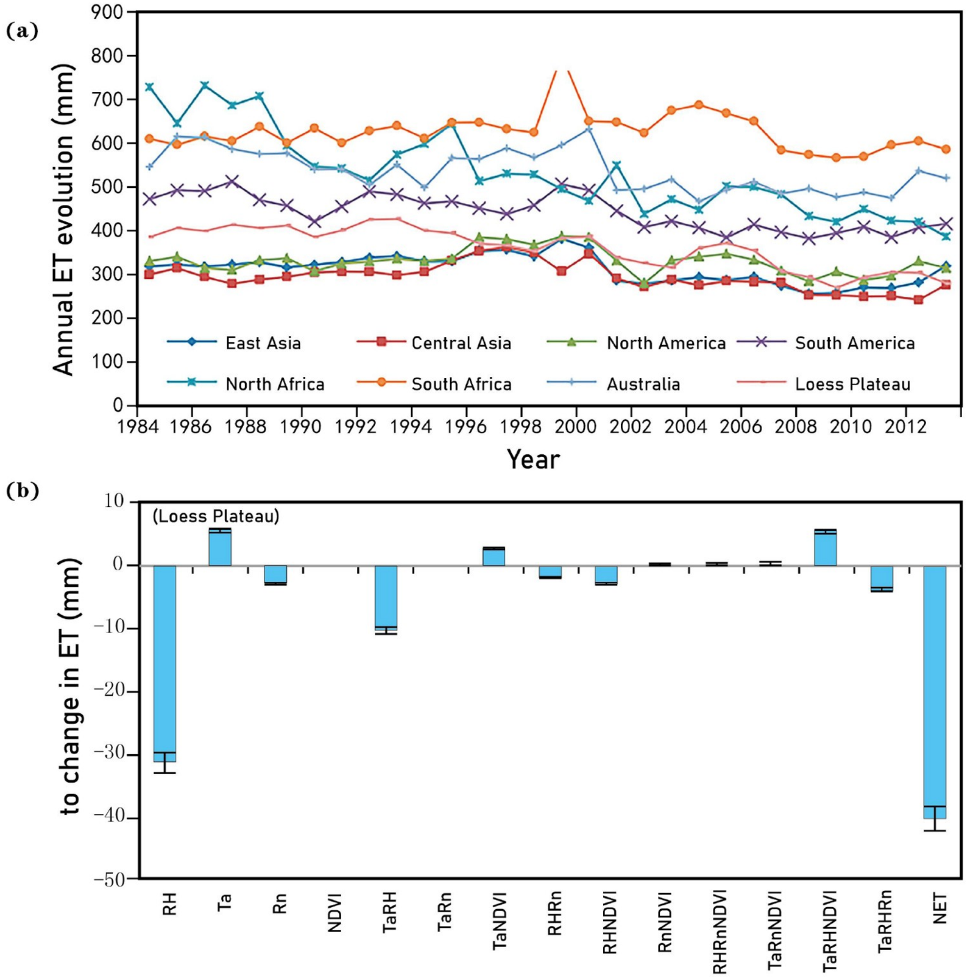

Figure 12 1984–2013 (a) ET changes in eight major semi-arid regions of the world during 1984–2013; (b) contributions of different environmental variables to ET change in the semi-arid region of the Loess Plateau (including main effects and cross-effects) (adapted from Yang Z S et al., 2019).

$$C_H=\begin{cases} k^2/\left[In(z/z_0)-\psi_m\right]\left[In(z/z_0)-\psi_h\right], \\ -H/\left(\rho c_p(\theta_a-\theta_s)V_a\right), \end{cases} \tag{5}$$

In these equations, τ is the surface momentum flux, H is the surface sensible heat flux, ρ is the air density, c_p is the atmospheric specific heat coefficient, θ_s is the surface atmospheric potential temperature, V_a and θ_a are the horizontal wind speed $\left((u^2+v^2)^{1/2}\right)$ and potential temperature of the near surface atmosphere, usually taken at a height of 10 m. ψ_m and ψ_h are the Monin Obukhov similarity functions ϕ_m and ϕ_h, respectively.

$$C_D=\begin{cases} (-0.0001U^2+0.0021U-0.0057) \\ \left(1-3.227R_i-1.014R_i{}^2\right), & R_i\leqslant 0, \\ (-0.0001U^2+0.0021U-0.0057)e^{(-9.885R_i)}, & R_i>0, \end{cases} \tag{6}$$

$$C_H=\begin{cases} (0.000005T^2-0.00005T+0.0009) \\ \left(1-9.133R_i+6.667R_i{}^2\right), & R_i\leqslant 0, \\ (0.000005T^2-0.00005T+0.0009)e^{(-9.042R_i)}, & R_i>0, \end{cases} \tag{7}$$

In the above equations, U and T represent the 2 m horizontal wind speed and temperature, respectively. These newly constructed parameterized relationships not only avoid the calculation of roughness length, but also solve the problem of poor reliability in previous non-iterative schemes.

2.4.3 A new parameterization scheme for multi factor and multi-scale dynamic roughness has been developed

The traditional theory holds that aerodynamic roughness is only related to the geometric characteristics of the Earth's surface. However, the research shows that the influencing factors of aerodynamic roughness are relatively complex. It is not only related to the geometric properties of the underlying surface, but also is affected by various factors such as the dynamic and thermal conditions of the near surface atmosphere, the natural growth cycle of vegetation, and the disturbance of vegetation caused by changes in climate elements (Li H Y et al., 2012; Zhang Q et al., 2015b). Based on the above understanding, we have constructed a parameterization scheme for the dynamic roughness (Z_0) over the underlying surface of semi-arid natural vegetation in northern China, which includes the combined effects of multiple factors such as atmospheric thermodynamic characteristics in the near surface layer, vegetation growth patterns, interannual variability of precipitation, and ecological effects (eq. (8)). The scheme is expressed as

$$z_0=\begin{cases}\overline{z}_0\times 2.07\times\left[\left(0.67+0.57\sin\left(\dfrac{\pi}{11}(t-1)\right)\right)\right. & \xi>0,\\ \left.\times\left(1.14-0.06\mathrm{e}^{-d\frac{u^2-\overline{u}^2}{u^*}}\right)\right]/\,1+8.25\xi, & \\ \overline{z}_0\times 2.07\times\left(0.67+0.57\sin\left(\dfrac{\pi}{11}(t-1)\right)\right) & \xi\leqslant 0,\\ \times\left(1.14-0.06e^{5.2(1-B_e)}\right)\mathrm{e}^{\left(3.93\xi-d\frac{u^2-\overline{u}^2}{u^*}\right)}, & \end{cases}\tag{8}$$

where t is the annual cycle time (month), u^2/u^* and $\overline{u}$ are the comprehensive dynamic parameters and climatic average wind speed (m s^{-1}), ξ is the thermal stability parameter, and d is the vegetation characteristic parameter, which characterizes the response of vegetation to wind speed and is mainly related to vegetation type.

In addition, the study also found that the aerodynamic roughness in this region has an obvious characteristic of annual variation, and significant changes in vegetation height, density, and leaf area index during the growing season will also cause large differences in roughness. Therefore, the normalized roughness Z_0/Z_a is derived, in which Z_a is the aerodynamic roughness, and Z_a is the average roughness of each year. Parameterization of the annual variation of the normalized roughness is expressed by eq. (9), in which t and ω_d are time and wind direction in months, respectively (Yao et al., 2014).

$$\frac{Z_0}{Z_a}=\begin{cases}0.3691-0.0021\sin\left[\dfrac{\pi}{11(t-1)}\right],\\ 112.5^\circ<\omega_\mathrm{d}<157.5^\circ\\ 1.4218+2.0303\sin\left[\dfrac{\pi}{11(t-1)}\right].\\ 270^\circ<\omega_\mathrm{d}<337.5^\circ\end{cases}\tag{9}$$

2.4.4 A drought stress model for agricultural evapotranspiration has been developed

Due to the lack of direct, long-term and operational observation methods for ET, many ET estimation models based on ET_0 and crop coefficient (kc) have been established in recent years (Doorenbos and Pruitt, 1984). However, these models are not very effective in the severely drought stressed northern regions of China. Studies of spring wheat ET in water stressed areas of northern China suggest that ET in this region is highly dependent on drought stress and exhibits a significant response pattern. There is a strong exponential correlation between ET and drought stress, and kc is highly sensitive to drought stress especially when drought stress is less than 0.7. Based on this result, we have established a parameterized relationship between ET and kc in farmland with the consideration of drought stress (Equation (10)). The estimated ET based on this parameterized relationship is consistent with the actual observed ET, and the relative error is significantly reduced (Figure 13). The above result is much better than that of the model recommended by the International Food and Agriculture Organization (FAO) (Zhang Q et al., 2019d; Yang et al., 2014).

$$\mathrm{ET}=-0.9\ln(R_{aw}+0.1)k_{\text{c-FAO}}\times\mathrm{ET}_0,\tag{10}$$

In eq. (10), them, $k_{\text{c-FAO}}$ is the kc (Allen et al., 1998) recommended by the Food and Agriculture Organization for various crops, $k_{\text{c-obs}}$ is the observed crop coefficient, R_{aw} is the relative effective water quantity.

2.5 Characteristics of Land Surface Energy and Water Imbalance

2.5.1 The Causes of non-closure of Land Surface Energy have been revealed

A large number of field experiments on land surface processes have found a 10%–30% difference between available surface energy and turbulent heat flux, which is called the land surface energy non closure phenomenon (Foken et al., 2010; Xu et al., 2017). However, no consensus has been reached regarding the reasons for this non closure phenomenon (Wilson et al., 2002). Based on analysis of the distribution characteristics of land surface energy non closure phenomenon on the Loess Plateau in northern China, found that there is a good correlation between land surface energy non closure and vertical advection of sensible heat flux as well as soil thermal storage term. The maximum average values of vertical advection of sensible heat flux and soil thermal storage can exceed 25 and 65 W m^{-2}, respectively. Trends in their changes are often consistent with land surface energy non closure (Zhang and Li, 2010; Li et al., 2010). By adding these two items, most of the underestimation of surface effective energy can be corrected, and the land surface energy closure can be increased from 0.78 to 0.94 (Figure 14) (Zhang et al., 2012a). Zhang and Li (2010) studies have also found that the ascending motions in the near surface layer caused by the gully terrain on the Loess Plateau

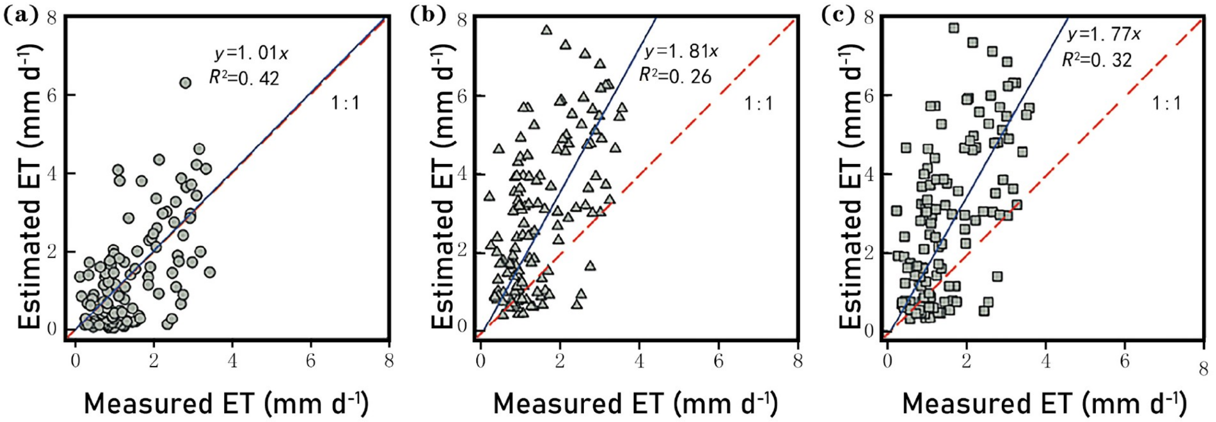

Figure 13 Comparison of correlations between ET estimates and ET observations using (a) improved parametric relationship, (b) Kumar and (c) FAO Recommended Crop coefficient (kc) (adapted from Zhang Q et al., 2019d).

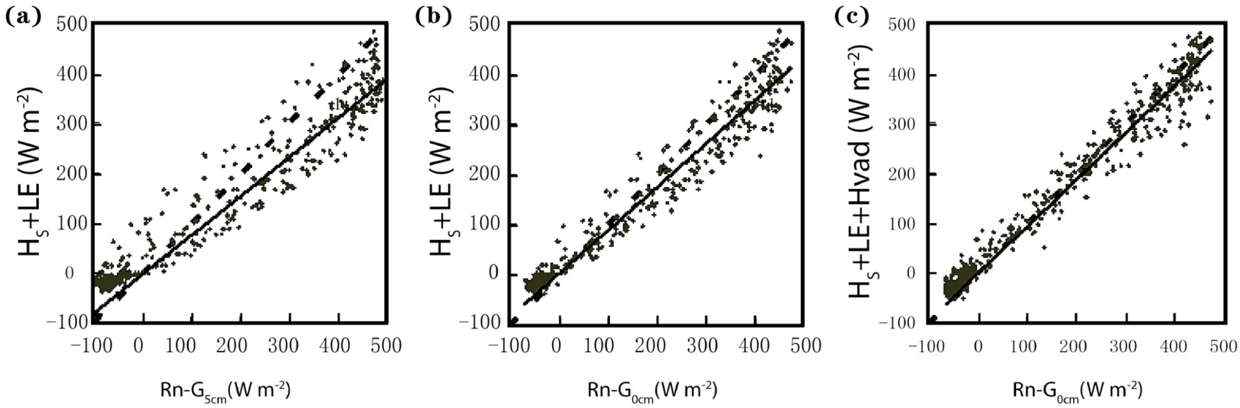

Figure 14 Comparison of surface available and effective energy before improvement (a), after introduction of heat storage term (b), and after introduction of both heat storage term and vertical advection term of sensible heat flux (c) (revised from Li H Y et al., 2012).

provides the dynamic condition for the formation of vertical advection of sensible heat flux, and the strong temperature gradient in the near surface layer in the northern region is the energy basis for the generation of vertical advection of sensible heat flux.

2.5.2 The contribution of non-precipitation land moisture to water balance and crop growth has been revealed

Unlike the widely studied problem of land surface energy imbalance, the issue of land surface water imbalance has received little attention. In fact, Zhang Q et al. (2015a) have also found in our observational experiments in northern China that precipitation is always less than actual evapotranspiration and accounts for only 85% of land surface evapotranspiration. Thereby, there is a significant land surface water imbalance phenomenon, which is mainly due to the lack of consideration of the contribution of non-precipitation water (NRW) on the land surface in traditional surface water balance studies. Our research shows (Zhang Q et al., 2019b) that for the 15% imbalance of land surface moisture in the semi-arid region of northern China, non-precipitation moisture accounts for 10.4%, while dew (Dew) and adsorbed water (WAV) account for 5.0% and 5.1%, respectively (Figure 15). The remaining 4.6% imbalance may be related to climate warming and drying, as well as observational errors. Compared with natural precipitation, NRW occurs almost year-round and has strong seasonal complementarity with precipitation. It makes a special contribution to crop growth in the semi-arid region of northern China, especially during non-monsoon periods, its contribution exceeds twice that of precipitation. NRW can provide the major water source for winter wheat during its primary growth period and for spring wheat during certain parts of its growth period (Zhang Q et al., 2019b).

2.6 Spatiotemporal characteristics and formation mechanisms of atmospheric boundary layer

2.6.1 The characteristics of super thick convective boundary layer in summer over the arid region of northern China have been discovered

Classic literature suggests that the thickness of the con-

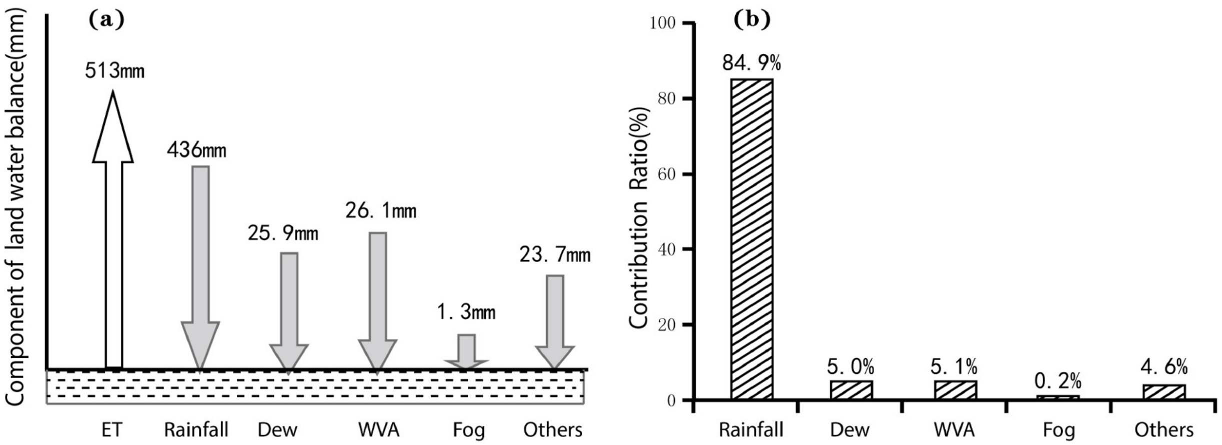

Figure 15 The semi-arid region of northern China (a) the budget of surface liquid water and its ratio to (b) ET. (Cited from Zhang Q et al., 2019b).

vective boundary layer (CBL) is generally between 1 km and 2 km. In northern China, the surface is relatively dry and the solar radiation is strong. In summer, the ground heats up rapidly, and the development of CBL is relatively unique. At the beginning of the 21st century, we conducted several atmospheric boundary layer observational experiments in the arid northwestern region of northern China and found (Zhang et al., 2004; Zhang, 2007) that the features of the CBL thickness are very unique in the extremely arid areas, i.e., Dunhuang desert and Gobi desert, in the sunny days of summer. The CBL can break through the inversion cap at around 9am and reach the residual layer, where the condition is favorable for convective development. Since this time, the CBL will rapidly develop, and its thickness can exceed 4 km by 13pm (Figure 16). This deep CBL structure actually challenges traditional scientific knowledge. The development process of the ultra thick CBL indicates that whether the daytime CBL can break through the nighttime inversion layer is critical for the formation of an ultra thick CBL (Wang R et al., 2020). Further research has also revealed that the ultra thick CBL structure observed in arid regions is closely related to the significant atmospheric heating effect caused by surface sensible heat flux generated by strong solar radiation and dry soil environment (Zhang et al., 2007, 2009b).

2.6.2 Staircase-like spatial distribution characteristics of boundary layer height in the northern region of China have been discovered

The significant spatial differences in surface thermal processes caused by geographical distribution and monsoon activities will inevitably lead to spatial variations in the atmospheric boundary layer (ABL) height. Qiao et al. (2019) studies on the spatial distribution of ABL in northern China suggest that from an arid region to semi-arid region and on to a humid region, the ABL height exhibits a significant staircase-like distribution characteristic (Figure 17a). Among them, the stable boundary layer thickness (SBL), the residual layer (RL) top height, and the CBL thickness decrease by 58.3%, 28.5%, and 25.6% respectively from arid to semi-arid regions, while they decrease by 41.8%, 75.5%, and 81.8% respectively from semi-arid to humid regions. In the climate transitional zone, the ABL height also shows a staircase-like steep drop phenomenon. Further comparative studies have been conducted from the perspectives of the thermal condition (e.g., ground temperature difference) for the development of thermal convection in the ABL over different climate zones, the original source for turbulence development (e.g., surface net radiation), and the heat maintenance mechanism for convective development (e.g., near surface sensible heat flux). It is found that from the northern arid region to the semi-arid region and then to the humid region, individual thermal factors also show a clear decreasing trend in sequence. Therefore, the spatial differences in land surface thermal states are the main driving factors for the staircase-like changes in ABL height in the northern region (Figure 17b). In fact, Wang et al. (2023) have also explored the reasons for the differences in ABL height between the northern monsoon region of China and other monsoon regions around the world and found that the changes in spatial patterns of land surface energy caused by monsoon precipitation are the dominant factors for the regional differences in ABL height between various monsoon regions.

2.6.3 The impact mechanism of the entrainment effect of residual layer energy on boundary layer development has been revealed

From the perspective of the energy mechanism for boundary layer development, the energy solely provided by surface sensible heat sometimes may not fully meet the energy requirement for the development of an ultra thick CBL. Research has found that in the arid regions of northern China, in addition to the effect of surface sensible heat, sufficient re-

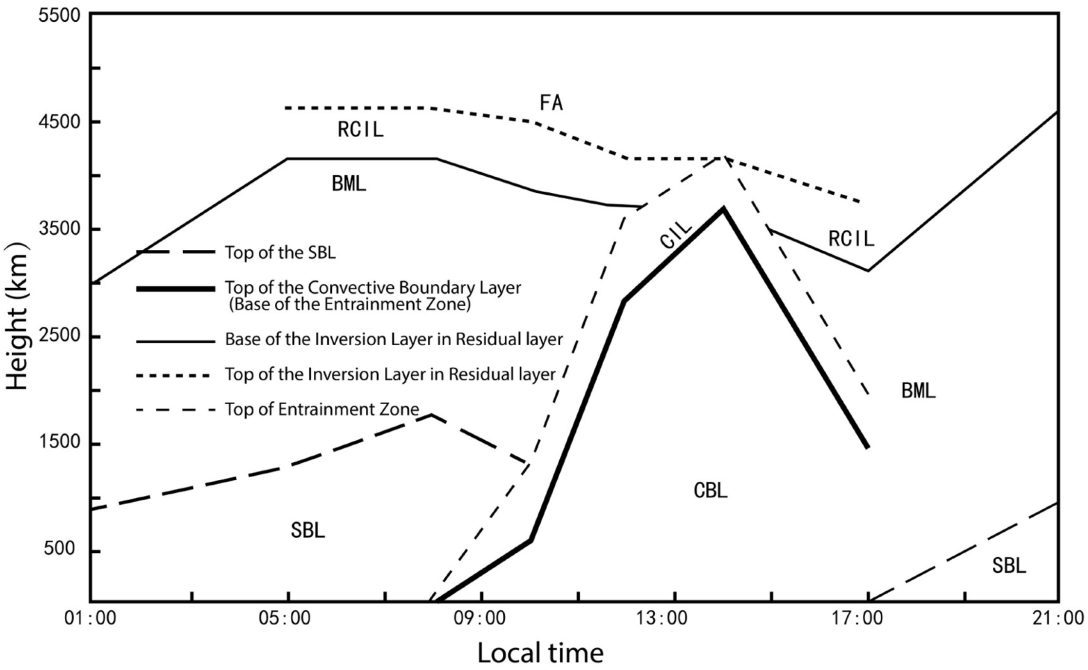

Figure 16 Daily variation of potential temperature structure in atmospheric boundary layer (ABL) over Dunhuang desert during typical sunny days of summer. FA, RML, CBL, SBL, CIL and RCIL represents the free atmosphere, residual mixing layer, convective boundary layer, stable boundary layer, top of the inversion layer, and top of the residual inversion layer, respectively (from Zhang and Wang, 2008).

sidual layer energy on sunny days can also provide important energy supplements for the development of an ultra thick CBL through the entrainment effect at the top of the ABL (Figure 18a). However, it is exactly under the premise of the great heating effect caused by strong sensible heat flux on the surface that a relatively deep CBL can develop and a nearly neutral RL can remain later, providing favorable energy supplementation for the development of CBL the following day. This process repeatedly occurs over multiple days, and the CBL will eventually develop into an ultra thick CBL. That is to say, the mechanism that promotes the growth of both CBL and RL is the positive feedback loop between them (Figure 18b), which can only be broken when precipitation or other weather processes occur (Zhang Q et al., 2019a). The above result has provided a new understanding of the mechanism for the ABL development.

2.6.4 *The main mechanism for turbulent motions in convective boundary layer has been revealed*

Turbulent motion is the primary form in and development mechanism for ABL. Zhang et al. (2022a) have recently validated the physical image of turbulent motion during the evolution of thick CBL in northern China based on numerical simulations and observation results. Strong turbulent motions can cause energy exchanges at multiple interfaces such as land surface and CBL, CBL and RL, and RL and free atmosphere (FA), and thereby provide a unique energy supply mechanism for the formation of deep CBL (Figure 19). The above understanding from another perspective confirms the positive feedback loop and growth mechanism between deep CBL and RL (Zhang et al., 2019c). Compared to shallow CBLs, in deep CBLs in northern China, thermal bubbles often undergo through convection in the mixed layer (ML), followed by two key stages: bubble overflow from the top of the CBL and bubble penetration through the RL. It is the strong turbulent motions and repeated energy exchange and replenishment between the interfaces inside the ABL that promote the development of deep CBL in the northern arid region.

2.7 Relationship between Land-Atmosphere Interaction and Weather and Climate

2.7.1 *Understanding the relationship between deep boundary layer thickness and sandstorm weather*

The northern region of China is one of the areas with the most severe sandstorms, which are not unrelated to the unique ABL structure in the region (Zhang et al., 2022a). Studies have shown that the specific effects of ABL on sandstorm weather are mainly manifested in three aspects: firstly, the vertical movement caused by strong dry convective activities contributes to the transport of sand and dust; secondly, the radiative forcing effect of abnormal sand and dust distribution within ABL strengthens wind speed and shear; thirdly, the relatively deep ABL structure is prone to trigger strong convective weather (Zhang and Wang, 2005; Zhang et al., 2011). Previous studies also found that CBL is thicker during periods of frequent strong sandstorms, gen-

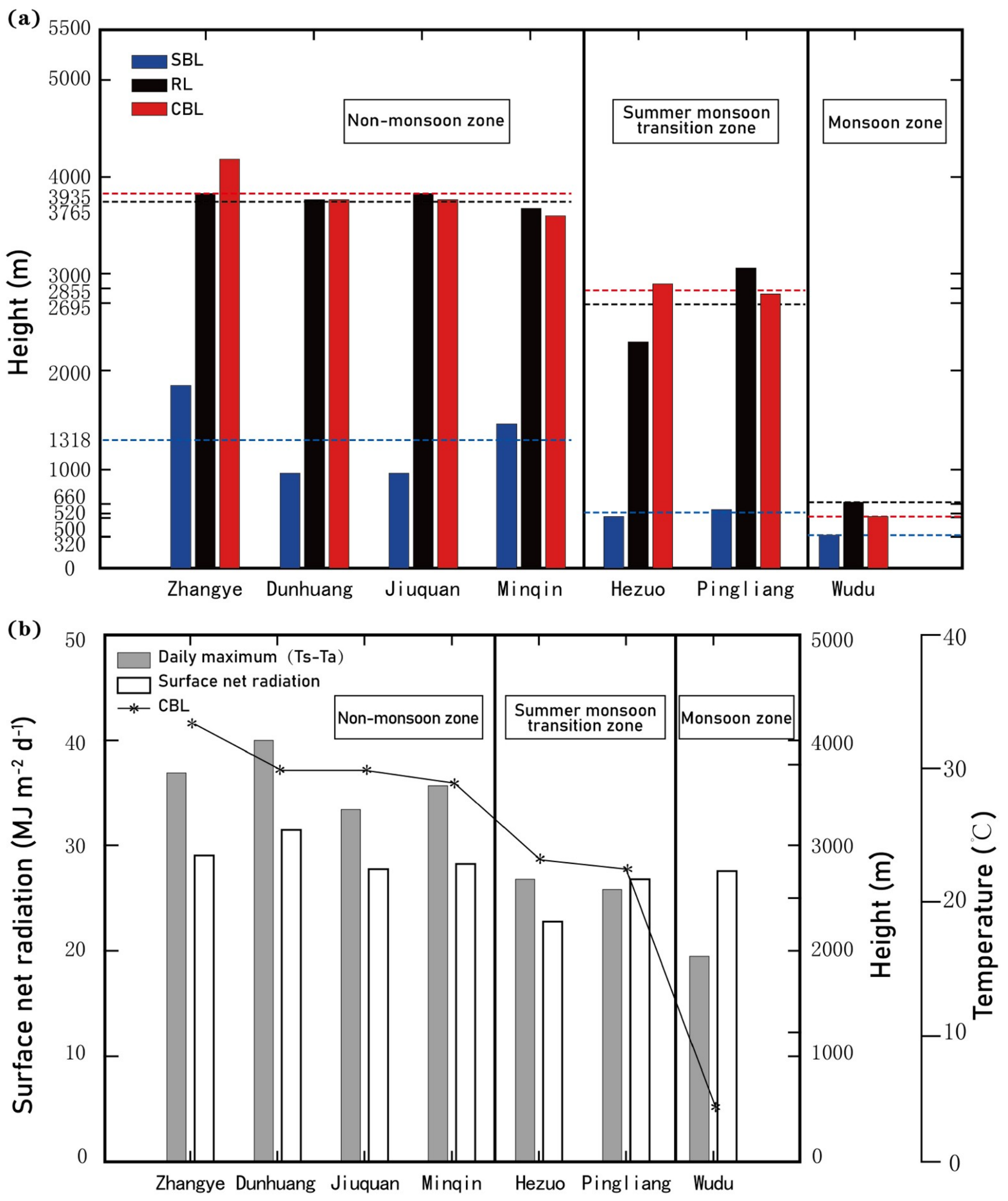

Figure 17 (a) Comparison of mean ABL height, (b) comparison of net surface radiation, maximum daily land-atmosphere temperature difference and CBL thickness over typical arid and semi-arid areas of northern China and humid areas of southern China in summer (modified from Qiao et al., 2019).

erally reaching around 3 km (Figure 20). At the same time, from the end of April to early May is the period when strong sandstorms occur frequently in northern regions, and it is also the period when deep CBL frequently forms (Li Y Y et al., 2011, 2019). The above scientific understanding provides guiding significance for predicting sandstorm weather.

2.7.2 The impact characteristics of land surface aridification on regional precipitation have been discovered

The aridification of land surface in the semi-arid region of northern China is relatively evident (Cheng and Huang, 2016), and the significant changes in land surface characteristics have an undeniable impact on regional weather and climate. Ren Y L et al. (2021) numerical study on changes in land surface characteristics in the semi-arid northern region and their impacts on summer precipitation shows that land desertification and aridification in this area have reduced summer precipitation by more than 50 mm in most areas, and local reductions can even reach 90–110 mm, which is about 15%–20% of the annual mean precipitation. The study also found that land surface aridification not only affects precipitation, but also changes the nature of precipitation by reducing the probability of light rain and moderate rain but increasing the probability of rainstorm. The feedback relationship between land surface aridification and local precipitation (Figure 21) indicates that, on the one hand, land surface aridification reduces surface heat capacity, accelerates surface temperature rise, increases SHF

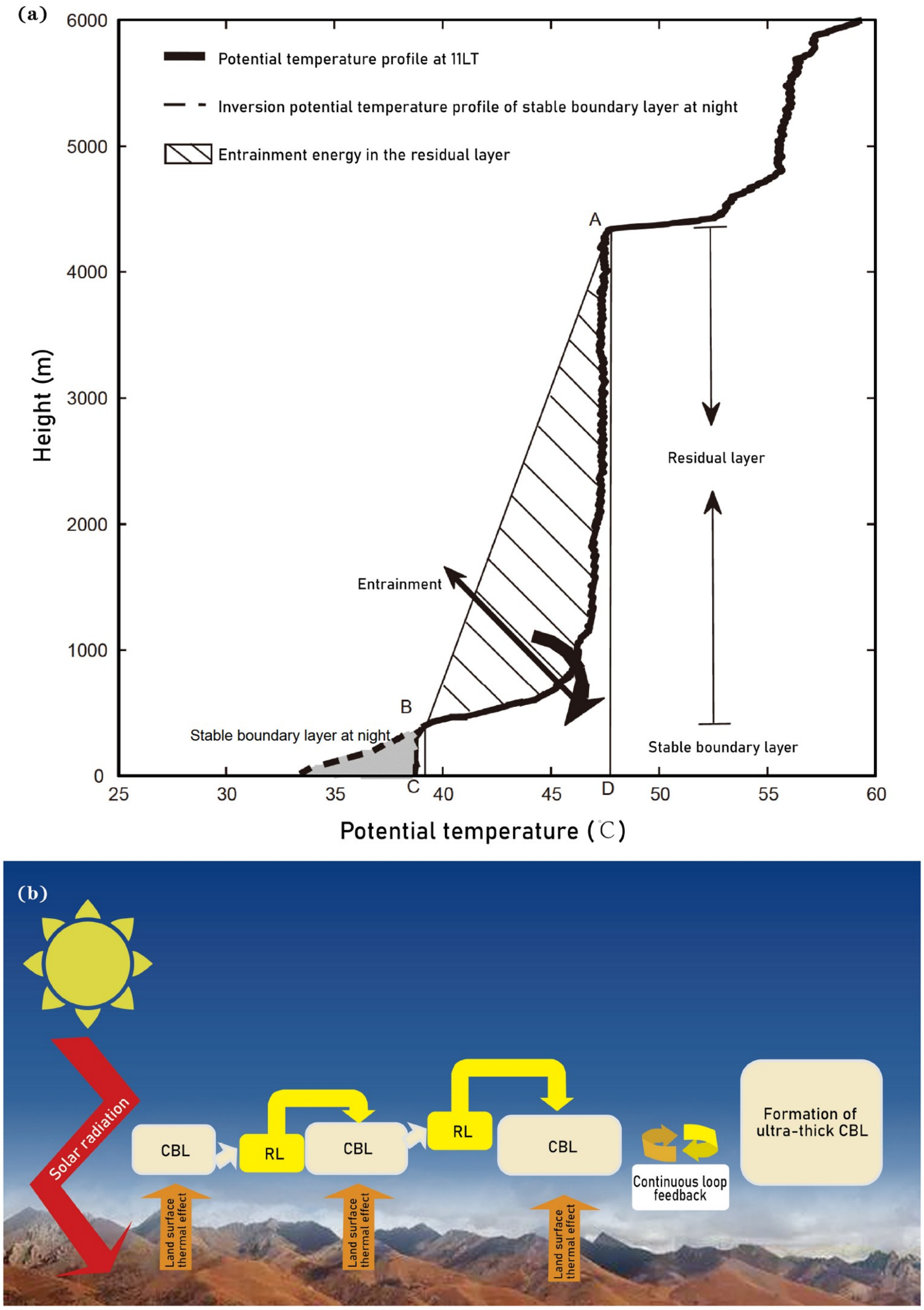

Figure 18 Arid and semi-arid regions in northern China (a) schematic diagram of the energy provided by the energy entrainment of RL for the development of CBL, where the thick solid line is the potential temperature profile at 11LT, the dashed line is the inverse potential temperature profile of SBL at night, line segment AB is the ideal inverse potential temperature profile without RL, and the oblique line area is the energy entrainment region of RL. (b) Schematic diagram of the positive feedback loop between CBL and RL and their impacts on the formation of ultra thick CBL (adapted from Zhang et al., 2019c).

transported from the surface to the atmosphere, thickens ABL, reduces atmospheric wet static energy, decreases atmospheric precipitation, and further exacerbates the degree of aridification; but on the other hand, surface aridification enhances the gradient of surface vegetation landscape, increases the gradient of surface albedo, and causes more uneven ground heating, leading to an increased likelihood of strong convection. In fact, other research also shows that whenever the thickness of the mixed layer exceeds 3 km or the cumulative SHF exceeds 2000 W m^{-2}, the probability of convective precipitation exceeding 17 mm the next day is significantly higher (Zhang and Zhang, 2017).

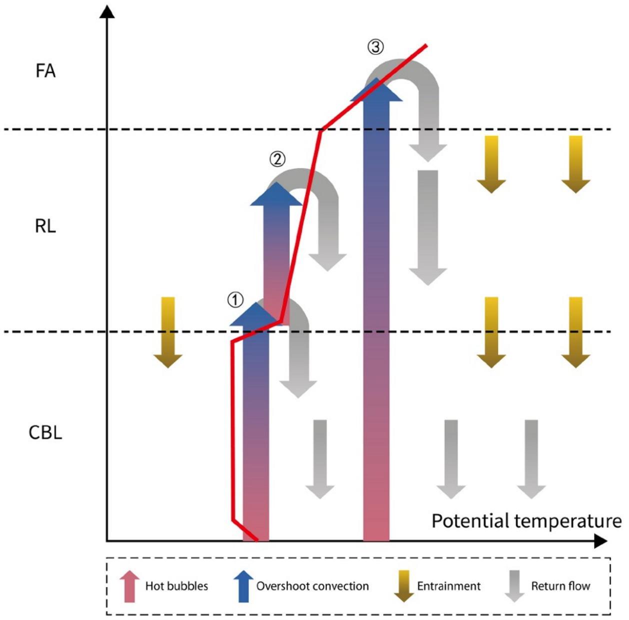

Figure 19 Schematic diagram of turbulent motion in the ABL over northern China. The red solid line represents temperature contour; the numbers represent different ABL processes: ① Through convection; ② Hot bubbles overflow from the top of the CBL, reach the RL, and return; ③ Hot bubbles penetrate the RL, reach the FA, and return to the CBL (from Zhang et al., 2022a).

2.7.3 The teleconnection mechanism of land-atmosphere coupling on extreme droughts in northern regions has been presented

Droughts in northern China are not only related to local land-atmosphere interaction, but also under the influence of teleconnection of upstream land-atmosphere coupling (Wang et al., 2019; Zeng et al., 2019). In fact, Research has found that an increase in kinetic energy in the North Atlantic, Europe, and the Mediterranean can cause changes in the position and intensity of the westerly jet streams, leading to an increase in atmospheric baroclinicity as well as the transfer of buoyancy and vertical kinetic energy from the lower troposphere to the upper atmosphere in Europe and the Mediterranean. At the same time, the diabatic heating over Europe caused by surface heat anomalies can contribute to the westward extension of the westerly jet stream, resulting in stationary Rossby wave anomalies and exacerbating the decadal drought process in the northern region of China (Figure 22). The land-atmosphere interaction in this region plays a key role in drought maintaining and development (Zhang et al., 2019a, 2019b, 2021). This is a more comprehensive understanding of the relationship between land-atmosphere coupling and drought on different spatial scales.

2.7.4 The relationship between the dryness of the climate in northern China and the position of the northern edge of summer monsoon has been revealed

Although the climate in northern China is significantly influenced by the Asian summer monsoon, the correlation between the dryness of the climate and the intensity of the summer monsoon in the region is not always significant (Hu and Qian, 2007). Zhang H L et al. (2016) research indicates that compared with the summer monsoon index, the position and advance/retreat process of the northern edge of the monsoon are more appropriate for expressing the relationship between monsoon the dryness of the climate in this region (Figure 23). The drying trend in the northern semi-arid region is distinctly related to the southward retreat of the northern edge of the monsoon (0.24° $(10\ \mathrm{yr})^{-1}$), especially in the Loess Plateau region. The increase in the dryness index of 0.11/10 yr corresponds better to the southward retreat

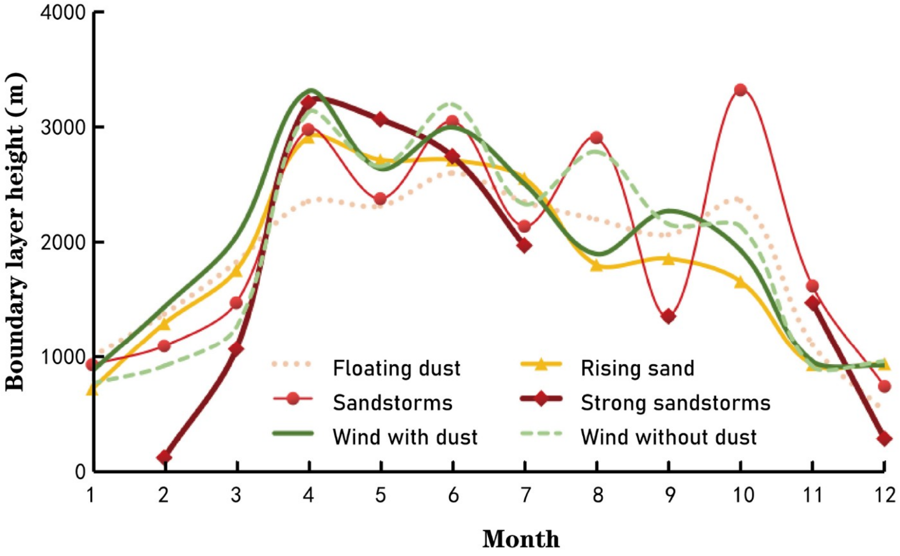

Figure 20 Monthly distribution of different aeolian sand intensities corresponding to boundary layer height over Hexi area in northern China (adapted from Li Y Y et al., 2019).

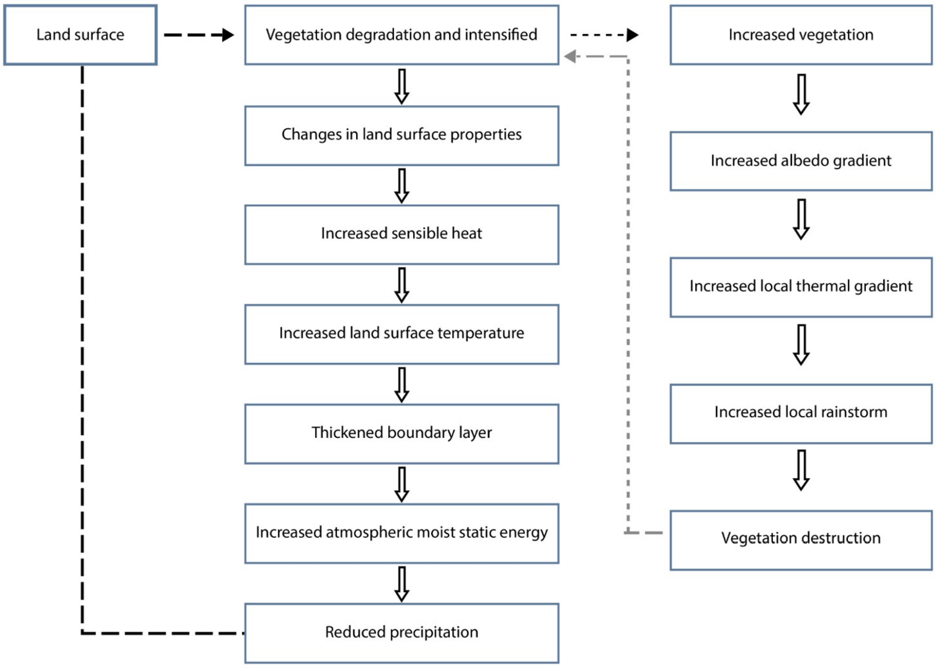

Figure 21 Mechanism for the influence of land surface aridity on precipitation changes in northern China (adapted from Ren Y L et al., 2021).

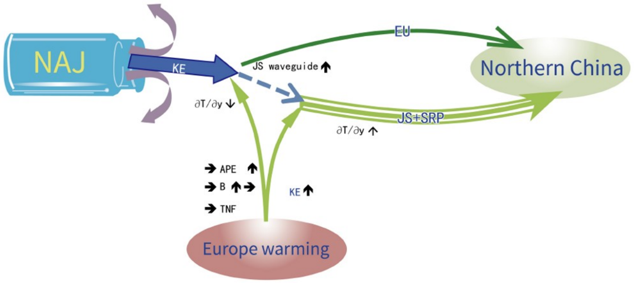

Figure 22 Schematic diagram of the effects of surface warming processes in Europe and the North Atlantic *SST* pattern on the jet stream and baroclinicity, which result in seasonal kinetic energy conversion; and the effect of low-frequency waves on stationary wave amplitudes, which affects the physical processes of drought in northern China. JS and KE represents jet stream and seasonal kinetic energy; EU and SRP are low frequency waves; NAJ, B, TNF and $\partial T/\partial y$ represents the North Atlantic jet stream, the baroclinic energy converted to seasonal KE, the wave activity flux, and the zonal temperature gradient, respectively (Cited from Zhang et al., 2021).

trend of the northern edge of the monsoon (0.28° $(10\ \mathrm{yr})^{-1}$). When the edge of the summer monsoon abnormally advances to the northernmost point and retreats abnormally early, abnormal drought events may occur in the Loess Plateau region. This undoubtedly provides important guidance for major drought prediction.

3. Prospect of future research directions

In recent decades, domestic research institutes in China have conducted extensive research and scientific experiments on land-atmosphere interaction, characteristics and mechanisms of land-atmosphere interaction, parameterization of land surface processes and boundary layers, and the impact of land-atmosphere interaction on weather and climate in northern region of China (Bao and Lv, 2006; Lin et al., 2008; Liu H Z et al., 2018; Guan et al., 2018; Ma et al., 2021; Zhou et al., 2024; Chen et al., 2024). This paper summarizes some new research progress has been made in this field since, for example, the establishment of a comprehensive observational and experimental system for land-atmosphere interaction in northern China, the spatiotemporal variation laws of physical quantities of land surface processes, the response characteristics of land surface evapotranspiration to climate warming, land surface process parameters and their parameterization schemes, land surface energy and water imbalance phenomena, the spatiotemporal variation characteristics and mechanisms of atmospheric boundary layer, and the relationship between land-atmosphere interactions and weather and climate, etc. However, the northern region of China is highly sensitive to climate change, and it is under significant influences of monsoon, while the atmospheric circulation evolution is quite active in this region. Meanwhile, the land-atmosphere interaction is unique in this region and the relationships between land-atmosphere interaction and the three features mentioned above are complicated. Thereby, there is still a significant gap between the research results of land-atmosphere interaction in this region and the ability to effectively solve core operational and technical problems of weather forecast, climate prediction, artificial weather modification, climate change assessment,

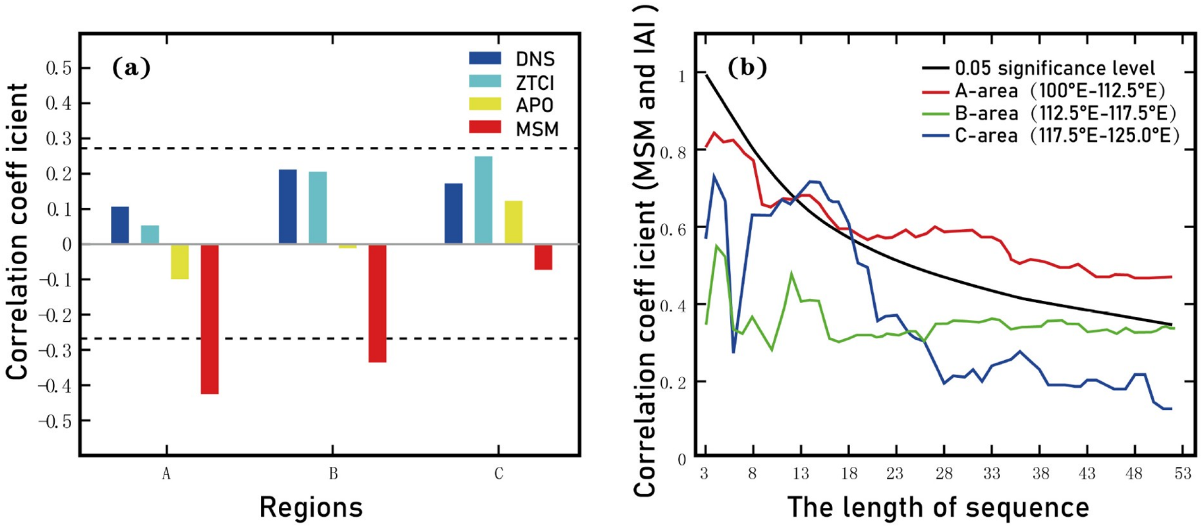

Figure 23 The semi-arid region of northern China (a) correlation coefficient between the drought index and the East Asian Summer monsoon index on an interannual scale (trends and interdecadal signals have been eliminated). (b) Changes in correlation coefficient between drought index and East Asian summer monsoon index. DNS, ZTCI, APO and MSM represents Dynamic Normalized Seasonal Index, East Asian Summer Monsoon Intensity Index, Asian-Pacific Oscillation and Northmost edge index of East Asian summer monsoon, respectively (adapted from Zhang H L et al., 2016).

and numerical model development, etc. The study of land-atmosphere interaction still faces many difficulties and challenges. Based on research progress in the past and current international trends, six research directions that need to be focused on in the future have been preliminarily summarized.

3.1 A new comprehensive operational observation system for routine observations and experiments of land-atmosphere interaction in northern region of China should be developed

The comprehensive observational and experimental system for land-atmosphere interaction established in northern China has obtained the preliminary ability to conduct comprehensive observations of multiple factors and experiments on ideal weathers and land-atmosphere interactions in certain layers (Lv et al., 2002; Hu et al., 2004; Lv, 2004; Xu and Chen, 2006; Huang et al., 2008; Li X et al., 2012; Liu et al., 2013; Zhao et al., 2018; Ma et al., 2020). However, its observational and experimental capabilities for the coupling processes of energy, hydrology, ecology, and strong weather processes in the multi-sphere system of the Earth as well as land-atmosphere interaction are still insufficient. In recent years, with the increasing application of high tech approaches and methods in land-atmosphere observational experiments, interdisciplinary and multi-scale coupled research on land-atmosphere interaction has become possible (Ma et al., 2021). Therefore, in future observational experiments, it is more important to fully utilize those new, rapidly developing and comprehensive operational observation systems such as GPS/Beidou sounding system, wind profile radars and lidars to improve the fine observation capability of the boundary layer (Li et al., 2024; Zhu et al., 2024). Meanwhile, it is also necessary to utilize the collaborative observation capabilities of the National Climate Observatory and the Ecological Meteorological Observation System for land surface water and heat fluxes, physiological and ecological processes, and soil moisture (Zhou et al., 2024). Microwave radiometers, Ka band radars, micro rain radars, dual polarization phased array radars, cloud radars, airborne detection, etc. should also be continuously developed to improve the real-time observation capability of weather processes such as sandstorms and severe convection (Liu et al., 2023; Cui et al., 2022). Based on the above work, a cloud platform and large database for rapid integration and historical case retrieval of multiple observation data fusion can be constructed to better support scientific research on the fine characteristics and underlying mechanisms of land-atmosphere interaction under different weather and climate conditions, including multi-sphere interactions and multi-process coupling.

3.2 The understanding of multi-interface exchange processes in land-atmosphere interaction should be improved

In recent years, a relatively clear understanding of the mechanism of land-atmosphere interaction in northern China has been achieved from the perspective of land surface energy and material exchanges (Bao and Lv, 2006; Ren X Y et al., 2021). However, in reality, land-atmosphere interaction not only involves land surface energy and mass exchanges, but also includes the transport process of ABL, interface exchanges between ABL and RL tops, interface exchanges between CBL and stratosphere, and interface exchanges between clouds and environmental atmosphere. All these processes are within the category of land-atmosphere interaction (Lu and Xu, 2021). Essentially, land-atmosphere interaction should be realized through the exchanges of mass, energy, and momentum at multiple interfaces and multiple stages of transport. In northern China, the thermal heterogeneity caused by the nature of underlying surface and the dynamic heterogeneity caused by complex terrain are very significant (Hong and Wang, 2010), and the sensitivity of land surface processes caused by dry environment will also cause rapid changes in the exchanges of land surface mass, energy and momentum (Yang et al., 2015). As a result, the multi-interface exchanges and multi- link transport become more prominent in land-atmosphere interaction, which is very likely to induce local micro-and meso-scale circulations (Figure 24), which subsequently affect the formation and development of droughts, rainstorms, hail and other disastrous weather (Ren et al., 2020). At present, our scientific understanding of above processes is quite limited. Therefore, in future research, it is necessary to strengthen the in-depth understanding of multi-interface exchange processes from land surface to ABL, and even between RL and FA and between CBL and stratosphere for the purpose to improve the physical description of key parameters such as turbulence exchange coefficient and entrainment flux ratio. At the same time, it is also necessary to extend the study of land-atmosphere interactions to the interaction between ABL and clouds, including the coupling between clouds and boundary layers (Koračin et al., 2000), the interaction between boundary layer turbulence and dynamics (Yeom et al., 2017), and the estimation of cloud entrainment rates in different cloud systems (Lu et al., 2016), and so on. Only by exploring details of multi-interface exchange processes, can we gain a deeper understanding of the essential characteristics and underlying mechanisms of land-atmosphere interaction in the region, and further improve the parameterization schemes in existing models.

3.3 The study of the multi-scale coupling mechanism between land and atmosphere should be strengthened

The modulation effect of land-atmosphere interaction on climate elements at multiple temporal and spatial scales is of great significance for predicting weather and climate changes, especially extreme events (Li Y H et al., 2021; Yuan et al., 2024). Land-atmosphere coupling can reflect the degree of surface influence on local and regional weather and climate (Chen, 2023; Wei et al., 2023). In fact, the land-atmosphere coupling involves a series of complex processes, including microscale, local small-scale, and regional mesoscale processes from the perspective of physics, as well as ground observation footprint scale, satellite pixel scale, model grid scale, and study area scale from the perspective of technique (Zhang et al., 2017a). On the time scale, there is

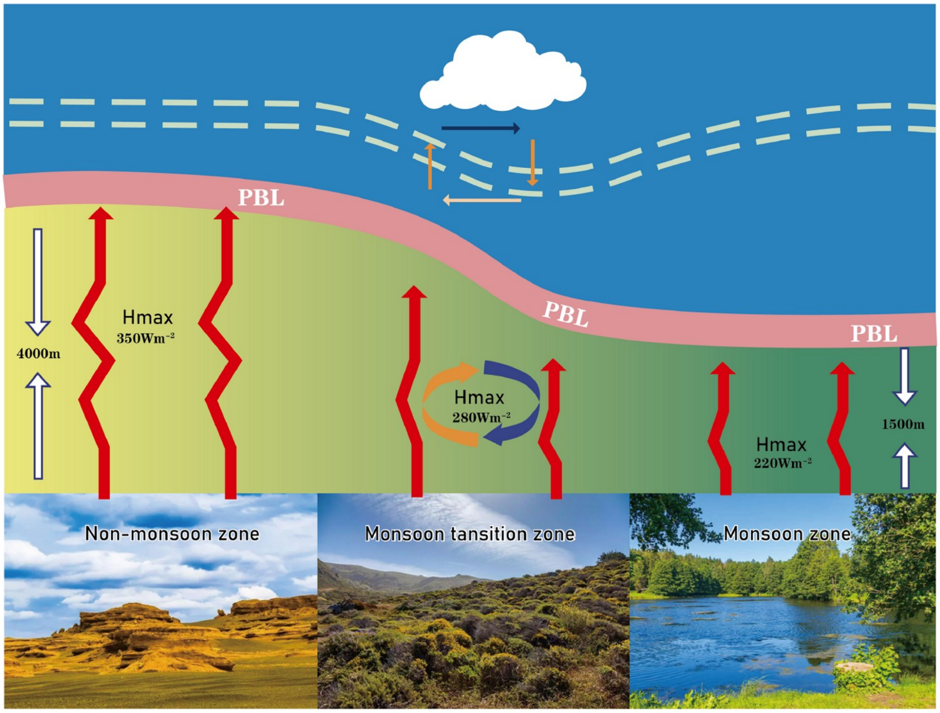

Figure 24 Schematic diagram of the influence of surface processes and convective boundary layer spatial variations on local atmospheric circulation in different climate zones. *H*max represents the maximum SHF based on half-hour data, PBL represents the planetary boundary layer (from Zhang et al., 2020).

coupling on the daily scale between surface radiation budget and boundary layer clouds through the land surface energy process and coupling on the seasonal scale between soil temperature and soil moisture through land surface evapotranspiration and boundary layer clouds as well as surface radiation balance. There is also coupling on the annual scale between solar radiation budget and vegetation through land surface radiation budget and aerosol processes (Betts et al., 1996) (Figure 25). The underlying surface in northern China is complex and diverse with a high spatial heterogeneity. The multi-scale characteristics of land-atmosphere coupling are more prominent. Previous studies have only gained some understanding of the feedback mechanism of land-atmosphere coupling from certain specific scales (Wang and Dickinson, 2013; Yang et al., 2022). However, the interaction between land and atmosphere often exhibits a complex multi-level and multi-channel cross coupling process through feedback loops among temperature, evaporation, humidity, and precipitation, and currently, there is a lack of understanding in this field. Therefore, future research in the field of land-atmosphere interaction should comprehensively and systematically explore the processes and mechanisms of land-atmosphere coupling on different scales, and avoid falling into the trap of “the blind man touching the elephant”.

3.4 Further studies are needed to deepen our understanding of characteristics of land-atmosphere interaction in special environments

In northern China, there are some special geographical environments such as the Qinghai-Xizang Plateau, the Gobi Desert, the Loess Plateau, the transitional zone between agriculture and animal husbandry, and large mountain ranges. Special weather and climate phenomena such as sandstorms and droughts often occur in northern China (Jiang et al., 2024). The dynamic and thermal effects of land-atmosphere interaction under these special environmental conditions are quite unique (Zhang et al., 2017a), and the structure of and transport processes in the ABL are also quite special. The surface heat source effect of the Qinghai-Xizang Plateau (Lai et al., 2021; Xu et al., 2023), the phenomenon of super thick CBL in desert area (Zhang et al., 2022a), the radiative forcing feedback mechanism of the windy and sandy boundary layer (Zhang et al., 2024), and the spatially steep drop characteristics of land surface flux and boundary layer thickness in the agriculture-pastoral transitional zone (Qiao et al., 2019) are just a few examples of the special features in northern China. It is found that these unique land-atmosphere interaction characteristics can not only cause special land surface evapotranspiration mechanism and atmospheric convection trigger factors, but also produce micro- and meso-scale circulations and some feedback mechanisms, which in turn have a cascading impact on the water and heat transport in the boundary layer and its atmospheric dynamic characteristics (Figure 26). As a result, it is easy to form unique extreme meteorological events such as droughts, sandstorms, local rainstorms, and hail (Cheng et al., 2023) under these special environmental conditions. At present, although the characteristics of land-atmosphere interactions are well understood in the typical environment in northern

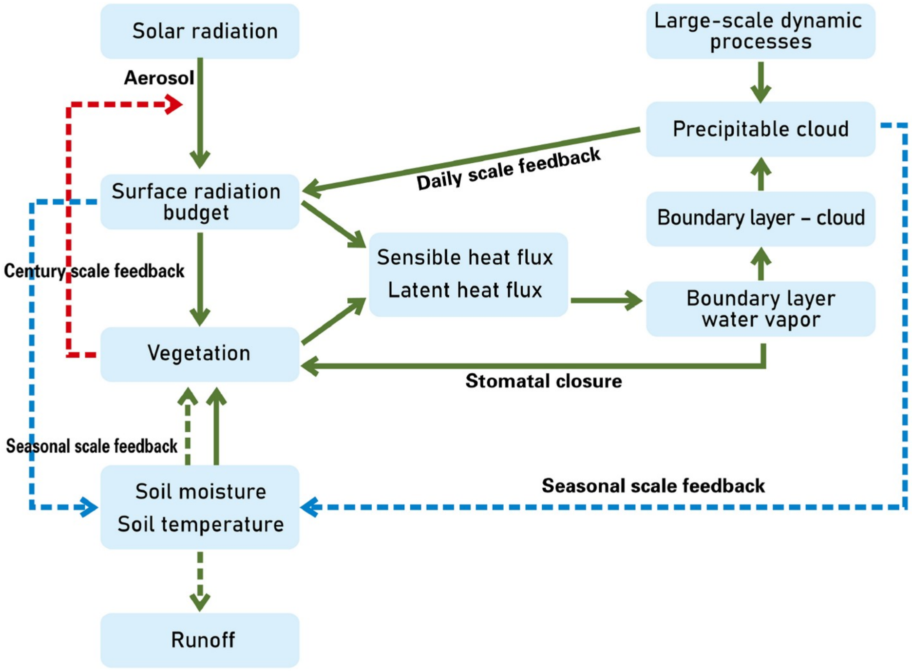

Figure 25 Schematic diagram of major land-atmosphere interaction processes at different time scales (modified from Betts et al., 1996).

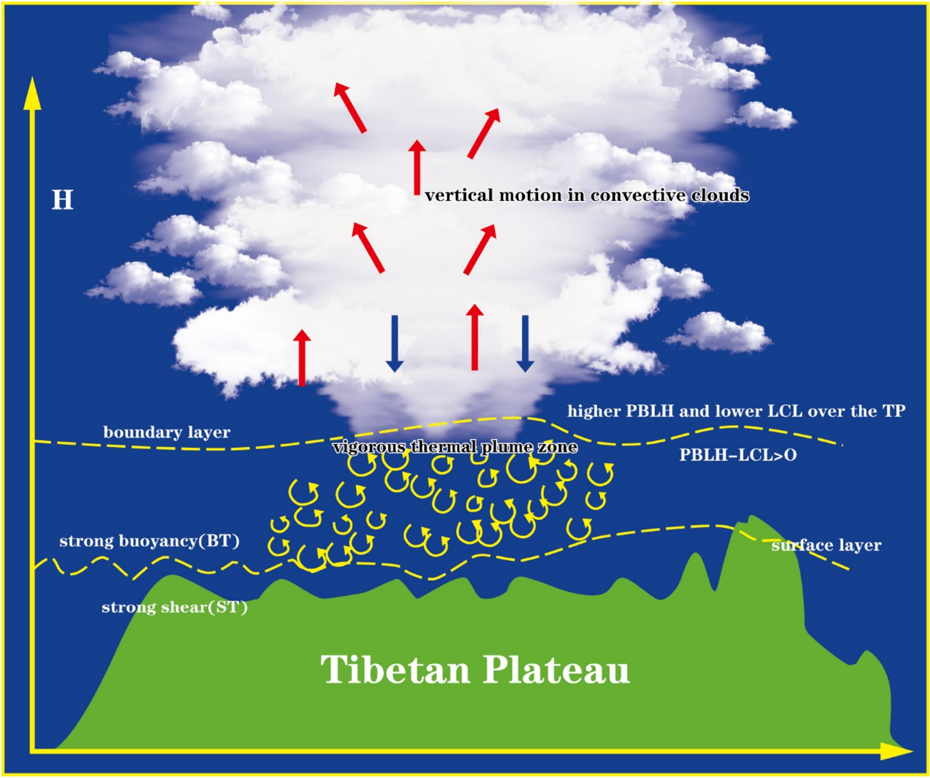

Figure 26 Schematic diagram of the "efficient" triggering mechanism of land-atmosphere interaction and convection over the Tibetan Plateau. The strong buoyancy and wind shear near the surface of the Qinghai-Xizang Plateau cause a higher boundary layer and a lower uplift condensation height, which, combined with the large-scale upward movement over the Qinghai-Xizang Plateau, lead to the transition from shallow clouds to deep convective clouds in the afternoon and evening (adapted from Xu et al., 2023).

China, there is still a lack of in-depth knowledge of land-atmosphere interaction under special geographical and meteorological conditions, which limits our understanding of the formation mechanisms of some special meteorological events such as sandstorms and droughts (Aitken et al., 2014; Sun et al., 2020). This is also one of the main reasons for those prediction errors in most of the numerical models (Zhao et al., 2017). Therefore, only through deepening our comprehensive understanding of land-atmosphere interaction and the mechanisms behind the interaction in these special environments, can we effectively improve our ability to better predict meteorological disasters.

3.5 The role of land-atmosphere interactions in extreme weather and climate events should be revealed

Global warming not only leads to more frequent extreme weather and climate events, but also makes these extreme events to exhibit characteristics such as group occurrence, persistence and complexity, which increase their unpredictability (Chen et al., 2024). Although both domestic and international scholars have done a lot of work trying to understand the formation mechanism and attributions of extreme weather and climate events (Nie et al., 2020; Neelin et al., 2022; Barriopedro et al., 2023), they still remain a difficult research topic in the field of global climate change. Research has found that extreme weather and climate events are not only related to oceanic forcing and human activities (Hsu et al., 2021; Wouters et al., 2022), but also modulated by land-atmosphere interaction (Schumacher et al., 2022). However, previous studies are more focused on the role of atmospheric circulations and frequently overlook the contribution of land-atmosphere interaction (Zhou et al., 2019). In fact, some studies have shown that in some special regions such as the climate transitional zone and the agriculture-pastoral transitional zone in northern China, land-atmosphere coupling is relatively strong, and its contribution to the formation and development of weather and climate events can sometimes be comparable to that of atmospheric circulations. In certain extreme cases, the impact of land-atmosphere coupling can even exceed the influence of atmospheric circulation (Seneviratne et al., 2006). Moreover, there exists both positive and negative feedback between certain land surface elements and weather and climate (Figure 27). As a result, the mutual feedback between heat, water, physiology, and ecology involved in the land-atmosphere process plays a crucial regulatory role during the process of meteorological disasters in this region (Zhang et

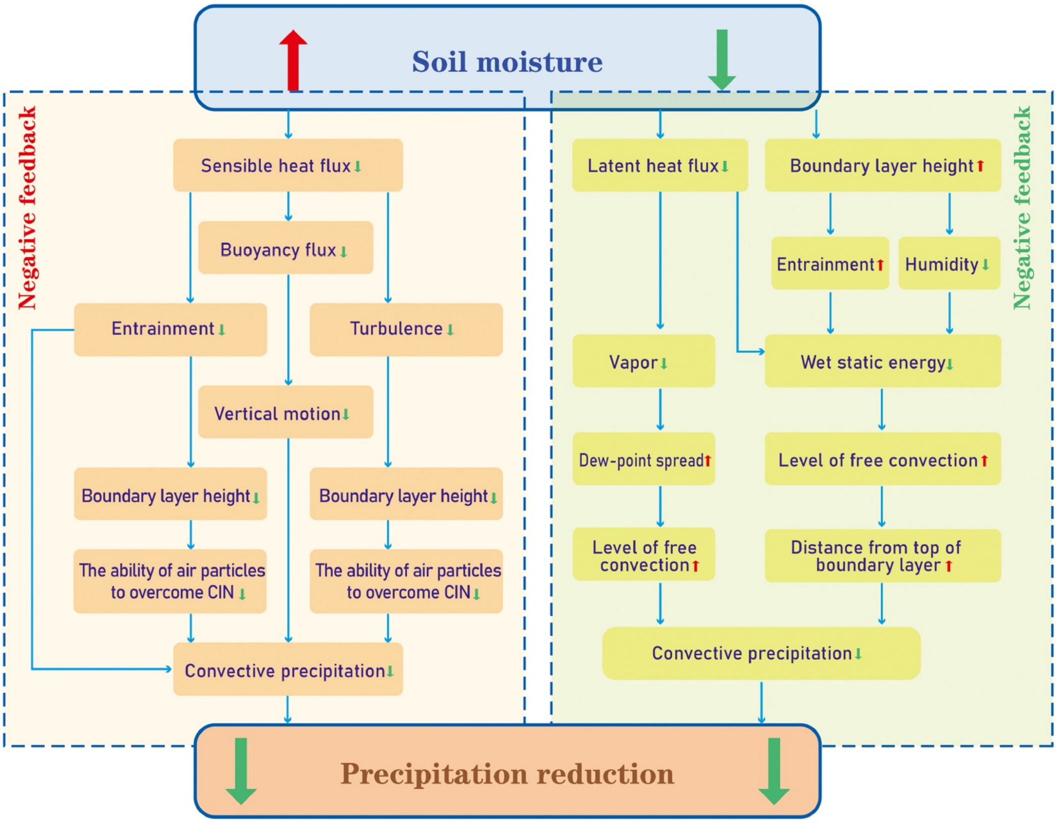

Figure 27 Schematic diagram of positive (negative) feedback mechanism between precipitation and soil moisture. The red arrow and the green arrow represent increase and decrease, respectively.

al., 2017b). Therefore, in the future, more emphasis should be placed on the connection between land-atmosphere interactions and extreme weather and climate events in the theoretical study of weather and climate prediction in northern China. The key physical processes and the unique role of land-atmosphere interaction in influencing extreme weather and climate events should be clarified, and new ideas should be proposed for the study in this field.

3.6 The multiple complex feedback mechanisms between land-atmosphere interaction and climate warming should be explored

Since the mid-19th century, the average global surface temperature has increased by about 1.26°C (Qiao et al., 2023). Predictions indicate that by the end of the 21st century, compared to the observed climate condition from 1980 to 2014, the climate will continue to warm due to the influence of "dry soil-hot climate" (Berg et al., 2016; Li K et al., 2019). Some studies have also found that the feedback relationship between climate warming and soil drying is nonlinear (IPCC, 2021; Zhang et al., 2023), and the "drying-heating" feedback loop between soil moisture and atmosphere is the main physical mechanism of land-atmosphere interaction that exacerbates surface warming, especially in the dry-wet transitional zone, where the warming effect is more significant (Qiao et al., 2023). In fact, from the perspective of mechanism, the impact of climate warming on extreme weather events is largely achieved through the feedback mechanism between land-atmosphere interaction and climate warming (Zhou, 2024). The response of land-atmosphere interaction to climate warming is almost reflected in all key components of the land-atmosphere interaction, and the response of each component to climate warming will almost always cause chain reactions in other components. Moreover, many factors in the land-atmosphere interaction process can respond to climate warming through multiple pathways, as well as through direct or indirect approaches (Santanello et al., 2017) (Figure 28). As an area sensitive to climate change and a hotspot for land-atmosphere interaction, the feedback effect between land-atmosphere interaction and climate warming in northern China can be more significant. This will not only accelerate the process of climate warming in the region, but also make the climate dynamics characteristics of land-atmosphere interaction more prominent. For example, in their responses to climate warming, dominant factors in land-atmosphere coupling such as land surface evapotranspiration are subject to complex constraints from both climate and environmental factors, and they may even exhibit completely opposite re-

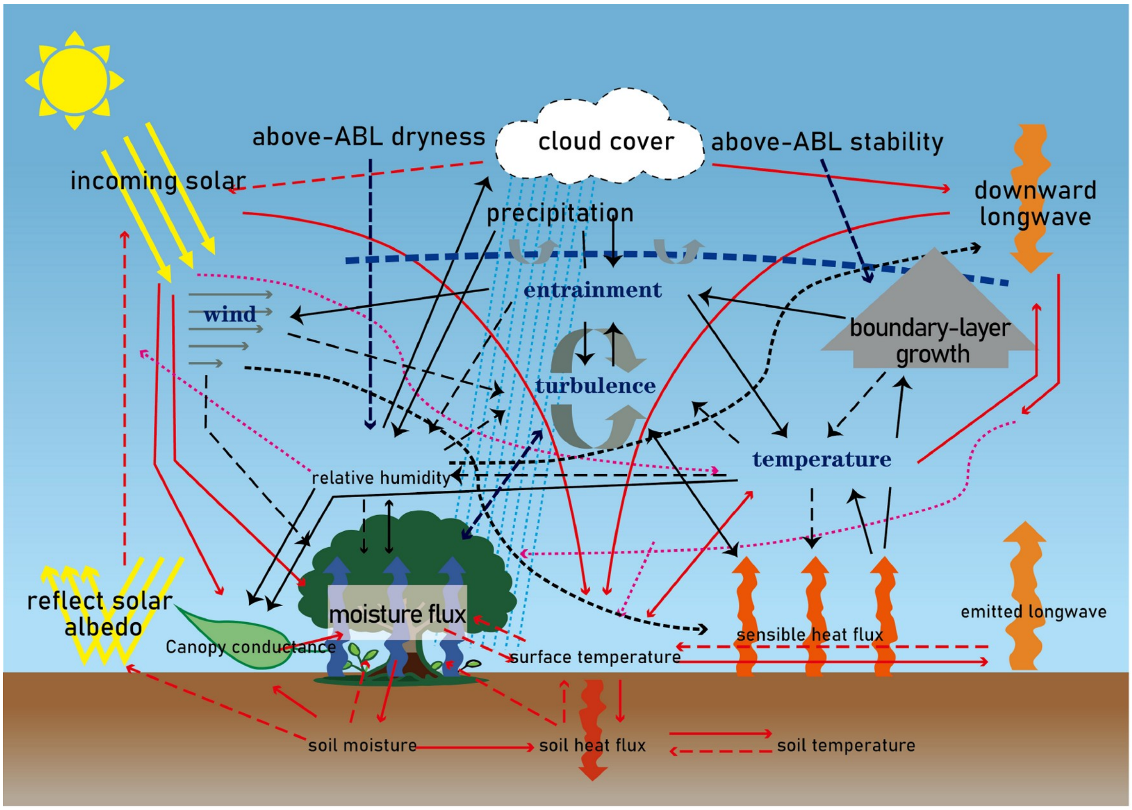

Figure 28 Multi-level and multi-channel cross-feedback relationship between land-atmosphere interaction and temperature and precipitation. The solid line indicates positive feedback, the dashed line denotes negative feedback, the red line represents the land surface process, and the black line represents the atmospheric process (adapted from Santanello et al., 2017).

sponse characteristics between different regions in northern China (Zhang et al., 2018). Therefore, in the current context of sustained climate warming, in order to provide scientific and reasonable response strategies for slowing down the rate of warming and reducing the adverse effects of warming, it is necessary to deeply explore multiple feedback relationships and impact mechanisms between land-atmosphere interaction and climate warming,

4. Conclusions

This article focuses on summarizing some important progress made recently by the Key Laboratory of Drought Climate Change and Disaster Reduction of China Meteorological Administration in the field of land-atmosphere interaction in northern China since the beginning of the 21st century. In fact, there have been numerous studies both domestically and internationally that have summarized many meaningful research achievements made by other teams in this area (Bao and Lv, 2006; Lin et al., 2008; Liu H Z et al., 2018; Guan et al., 2018; Ma et al., 2021; Zhou et al., 2024; Chen et al., 2024). Information included in these papers are not repeated here.

The study of land-atmosphere interaction in China began in the 1980s, and the first experimental study of land-atmosphere interaction (Hu and Gao, 1994) also began in the northern region of China (HIEFE). Back then, the research was mainly focused on understanding representative underlying surface land processes and atmospheric boundary layer characteristics. Since the beginning of the 21st century, following the international trend in this field, the study of land-atmosphere interaction in China has gradually emerged. At present, it has become an important component of many basic scientific research projects in basic Earth sciences. The study of land-atmosphere interaction in China has also focused on the recognition of long-term changes in land surface processes and atmospheric boundary layers, as well as their large-scale distribution characteristics. Moreover, in order to support the development of numerical atmospheric models, the research has focused on the development of land surface processes and atmospheric boundary layer parameterization schemes. Furthermore, we have gradually begun to explore the impact mechanism of land-atmosphere interaction on the formation and development of important weather and climate events, as well as its contribution to climate change.

In recent years, following the high-quality development of meteorology, new requirements have been put forward for breakthroughs in core technical issues of meteorological services, many of which are related to the interaction between land and atmosphere. For example, our understanding of the mechanism behind the restriction of land-atmosphere interaction on the accuracy of weather and climate forecasting is obviously not sufficient. However, the research on land-atmosphere interaction overall is still in the basic research stage, and there is still a long way to go to solve core operational and technical problems such as weather forecasting, climate prediction, artificial weather modification, climate change assessment, and numerical model development. The research on land-atmosphere interaction needs to continue to strive toward fundamental and technological applications. This requires the research of land-atmosphere interaction to go beyond the scope of classic analysis under ideal conditions and study of typical cases, and intentionally enter the field of real-data studies in real meteorological environments. It is necessary to deeply dissect and analyze the multi-level exchanges, investigate coupling processes between energy and hydrological and ecological cycles, and explore land-atmosphere interaction in the Earth system under special and complex conditions. The scientific understanding obtained through basic research should be closely combined with operational and technological innovations, so as to open up the channel for the continuous transformation of the study in land-atmosphere interaction from basic research to operational and technological applications. The objective is to make land-atmosphere interaction research not only a wonderful theory in books and papers but also a panacea in operational and technological systems.

Scientific research is essentially a process of understanding the world, which requires adherence to the laws of dialectical materialism, continuous negation of negation, and the courage and ability to constantly engage in self-denial. As a cutting-edge scientific field, the study of land-atmosphere interaction has complex, interactive, and implicitly inherent properties. Therefore, researchers engaged in this field cannot lie on the pile of achievements and be arrogant. They must constantly revise or even deny their past research knowledge, strive to propose new scientific knowledge, and further improve their understanding. Only in this way can we ensure that our research results continuously approach the scientific truth of land-atmosphere interaction and truly become the "insights" that promote the development of meteorological operation and technology.

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Conflict of interest The authors declare that they have no conflict of interest.

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