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Desertification and Related Climate Change in the Alashan Plateau since the Last 40 ka of the Last Glacial Period

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Abstract: Clues of climate change on the Alashan Plateau since the last glacial period (40 ka) are important for revealing the mechanism of desertification of middle-latitude deserts in the Northern Hemisphere (NH). Studies are still rare for the understanding of the specific relationship of climate changes between the Alashan Plateau and the global. Based on a systematic and comparative analysis of the existing research in China and the international academic community, this paper reviews the environmental evolution history of the Alashan Plateau since the last glacial period from the records of paleo-environment and geomorphological characteristics in different deserts of the plateau (e.g., Badanjilin, Tenggeli, and Wulanbuhe). From about 40 ka to the end of the last glacial maximum, the climate on the plateau was wetter than it is today, and to the end of the Pleistocene, the climate was generally dry and the aeolian activities were enhanced. However, the climate was arid during the whole last glacial period in the Wulanbuhe Desert, evidently different from the overall pattern of the plateau. The Tenggeli Desert was characterized by an arid climate in the early Holocene. The most controversial events for the Alashan Plateau are the drought events in the middle Holocene in the Badanjilin Desert. The role and impact of the westerlies and the East Asian Summer Monsoon (EASM) systems on the climate change of the desert and even the whole plateau is a vexed question that brings different views in different periods. There is still a lack of definite evidence representing the events of global environmental change that occurred on the plateau during the discussed period. The distinctive morphology of dune mountains and the distribution of sand dunes are mutually indicative of the direction and energy of wind systems on the plateau. It is suggested that appropriate wind energy is the significant key to the desertification in these middle-latitude deserts on the plateau. From a global-scale review of climate change, the desertification of the modern-scale sandy desert landscapes on the Alashan Plateau is generally related to the global glacial period and the cold and dry climate during the past 40 ka.

Keywords: last glacial period; Holocene; desertification; climate change; westerlies; monsoon circulation; Alashan Plateau; middle-latitude desert

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1. Natural Background

The arid and semi-arid regions of northwestern China, located in the middle latitudes of the Northern Hemisphere (NH), are widely distributed with two types of aeolian geomorphological landscapes: sand desert/sea and sandy land [1,2]. The interpretation given in geomorphology is that the sandy desert is mainly composed of mobile sand dunes, which are mainly distributed in the arid areas in the west of the Helan Mountain in China, while the sand lands consist mainly of fixed and semi-fixed dunes and are mainly distributed in the semi-arid areas in the east of the Helan Mountain [3]. The latter is described as a vegetated and stable dune land with an average annual precipitation of 200–450 mm [4]. However, the appearance of these sandy deserts and sandy lands in China is unique in terms of the formation of global desert landscapes [5]. Currently, the global distribution of sandy deserts has specific geographical locations where they are generally affected by the latitudinal zonal distributions of climate and ocean current activities. The formation of the sandy deserts in China is generally considered to be caused by the increased climatic continentality, the enhancement of land–ocean comparison, and the uplift of the Qinghai–Tibet Plateau in the interior of Asia [4–8]. However, there are still controversies about the specific reasons for the formation of these deserts in different periods, including the role and influence of various geomorphological processes in the sand sediment origin and deposition and the internal and external environments of the deserts, which involve tectonic activities, ice/glacier cover, atmospheric circulation/wind regimes, precipitation/relative humidity, the spatiotemporal interaction between rivers and lakes, as well as the changes of other local climatic factors [9–29]. Since the existence of a desert landscape is not conducive to the sustainable development of an oasis' ecological environment and social-economic activities and has an impact on the development of regional and even global landscapes, understanding the mechanisms of environmental change and the geomorphological evolution of the middle-latitude desert landscape in the past is significant. It is helpful to reveal the causes of environmental change in different areas and the interaction between them on a small spatiotemporal scale, and it is also significant to reveal the response of regional climate to global climate change on a large spatiotemporal scale [17,28]. More importantly, it provides a referential basis for the understanding of the teleconnection of global climate changes and helps to reveal the spatiotemporal effects of ocean and atmospheric circulation activities at different latitudes [19,26].

There are three large sand deserts on the Alashan (Alxa) Plateau. Geographically, they are located at the periphery of the subtropical high-pressure zone (the main distribution area of sandy deserts in the world) with an arid climate and the influencing area of the middle-latitude westerly circulation zone with a mild and humid climate [4]. Theoretically, they are not the ideal areas for the development of large desert tracts [5]. At present, although there have been a lot of academic opinions on the formation and evolution of these deserts on the plateau, the explanation of the relationship between climate change and the process of desert formation and evolution on the Alashan Plateau is not clear [18]. It lacks evidence in meteorology and climatology, and great disputes still exist. In addition, there is a lack of systematic comparative analysis of climate changes among the three desert regions within the same time scale and how it is related to global climate change—whether the process of climate change is relatively consistent or different among them [4]. Geomorphologically, there is still insufficient evidence to explain the differences in the sediment sources of these widespread sand dunes, and the role of wind regimes on the formation of the world's highest dunes needs to be improved [17,29]. In recent years, research on environmental change on the Alashan Plateau since the Holocene has been concentrated, while research since the last glacial period has been relatively weak. To solve these problems, this paper attempts to explore the environmental change of the Alashan Plateau since the last glaciation of 40 ka before present.

The Alashan Plateau is located in the west part of Inner Mongolia between 37°30′~42°36′ N and 93°6′~106°36′ E, with an altitude of about 1000~1500 m and the lowest place at about 820 m (the Juyan Lake) (Figure 1). The whole plateau is high in the south and low in the north, with the Mazong Mountains in the west and the Helan Mountains in the east. The southern boundary of the plateau is not obvious, and to the north of it is the border of China and Mongolia (Figure 1). The types of landscape on the plateau are mainly sandy desert, gobi desert, bare mountains, desert steppe, and active dune sheets. Some dry and denuded hills about 100~200 m high divide the plateau into many inland basins [22]. Geologically, the Alashan Plateau is a stable uplifted denudation platform. The Zaduo–Yabulai fault belt and the Langshan–Shigatse fault belt in the middle divide the plateau into east and west parts [30,31]. These fault zones have a great impact on water transport on the Alashan Plateau as potential flow passages for groundwater resources.

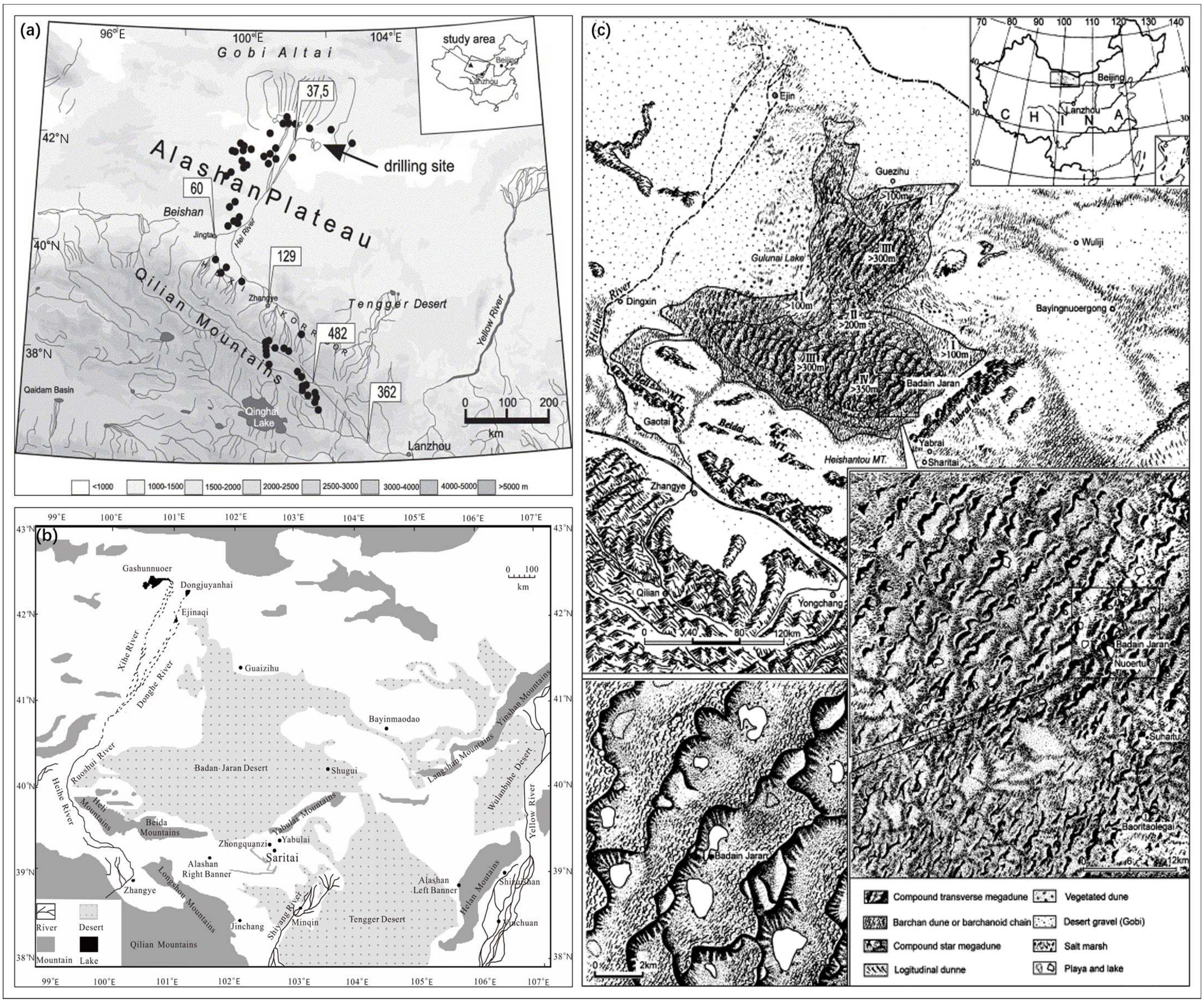

Figure 1. (**a**) Geographical locations of the pollen sample sites and the coring site on the Alashan Plateau discussed in this paper; (**b**) spatial distribution of the tree-lined large sand deserts on the Alashan Plateau; and (**c**) the aeolian landforms in the Badanjilin Desert (modified after [11,16,32]). Black dots in (**a**) indicate the detailed pollen sample sites and the coring site, and the numbers indicate the annual sum of precipitation in mm.

The northwestern part of the plateau is covered with wide gobi deserts, which are considered to be an important source of dust emission in Central Asia [33]. According to the sediment composition of the gobi desert, it can be divided into two categories: rocky desert and gravel desert. The Badanjilin (Badain Jaran) Desert is in the mid-west of the plateau, the Tenggeli (Tengger) Desert is in the south, and the Wulanbuhe (Ulan Buh) Desert is in the east (Figure 1).

The Badanjilin Desert is the second largest mobile sand desert in China, with an area of 49,000 km^2. It is known for its tall sand dunes and a large number of interdune lakes. Most of the lakes are highly mineralized and are mainly located in the interdune depressions downwind of the dune slopes in the southeastern part of the desert [22]. The landforms of the Badanjilin Desert are centered on active sand dunes and surrounded by desert plains [10]. Large sand dunes with a height of about 200~300 m are densely distributed in the south and southeast parts of the desert, and the largest dune is about

460 m high [17]. Geologically, the Badanjilin Desert is mainly developed on faulted basins. Climatically, the annual average temperature is 7.7 °C in the southeastern edge of the desert (e.g., Erkenhuduge) and 8.2 °C in the northwest (e.g., Dalaihubu). The average annual precipitation ranges from 120 mm in the south to 40 mm in the north, and the average annual precipitation is 84.5 mm [24]. The multi-year average meteorological records of different weather stations around the Badanjilin Desert are shown in Figure 2.

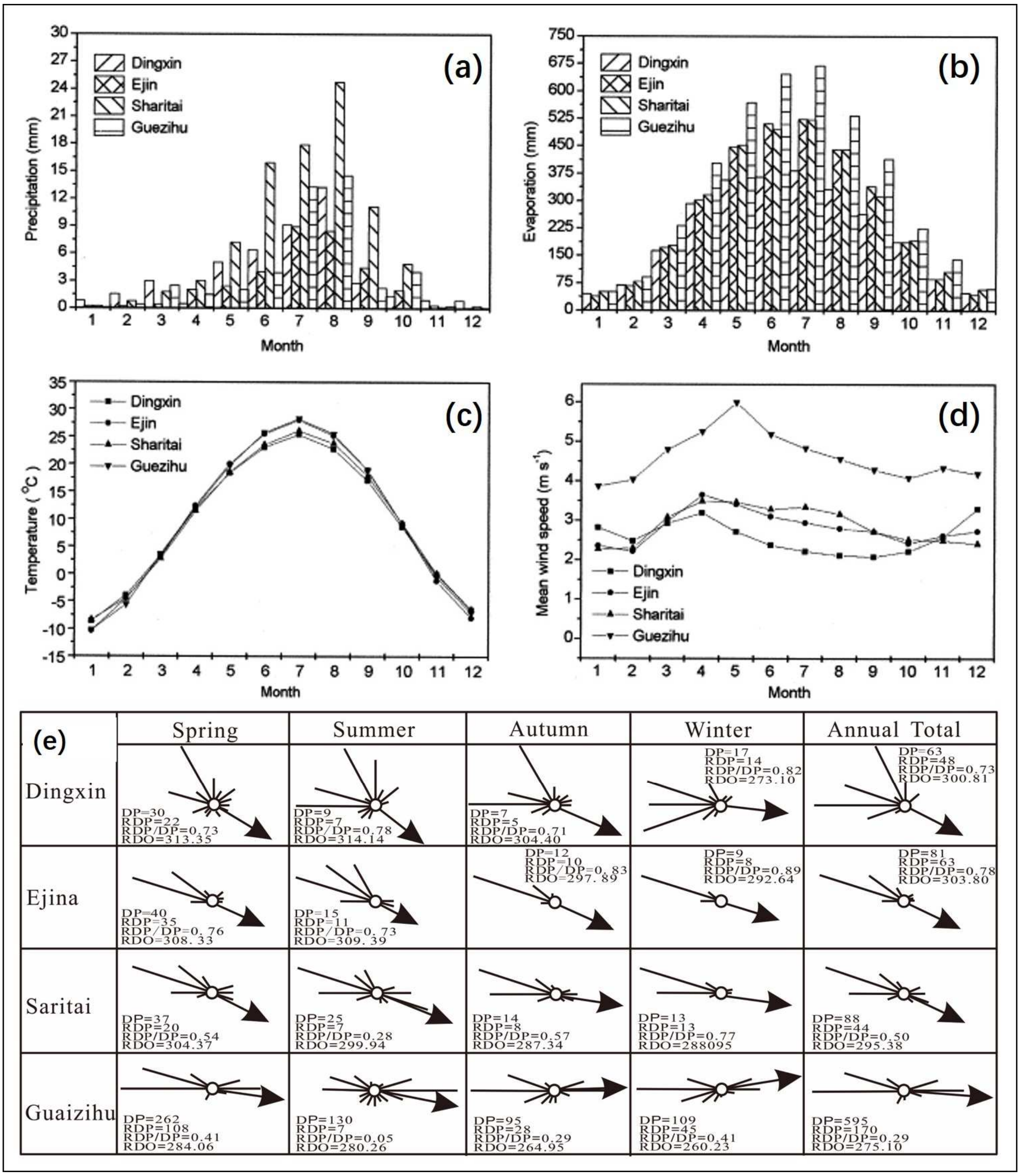

Figure 2. The climatic elements such as precipitation (**a**), evaporation (**b**), temperature (**c**), mean wind speed (**d**), and the sand drift potential (SDP) (**e**) in the different areas of the Badanjilin Desert (revised from [11]). DP, sand drift potential; RDP, resultant drift potentials; RDP/DP, directional factor; RDD, resultant drift direction. The background values of these modern climate parameters provide a necessary contrast for understanding the palaeo-environment of the Alashan Plateau.

The Tenggeli Desert is the fourth largest sandy desert in China, with an area of about 36,000 km^2 and an elevation of 1000~1500 m [34]. The desert is mainly composed of sand dunes, with a small area of lake basins and rock hills [35]. About 93% of the dunes are mobile dunes, and the dune land is separated by lake basins and rock hills [3]. The climate is generally cold and dry in the desert, with an average annual temperature of 7.8 °C and an average annual precipitation of 115 mm [34].

The Wulanbuhe Desert covers an area of about 11,000 km^2. The sand dunes in the central and southern parts of the desert are high, while those in the north are low. In the south, there are mainly pyramidal dunes and complex high sand mountains with a height of about 100 m, and in the north, there are mainly fixed and semi-fixed dunes [36]. Geologically, the Wulanbuhe Desert is a part of the Hetao Plain and is surrounded by the Cenozoic Ordos rifted basin. The average annual temperature is 7.8 °C, and the average annual precipitation is 102.9 mm [36].

2. Paleo-Climate Records and Paleo-Environmental Reconstruction since the Last 40 ka Period

In climatic geomorphology, climate is one of the five indispensable elements in the natural geographical environment. As an external force, it controls the changes in the natural geographical environment and landforms of a region. Specific climatic conditions control specific vegetation and associated landscapes. However, different regions also show different interference and adaptation abilities to the impacts of climate change. Since the last glacial period, the climate evolution of the Alashan Plateau has become very important because it is an important basis for the evolution of the plateau desert landforms. According to the existing literature, the research results on climate change during the last glacial period mainly focused on the period from 40 ka to the end of the Pleistocene (11 ka).

Specifically, the eroded piedmont plain in the Badanjilin Desert was found to have expanded during the last glacial period, according to the investigation of landforms [37]. In climatic geomorphology, the piedmont erosion plain is related to the annual average precipitation of 150~300 mm and a cold winter (Table 1). That is, it had more precipitation and colder temperatures during that period. Wünnemann and Hartmann (2002) [38] documented that the water levels of the Juyanhai Lake during about 37~34 ka, 31 ka, and 28~26 ka BP were high according to the oxygen isotope records of the ancient lake core (Table 1), which was consistent with the research results that the highest water level of the Sugunuoer Lake occurred in ca. 33 ka BP (^{14}C dating results, [39]). The core records from the Gashunnuoer Lake show that the highest lake water level occurred at ca. 34 ka BP and ca. 21 ka BP [40]. The climate in the central part of the Badanjilin Desert was wetter than that at present during the periods of ca. 30 ka BP, ca. 20 ka BP, and ca. 19 ka BP [39], which suggests that the climate during the last glacial period was wetter than the current. Thermoluminescence and radiocarbon dating data of sedimentary profiles along the eastern and southeastern edges of the Badanjilin Desert show that the drought index decreased during the period of ca. 30~20 ka [41], and the dating results of sandy loess deposits at the southeastern edge of the desert indicate that the climate was not very dry during ca. 25~18 ka (Table 1). The ancient shoreline of Yindernertu Lake also suggested that the lake was at a high water level at the end of the last glacial period (Table 1). By establishing a water balance and energy balance model [42], calculated that the precipitation in the hinterland of the Badanjilin Desert during the 31 cal ka period was about 260 mm, which was higher than the modern precipitation in this area. However, it was not always arid during the last glacial period because no organic matter was found during the period of 18.6 to 12.8 ka BP in the Badanjilin Desert [3], suggesting an arid environment during this period.

For the Tenggeli Desert, evidence from sedimentary structure, geochemical composition, and ostracod records from lake cores suggests that there may have been large ancient lakes in the Tenggeli Desert during the period of 39~23 ka ^{14}C BP [40]. The results of this study are relatively consistent with those of [34], i.e., the large lakes in the Tenggeli

Desert were established at about 35 ka^{14}C BP and maintained until 22 ka ^{14}C BP (Table 1). Stratigraphic evidence from [34] further indicates that there were no lakes in the Tenggeli Desert around 18 ka^{14}C BP during the Last Glacial Maximum. Research by [34,43] showed that the inland lake before the formation of the Shiyang River dried out completely at about 18 ka^{14}C BP and reappeared at about 13 ka BP. The study of lake sediments in the Tenggeli Desert by Pachur and Wunnemann (1995) [40] also showed that the climate had become drier after ca. 20 ka^{14}C BP, accompanied by increased sandstorm activities and declining lake water levels. The above literature reports show that the research results on climate change in the Tenggeli Desert during the last glacial period have good consistency.

Table 1. A study of the environmental wetness between 40 ka and the end of the Pleistocene on the Alashan Plateau.

Region	Location	Research Object	Dating Method	Dating Results	References
Badanjilin Desert	Piedmontplain	Landforms and landscape	Climatic geomorphology	Last glacial period	[37]
	Sand mountains	Calcareous cements	^{14}C dating	ca. 30, 20, 19 ka BP	[39]
	Southeastern edge	Loess deposits	TL dating	ca.30~20 ka	[41]
	Juyan Lake	Lake cores	Palaeomagnetism, radioisotope analysis, TL/IRSL dating	37~34, 31, 28~26 ka BP	[38]
	Gashunnuoer Lake	Calcium carbonate deposits	^{14}C dating	ca. 34, 21 ka BP	[40]
Tenggeli Desert	Duantouliang, Baijing Lake	Calcium carbonates, shells	^{14}C dating	39~23 ka BP	[40]
	Palaeolakes	Organic matter, shells, calcium carbonates	^{14}C dating	35~22 ka BP	[34]

There are relatively few paleoenvironmental studies from the Wulanbuhe (Ulan Buh) Desert. Recently, based on sedimentary records in bore holes [22], showed that during the last glacial period until the early Holocene, there had been sand-blowing aeolian activity and sand dune deposition in the Wulanbuhe Desert, and the environment here was very dry. The study of WL10ZK-1 pollen records by [44] also showed that during the last glacial period, desert vegetation was dominant in the Wulanbuhe Desert and the climate was arid. During the Holocene, the core records from the northern part of the Wulanbuhe Desert (Figure 3) suggest that the northern part of the desert may have been covered by shallow lakes or swamps during the period of 8.4~6.4 ka, and the eolian sand began to accumulate from about 2 ka [15]. This study proposed that the formation of the Wulanbuhe Desert may be composed of two parts: the ancient southern desert and the young northern desert.

Through the comparison of the above research results, it can be found that the research results of the Badanjilin Desert and the Tenggeli Desert are relatively consistent, that is, the climate from about 40 ka to the end of the Last Glacial Maximum (19 ka) is generally wetter than the present, and thereafter to the end of the Pleistocene, the climate is arid in these areas. While the climate change patterns of the Wulanbuhe Desert in the first stage are contrary to the previous two findings, of course, there are different fluctuations in the degrees of the cold, warm, dry, and wet conditions during these stages.

As far as the entire Alashan Plateau is concerned, research on Holocene climate change is relatively more complete than that of the last glacial period. However, the debate on climate change in the Holocene period is far more intense than that in the last glacial period. One of the focuses of the debate is the Holocene environmental changes in the Badanjilin Desert. There are two main viewpoints on this question. One, the climate was humid in the early and middle Holocene and arid in the late Holocene. Two, the mid-Holocene was dry.

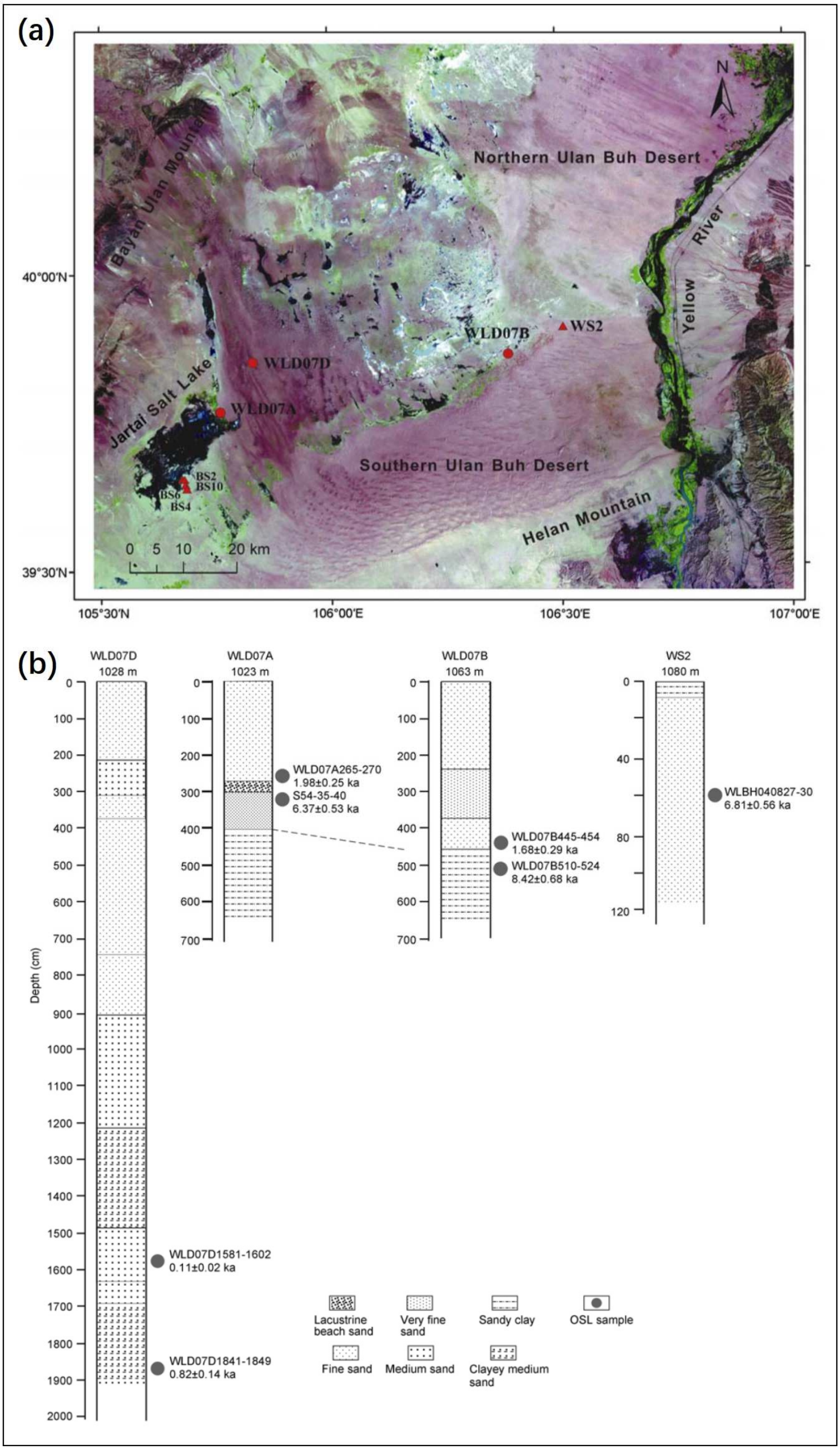

Figure 3. Remote sensing image (**a**) of the Wulanbuhe (Ulan Buh) Desert and the sedimentary cores studied (**b**) (modified from [15,45]). The filled circles in the upper figure are sites of cores in the northern Wulanbuhe Desert reported in [15]; filled triangles are sites of the profiles reported in [45].

There are relatively more studies supporting the first viewpoint. It shows that the lake water levels in the Badanjilin Desert were higher in the early and middle Holocene, and they began to decline since ca. 5 ka BP, while the dunes began to reactivate (although there may have been a short-term rise in lake water levels at ca. 2 ka BP) [16,39]. Reconstruction of the ancient shorelines between the desert hills also indicates that the lake water levels were high in the early and middle Holocene [10]. The humidification of the climate in the Badajilin Desert reached a maximum in the middle Holocene [37]. The above research results from different environmental records indicated that the climate was humid in the early and middle Holocene and was dry in the late Holocene (Table 2).

There are relatively few studies supporting the second view. The research results from the core sediments of inland lakes in the southern, western [9], and northwestern [46] of the Badanjilin Desert suggest that the mid-Holocene was arid (Figure 4). These lake sedimentary records also suggest that there were significant differences in the environments between the early Holocene and the middle Holocene (Figures 4 and 5). These lakes were in a high lake level and humid climate during the period of 10.7~8.9 ka but tended to be arid after 8.2 ka and were the most arid at 7.5~5.4 ka (Figures 4 and 5). Therefore, they put forward the hypothesis that the arid region of northwest China was humid in the early Holocene and was arid in the middle and late Holocene (Figure 5). However, refs. [16,18] pointed out that the interpretation of the early work on these lake cores may be inaccurate, and the climate during 8~5 cal ka BP was indeed wetter than that in the early and late Holocene. At present, these two views have not been well unified, and further work is needed to verify them.

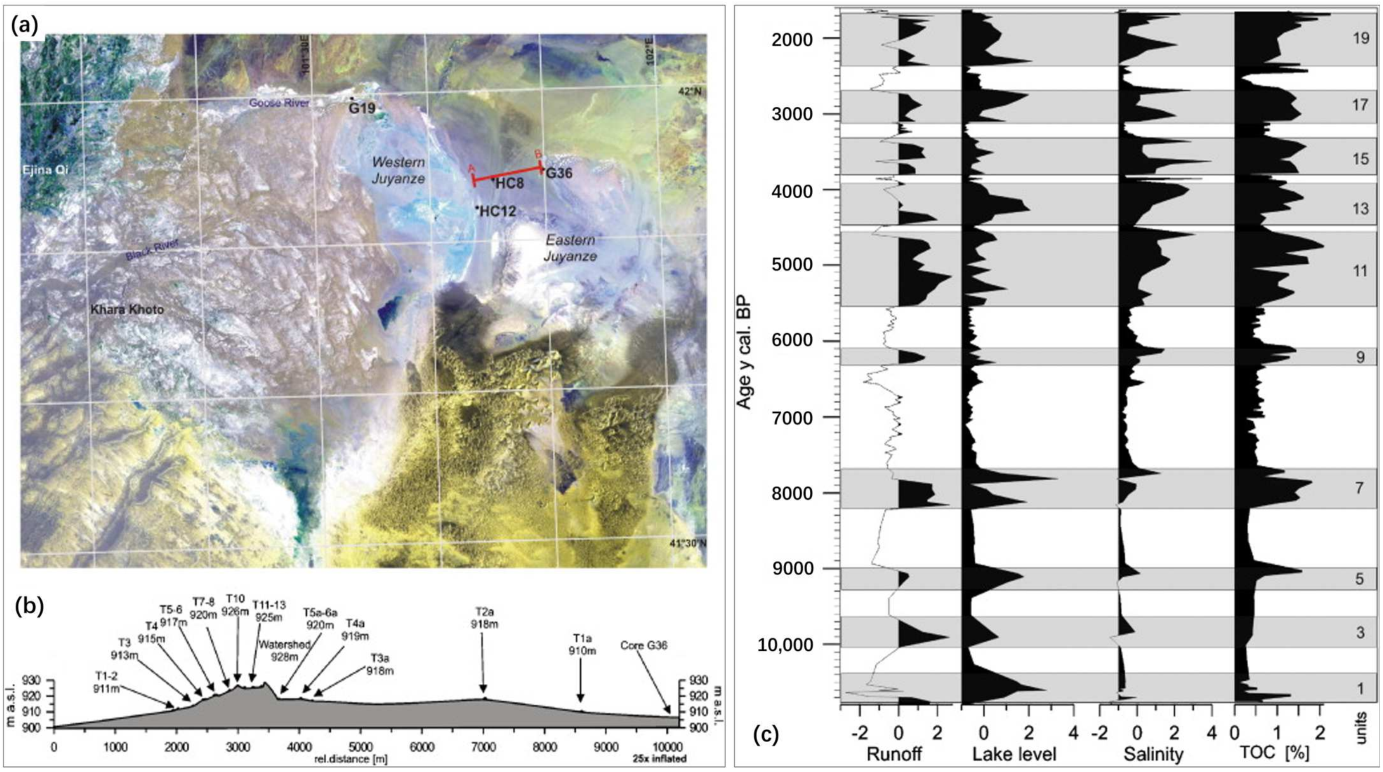

Figure 4. Landsat satellite image (Landsat ETM+, RGB 7-4-2) of the Juyanze palaeolake area (**a**), cross-section through the western and eastern sub-basins with measured shorelines (**b**), and factor values plotted against the age model (**c**) in the northwestern part of the Alashan Plateau [46]. TOC, total organic carbon.

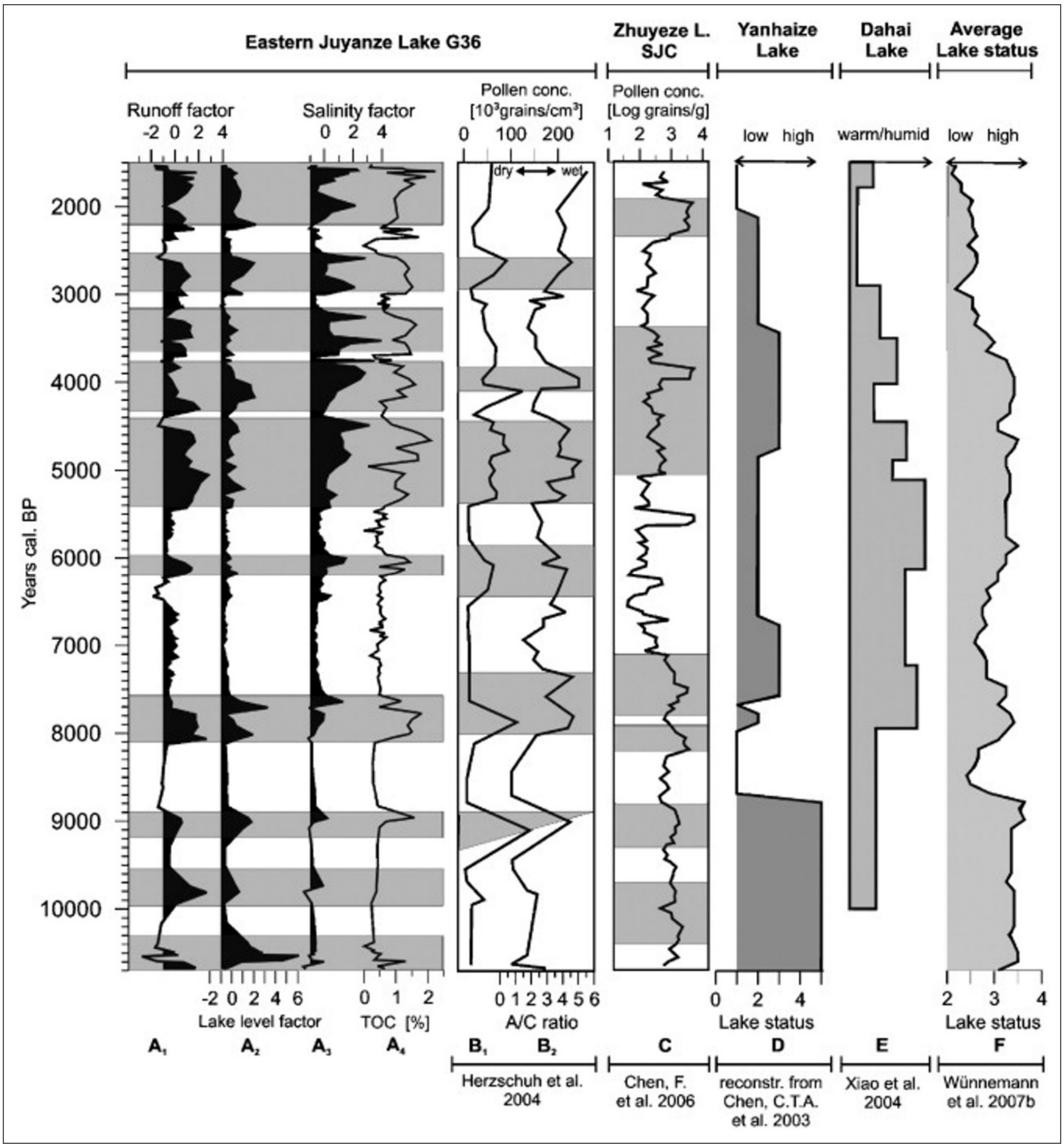

Figure 5. Comparison of climatic records in arid areas of Northwestern China from the northern Alashan Plateau to the northern margin of the Tibetan Plateau in a west–east transect (modified from [32,46–50]). TOC, total organic carbon.

For the Tenggeli Desert, Zhao Y et al. (2008) [35] studied the lithology and palynological fossil records of a 348 cm sedimentary section of the Qingtuhu ancient lake, and both showed that the climate was extremely dry in the early Holocene, humid in the middle, and arid in the late Holocene. The sporomorphs of the Hongshuihu section also showed that the climate was wet in the middle Holocene (Table 2). Long et al. (2012) [51] also analyzed the sequence stratigraphy of lakes and shorelines in the Tenggeli Desert, showing that the climate was wet from 8 to 5 ka (Table 2). The Zhuyeze ancient lake had a trend of shrinking since 5.0 ka, and the climate became dry in the late Holocene. Chen F. et al. (2003) [9] showed that the climate here was warm and dry in the early Holocene, cold and wet in the middle period, and arid conditions increased in the late period. Li Z (2012) [42] studied the ^{14}C dating of 16 root canals in the Tenggeli Desert and found that most of these root canals were formed in the mid-Holocene, indicating wet conditions during this period. However, another study by Chen F et al. (2006) [48] showed the completely opposite result: the climate was arid at 7.1~3.8 cal ka BP during the mid-Holocene, and the climate was wetter during the early and late Holocene. Since the three pollen samples inferred here were mainly from the Qilian Mountains, the results will not be considered for the time being.

Table 2. A study of the environmental indicators since the Holocene on the Alashan Plateau.

Region	Location	Research Object	Dating Method	Dating Results	References
Badanjilin Desert	Sand mountains	Calcareous cement layers	14C	ca. 9, 2 ka BP	[39]
	Lakes	Organic matter	^{14}C	9~4 ka BP	[10]
	Yindeertu Lake, Badan Lake	Organic matter, sands	^{14}C, TL	7 ka ^{14}C BP, ca.1 ka	[41]
	Huhejilin Lake	Organic matter, sands	^{14}C, TL	8~7 cal ka BP	[16]
	Lakes	Organic carbon, inorganic carbon, shells, travertine	^{14}C, Uranium series dating	ca. 10 ka, 9~4 cal ka BP	[16]
	Juyanze Lake	Calcium carbonates	AMS	10.7~8.9, 5.4~5 cal ka BP	[46]
Tenggeli Desert	Qingtuhu Lake	Organic matter, calcium carbonates	AMS	7.2~3.5 cal ka BP	[35]
	Hongshuihu Lake	Sporomorphs	AMS	7.4~5.7, 4.5~3.5 cal ka BP	[35]
	Zhuyeze Lake	Sand sediments	OSL	8~5 ka	[51]
Wulanbuhe Desert	Palaeolakes	Sand sediments	OSL	8.3~6.5 ka	[36]
	North part of the desert	Sand sediments	OSL	8.6~6.4 ka	[15]

Regarding the Holocene climate of the Wulanbuhe Desert, ref. [35] suggested that the climate was humid in the early and middle Holocene, mainly manifested as a lake environment. After 6.5 ka, the ancient lakes shrank and separated, indicating that the climate was arid in the late Holocene. Spore pollen records show that the humid climate of 8.6~6.4 ka in the mid-Holocene was favorable for the development of lakes, which is consistent with the findings of Fan et al. (2010) [15] that the northern part of the desert was covered by shallow lakes and swamps during this period and the environment was humid (Table 2). Based on the results of ^{14}C dating of the Jilantai ancient lake [12], pointed out that the lake began to shrink back and form a modern salt lake at about 5.5 cal ka BP, which also indicates the arid climate of the late Holocene. However, some studies suggest that the climate of the Wulanbuhe Desert may have been arid in the mid-Holocene [52]. The reasons for these two different conclusions remain to be explained by further studies and records.

Through the above research results, it can be found that the patterns of climate change in the Badanjilin and Wulnabuhe Deserts are relatively consistent in the Holocene period; that is, the climate was humid in the early and middle Holocene and was dry in the late Holocene. The climate in the Tenggeli Desert is generally considered to be arid in the early and late Holocene and humid in the middle. Clearly, the patterns of desert environmental evolution during this period in different regions of the Alashan Plateau revealed by these research results are inconsistent. However, at present, it is still difficult to determine whether this inconsistency is an artificial interpretation error or a real regional environmental difference.

3. Potential Causes of Paleo-Climate Changes and the Controversy Views about the Alashan Plateau

3.1. Causes of Climate Change during the Last Glacial Period on the Alashan Plateau

As for the causes of climate change, the academic community generally believes that the climate change since the last glacial period on the Alashan Plateau is related to the westerlies and the East Asian Monsoon (EAM). In this process, the humid climate of the last glacial period was more affected by the westerlies [53–55], and the water vapor came from the North Atlantic [54], because the East Asian Summer Monsoon (EASM) was weak during the glacial period [10]. In addition, the southward-moving polar high also brought water vapor from the Arctic region [41]. The dry climate after the end of the last glacial maximum (LGM) may be related to the weakening of the EASM [3]. So, we can say from the above that the issue of the driving mechanism of climate change on the Alashan Plateau involves the interaction processes between the westerlies, the EAMs, and the polar air masses. Since these three atmospheric circulation systems have intercontinental, hemispherical, or global scales in their origin and circulation range, the problem of paleoclimate change on the Alashan Plateau is not only a regional problem but also responds to global climate change, which has attracted extensive attention from international scholars.

From the above-mentioned studies on the environmental records of the Alashan Plateau, it can be seen that the climate evolution of the last glacial period is not very controversial. Considering the regional scale of climate change, many studies in the surrounding areas of the plateau also have similar conclusions. For example, due to the intrusion of the summer monsoon and the changes in the intensity of the westerly circulation in the northern hemisphere, the climate in northwestern China was generally humid during the period of about 41~30 ka, which corresponds to the period when the largest lake in the adjacent Qinghai–Tibet Plateau existed. In addition, the deserts in western China once again experienced a wetter environment during the last glacial maximum (Figure 6) [16], during which the lakes in western China were fresher and the significantly higher water levels than the current were associated with a positive precipitation/evaporation anomaly, low temperature, and reduced evaporation. This anomaly was the result of an intensification of the westerlies and their east-to-south shift [56]. By reconstructing the drought index of the desert regions in northwestern China [37], found that the climate in the last glacial period was wetter than that at present. Due to the intensification of the EASM circulation, the lakes in the Qinghai–Tibet Plateau expanded on a large scale at about 40 ka and 35~30 ka [57]. The climates of the Tarim Basin, the Jungar Basin, and the Alashan Plateau were humid at ca. 30 ka BP, and the precipitation was increased in the western Alashan Plateau at this time, which was the result of the enhancement of the westerlies [41,54]. It is pointed out that most parts of western China exhibited a humid environment during the period of 40–30 ka (Figure 6) [16]. Compared with the west part, the paleoenvironment in the eastern part of the desert belt in China was characterized by an expansion of the range of dune formation during the period of about 21~13 ka, reflecting the weakening of the EASM [3]. Optical luminescence dating and stratigraphic analysis of sand dunes in western Mongolia show that fine sands were strongly blown away from lake depressions during the last glacial period of 18~13 ka, reflecting the drought of the environment [58]. It can be seen from the above that the climate change at a regional scale on the Alashan Plateau during the last glacial period has an environmental signal consistent with the large-scale climate change in northern China.

In addition to this large-scale regional environmental signal, the climate change of the last glacial period on the Alashan Plateau was also superimposed with the signal of climate change on the local scale of the plateau itself. For example, from the above paleoclimate records and compared with the other two deserts, the patterns of climate change in the Wulanbuhe Desert during the first stage of the last glacial period were different, but there was no relevant explanation for this difference at present. We speculate that it may be because this desert is closer to the northeastern end of the plateau than the other two, that is, the downwind direction and the edge of the westerlies. Coupled with the topographic clamping effect of the Yabulai Mountains (west of the desert) and the Langshan Mountains (northwest and north of the desert), the water vapor transmitted by the westerlies cannot reach, and the Arctic air mass is also suppressed. Relatively speaking, the explanation of the humid climate of the last glacial period by the westerlies may be more convincing than that by the polar high, because the latter (the polar cold vortex) is usually difficult to create water vapor.

On a global scale, the world was generally in a cold environment during the last glacial period, but whether the environment was wetter than the current one needs further exploration. According to the above explanation of the regionally humid climate during that time, the Alashan Plateau was not only affected by the westerly rain belt but may also be affected by the Asian Summer Monsoon rain belt. However, there is still a lack of detailed research results about the dynamic relationship between the two circulation systems that can bring precipitation to the climate change of the plateau during the glacial period. Jin et al. (2007) [59] and An Z et al. (2012) [60] suggest that the change of the westerlies may be opposite to that of the summer monsoon during the glacial period, which provides a way to explore the issue, but this explanation needs to be further deliberated and confirmed from the mechanism.

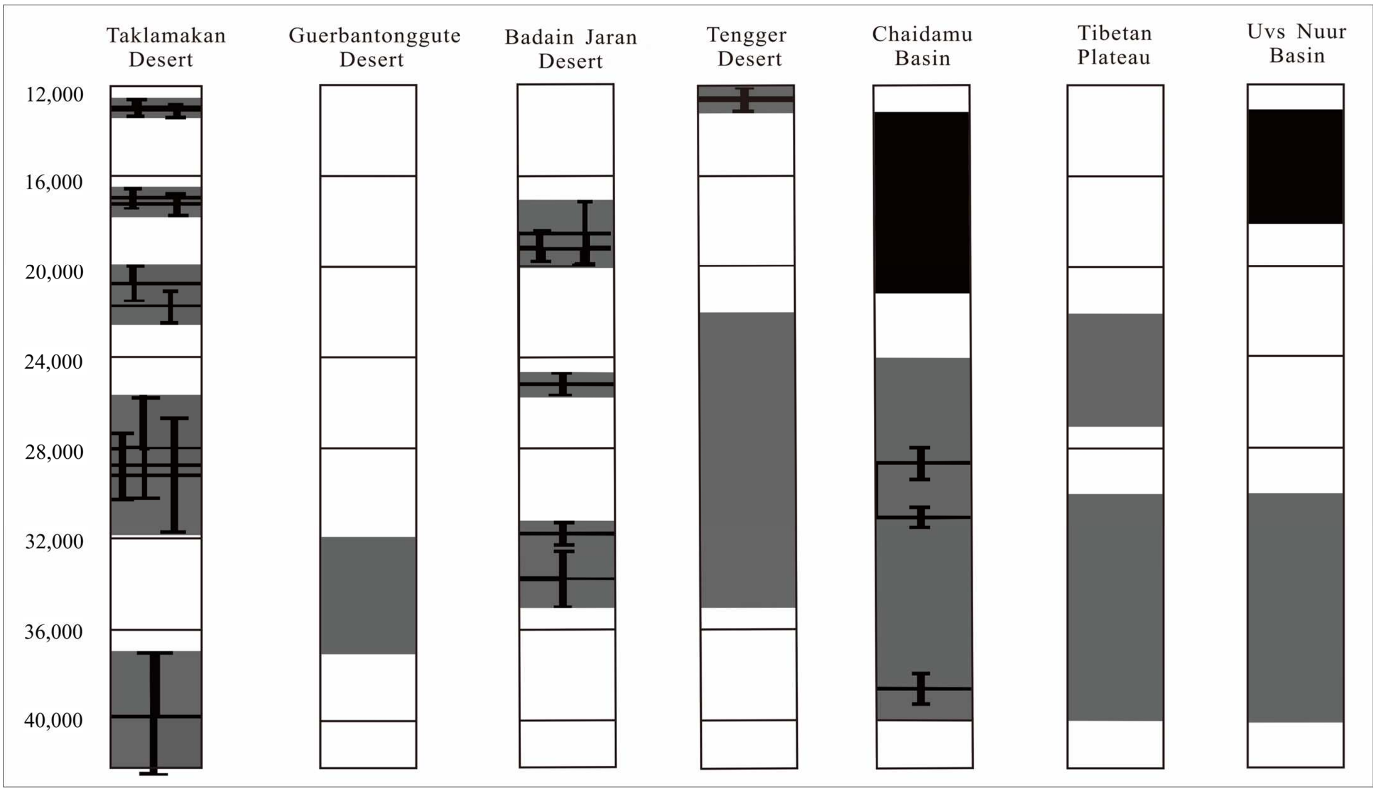

Figure 6. Histogram of Pleistocene wetter epochs (gray, the solid lines indicating ages with error bars) and distinct drier periods (black) recognized in the sandy deserts of northern China in a west–east transect (modified after [61]).

3.2. Causes of Holocene Climate Change on the Plateau

Compared with the last glacial period, the causes of Holocene climate change on the Alashan Plateau are more controversial, especially in the early and middle Holocene. We present these different perspectives here as clearly as possible and discuss them comprehensively.

The first is about the reasons for the humid climate in the middle Holocene. If the climate of the Alashan Plateau in the early and middle Holocene was humid (Figure 7), it is generally considered to have been caused by the EASM [9,39,57]. This is different from the influence of the westerlies in the last glacial period. For example, refs. [37,39] believed that the northern edge of the EASM rain belt in the mid-Holocene reached the Badanjilin Desert and brought higher precipitation to the gobi region of the desert. However, ref. [35] suggested that the pattern of Holocene climate change in the Tenggeli Desert was neither a response to the northern hemisphere westerlies nor to the EASM but was related to the upward and downward movements of the air flow near the Qinghai–Tibet Plateau. That is, before 7.2 cal ka BP of the early Holocene, strong summer insolation enhanced the subsidence movement of the air mass in the low-altitude areas near the Qinghai–Tibet Plateau, resulting in an arid climate. During the period of 7.2~5.2 cal ka BP of the middle Holocene, the climate was relatively humid due to the weakening of summer insolation, less subsidence air flow, and the enhancement of the summer monsoon. During the period of 5.2~3.0 cal ka BP, the interaction between downdraft air flow and direct monsoon precipitation reduction in low-altitude areas was the main reason for the climate change of the desert in this period. After 3.0 cal ka BP of the late Holocene, due to the continuous weakening of solar radiation, the weakened subsidence movement of the air around the plateau, and the weakening of summer monsoon precipitation, the desert climate in this period tended to be arid. Clearly, this point of view emphasizes the regulating effect of the Qinghai–Tibet Plateau on the surrounding areas in millennium-scale climate change. Similarly, refs. [55,62] suggested that the spatial pattern of dry and wet climate change during the Holocene in the Qaidam Basin was also related to the upward and downward movements of the air flow over the Qinghai–Tibet Plateau. However, the differences in the patterns of climate change between the Tenggeli Desert and the other two large deserts during the Holocene shown by the above-mentioned paleoclimate records make it seem difficult to explain the climate change of the Alashan Plateau during the Holocene only by the regional impact of the Qinghai–Tibet Plateau. Because in terms of geographical location, we cannot rule out that in the same downwind region, only the Tenggeli desert is affected by the Qinghai–Tibet Plateau, while the Badanjilin and Wulanbuhe Deserts are not affected by the Qinghai–Tibet Plateau.

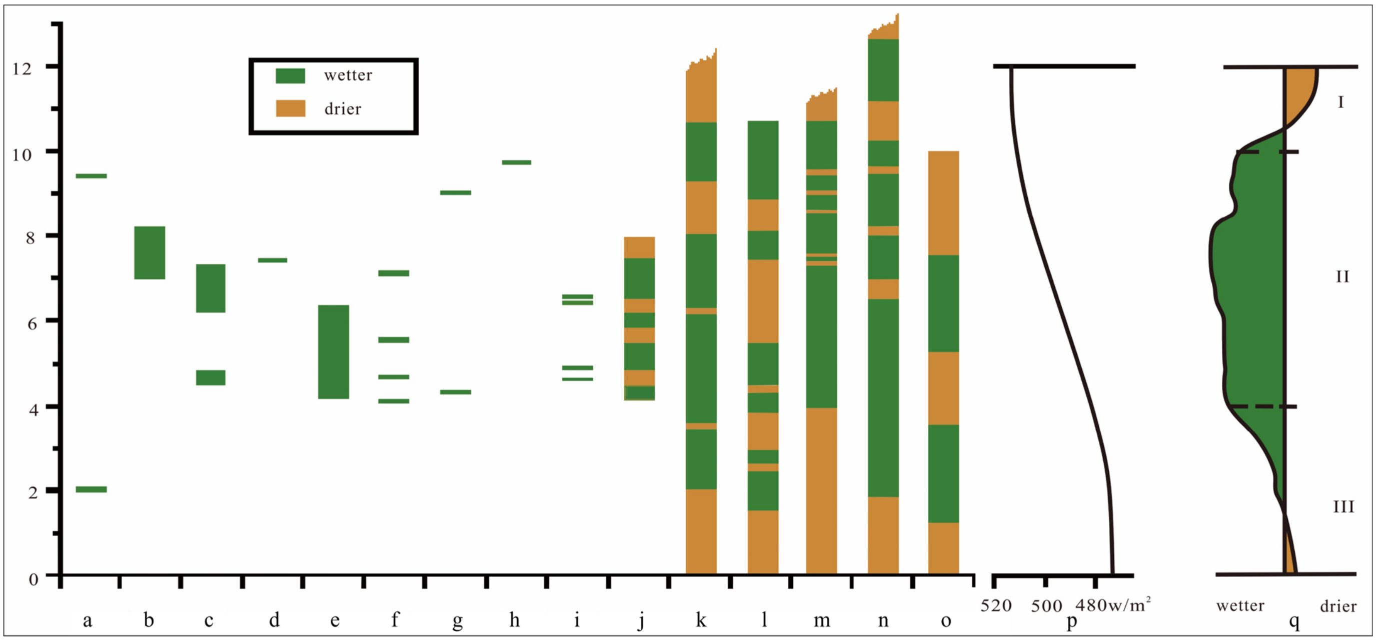

Figure 7. Distribution of dry and wet epochs during the Holocene period inferred from paleoenvironmental records in the Badanjilin Desert and other arid regions in China. (a) Calcareous cementations on the surface of sand dunes in the Badanjilin Desert, (b) Huhejilin Lake, (c) Zhalate Lake, (d) Sumujilin Lake, (e) Nuoertu Lake, (f) Shaobaijilang Lake, (g) Aomenjilin Lake, (h) Sayinwusu Lake, (i) Badan Lake, (j) Shugui Lake at the eastern edge of the Badanjilin Desert, (k) aeolian sequences in the southern edge of the Badanjilin Desert, (l) Juyanze Lake, the terminal lake of the Heihe River, (m) a terminal lake in the Tenggeli Desert, (n) Qinghaihu Lake in the northeastern Qinhai-Tibet Plateau, (o) Wulungu Lake at the northern edge of the Gurbantonggute Desert, (p) summer (May to September) solar insolation at 40° N, (q) synthesis of the above records (modified from [18]).

The second is the drought events in the middle Holocene on the Alashan Plateau. There is an implicit question in this dispute: is the mid-Holocene drought a mere feature of local climate or a reflection of regional and even global climate change? A study by Su and Zhang (2013) [63] in northwestern China concluded that the sandy deserts and gobi deserts were further expanded and the drought continued to develop in the middle Holocene. A study by Wang W and Feng (2013) [64] on the Mongolian Plateau showed that the middle Holocene was also arid (Figure 8). It was suggested that the drought during this period was more likely to exist than the fact that this drought event was not found in lake sporomorphs. Yin et al. (2013) [65] studied the high-resolution core records of the Angili Nuur Lake in Mongolia and found that the climate was arid in the middle Holocene in this region. They pointed out that the semi-arid areas in the western United States and the Mediterranean also showed the same climate characteristics. The authors believe that it may be influenced by the enhancement of the evaporation effect caused by large-scale high temperatures and, thus, has global significance. Some scholars also gave the same explanation for the mid-Holocene aridity on the Mongolian Plateau [66,67].

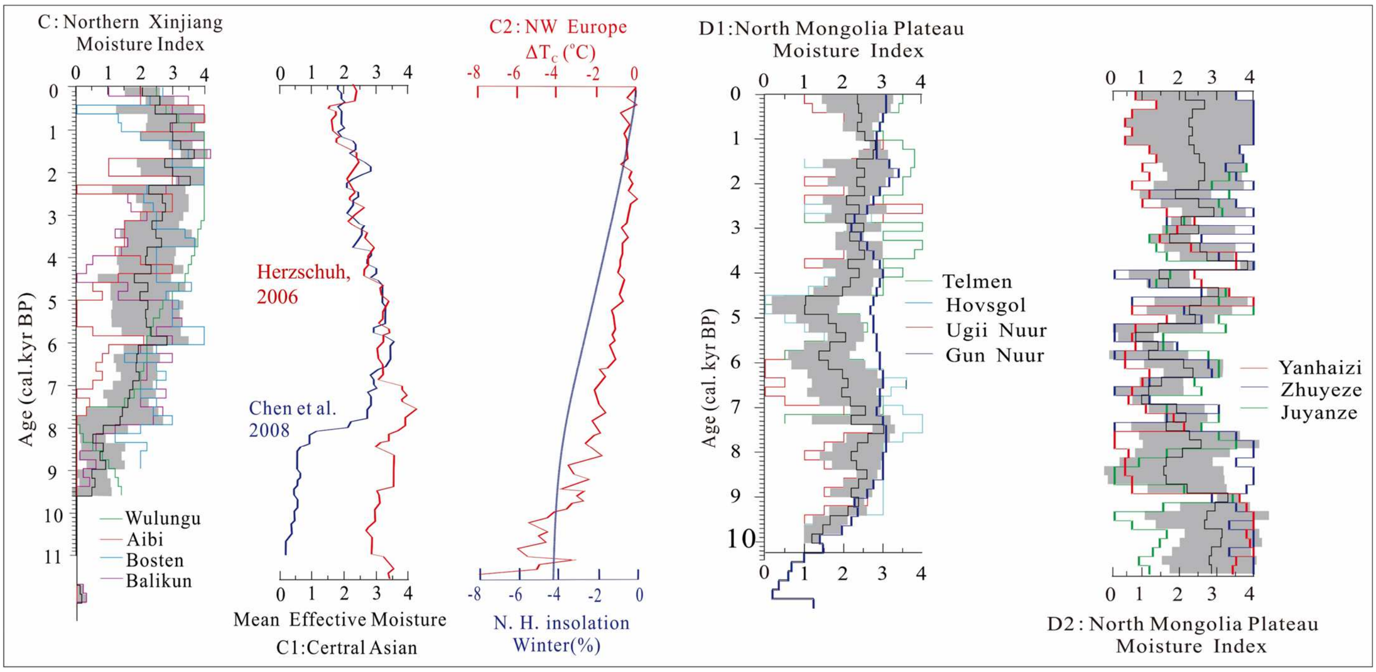

Figure 8. Comparison of humidity indices and related climate indicators in different regions of Central Asia (modified after [64]). The index from the northern part of Xinjiang (C) is compared with the average moisture index (C1) of Asian Central Area (ACA) by Chen F et al. (2008) [13], and Mean Effective Moisture index by Herzschuh (2006) [68], the cold-season temperature deviation (C2) in northern Europe [69], and the northern hemispheric winter insolation [70].

Clearly, the above two questions of wetting and drought in the middle Holocene have brought about a new problem, that is, the problem of scale. If the mid-Holocene drought events were real globally, why did environmental records in some areas of the Alashan Plateau show a humid climate at that time? Was the latter a small-scale regional event? However, many studies from China and other parts of Central Asia also recorded humid climates in the middle Holocene, such as the arid regions of northwestern China and the desert regions of western China [18], the semi-arid regions of China [64], the Gulbantonggute Desert [61], northern Xinjiang, and even Central Asia (Figure 8) [64]. Scholars' explanation for this humid climate is the influence of the EASM, which is generally caused by the enhancement and northward movement of the EASM, or the result of the action of the westerlies. However, whether it is the summer monsoon or the westerly belt, the influence range of this circulation system is also generally large, and it is difficult to have a discrepancy in the climate characteristics of a certain place in the region on a long-term scale. Therefore, based on the above discussion, it can be seen that no matter whether the climate in the middle Holocene was arid or humid, its mechanistic explanation needs to be further studied on the spatiotemporal scale.

In view of the different research results obtained from the above-mentioned different research objects and environmental records, as well as the consequent inconsistency in the understanding of the changes in the plateau paleoenvironment, we believe that there are some reasons that may lead to the occurrence of these problems, which are described here.

3.3. The Accuracy of Climatic Proxy Indicators and the Complexity and Uncertainty of Regional Environmental Elements

For the spatial differences in the patterns of climate change on the Alashan Plateau, the accuracy of research methods and environmental proxy indicators, such as dating methods, should be considered first [71,72]. For example, Herzschug et al. (2004) [32] made a conclusion contrary to the previous research results in the reconstruction of the climate change of the ancient Dongjuyan Lake. Their explanation is that the resolution of sporomorph records may be too low or the dating is inaccurate. Wang N et al. (2011) [71] found that there were great differences between the age data of the OSL dating method and the ^{14}C dating method in the study of late Quaternary high lake levels and the great lake period on the Alashan Plateau. Secondly, different scholars may have different understandings of the environmental significance indicated by the same climate proxy index. For example, some scholars believe that high calcium carbonate is representative of a high lake water level and humid climate environment [10,39,51], but Shi et al. (2002) [73] explained the high calcium carbonate as a low lake water level and arid climate environment and therefore believed that the Shiyang River Basin showed a trend of aridification in the middle Holocene. Thirdly, the indications and impacts of major environmental elements (such as the five elements of microclimate, landform, hydrology, biology, and soil) on regional climate change may be different under different physical and geographical conditions. As the soil environment of the three sandy deserts on the Alashan Plateau is similar, the impacts of climate, landform, hydrology, and biology may be relatively large compared with the soil. However, on a long-term scale, the effects of climate and landform on different regions of the plateau will not be very different. Since most of the paleoclimate records of the plateau are based on lakes or sporomorph records, the influence of hydrological and biological factors is more important. For example, the size of a lake indicates the amount of water resource available, and its change will affect the judgment of the degree of climate change. Small lakes may dry out under certain climatic conditions, while large lakes may remain unchanged or become wetter due to the deprivation of water from small lakes under the same climatic conditions, so the sedimentary records from the two kinds of lakes may lead to different or even completely opposite conclusions. Different organisms will respond differently to climate change, and thus their environmental implications are also different. For example, ref. [65] found that the timing of forest replacement by steppes in arid climates was inconsistent with the rate of climate change, showing a significant lag. Therefore, regarding the perspective of diverse environmental factors, although the research scale of regional climate evolution is relatively large and the difference and influence of a single factor may be insignificant, the superposition of the interactions of multiple factors cannot be ignored on this basis. For example, there are many lakes in the Badanjilin and Tenggeli Deserts, most of which are freshwater lakes [18,74], while there are no lakes in the Wulanbuhe Desert, which is adjacent to the Yellow River. Changes in the Yellow River and its water sources may have limited the formation of a lake in the Wulanbuhe Desert [20] and further affected the desert environment [36]. Therefore, when the temporal and spatial scales of the regional climate change studied by us are relatively large, the influence extent and intensity of boundary conditions and external conditions may be crucial on climate change in different regions, such as the impacts of the uplift of the Qinghai–Tibet Plateau and the change of the Yellow River on adjacent areas.

3.4. Different Understandings of the Roles of the Monsoon and Westerly Circulation Systems in the Mid-Latitudes

In the studies of paleoclimate reconstruction in the mid-latitude regions of NH, there are different explanations for the environmental effects of the two major circulation systems, the monsoon and the westerly (Figure 9), on climate change in northwestern China, resulting in disputes over paleoenvironmental changes in these areas.

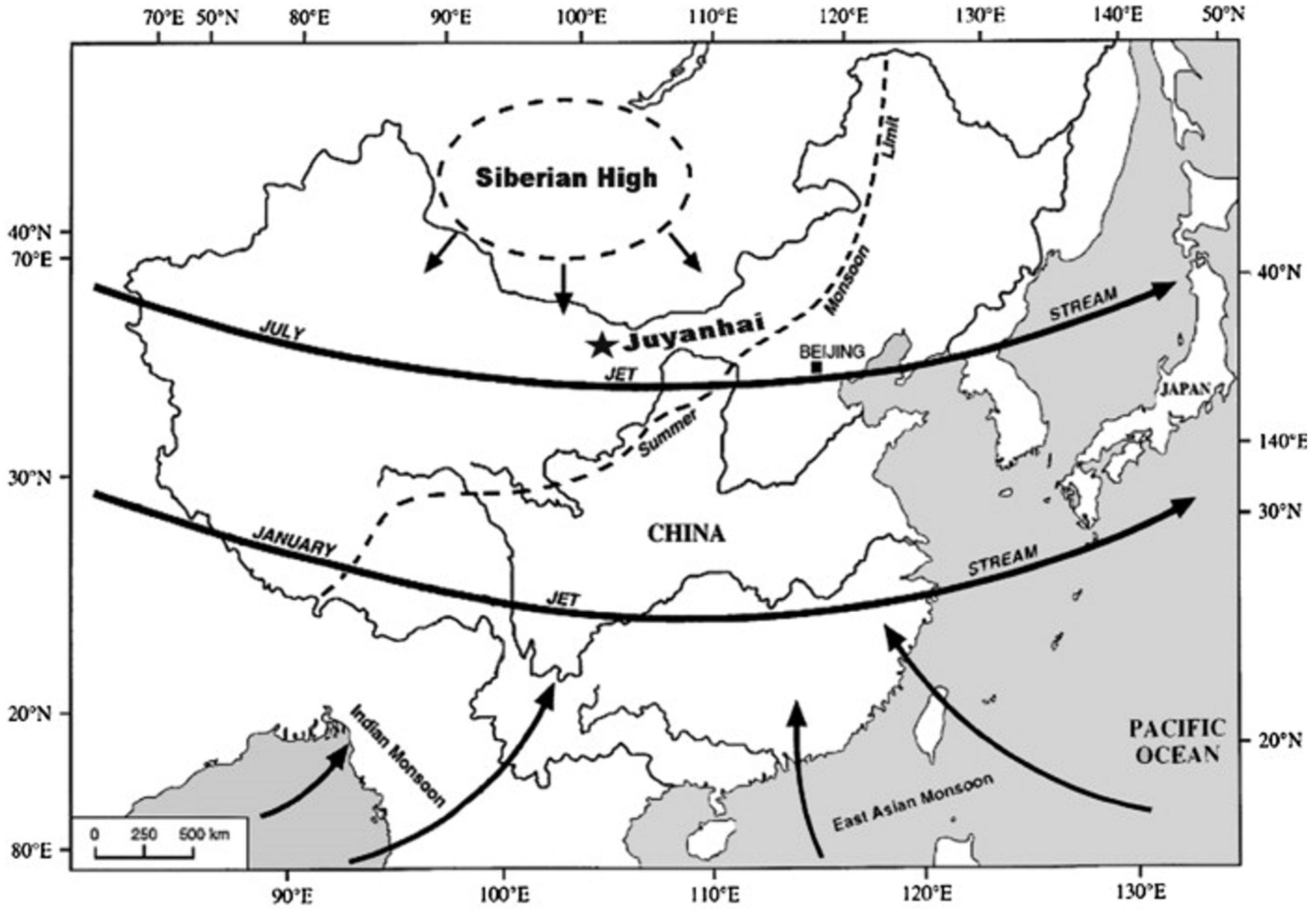

Figure 9. The geographical locations and relationship between the westerlies and the Asian Summer Monsoon. When the Asian summer monsoon is enhanced in summer, the westerly jet moves northward. When the Siberian High is enhanced in winter, the jet moves southward (revised from [14,50,75]).

Many scholars believe that the climate during the early Holocene was humid on the Alashan Plateau and its surrounding areas, and this humid environment was generally on a large scale, which was affected by the rain belt effect of the monsoon circulation. For example, environmental reconstruction studies of sporomorph assemblages and aeolian sediment records revealed that Mongolia experienced an increase in temperature and humidity in the early Holocene [67], and lake sediments in central Inner Mongolia identified the existence of large lakes in the early Holocene at about 8.5 ka [76]. The climate in the arid area of northwestern China in the early Holocene was humid, which may have been caused by the stronger Asian summer monsoon than at present [54]. The humid climate in the Asian monsoon region reached its maximum in the early Holocene [36].

From the above explanations, it can be seen that the humid climate of the Alashan Plateau in the early Holocene can only be attributed to the strengthening of the Asian summer monsoon. These explanations imply a precondition, namely, that the westerly circulation is not enough to cause a humid climate change at a regional scale on the Alashan Plateau. Some scholars even think that the westerly circulation will lead to an arid environment at certain times. For example, some studies suggest that the climate during the early Holocene in the surrounding areas of the Alashan Plateau was arid, and the climate in these areas was affected by the westerlies [36,64,77]. Some studies have pointed out that the climate in the Altai region of Mongolia was cold and dry in the early Holocene, which was affected by the westerlies [77]. It was documented that northern Xinjiang had an arid climate from about 11.5–10.0 to 7.5–6.7 cal ka BP in the early Holocene due to the influence of the westerlies (Figure 8). The arid region of Central Asia was the driest in the early Holocene under the control of the westerlies [78], etc.

However, many scholars suggest that the westerly circulation can bring a lot of water vapor to northwest China and make its climate moist at certain times. For example, the climate in Xinjiang, China, and Altai, Mongolia, was humid in the late Holocene [16,58]. Yang X et al. (2006) [58] analyzed aeolian and lacustrine sediments in the southern margin and center of the Taklimakan Desert, and the stratigraphic evidence indicated that the climate was humid in the late Holocene. The global westerlies and a moving polar high pressure drove the fluctuation of precipitation in the desert, but it was the intensity of the winter monsoon that mainly controlled the change of temperature in the desert. The climate in the Guerbantonggute Desert was arid after 5.3 cal ka BP and was mainly affected by the westerlies [16].

It can be seen from the above that different scholars have two contradictory views on the humidification effect of the westerly circulation, both of which are related to the Asian summer monsoon. One view is that the role of the westerly circulation is similar to that of the Asian summer monsoon, both of which can lead to the humidification of the climate in northwest China, while the other view is the opposite. It believes that the Asian summer monsoon is responsible for the humidification of the climate in the arid areas of northwest China, but the westerly circulation is not. Clearly, these contradictory explanations about the westerly circulation need further work to be identified, the key to which is to deeply understand the dynamic relationship between the westerly circulation and the Asian monsoon circulation.

3.5. Complexity of Dynamic Connection between Westerly and Monsoon Circulation Effects and Ocean Circulation in Mid-Latitude Regions

China is a major monsoon region in the world. Due to its wide territory and complex underlying surface types, whether each region can be used as a monsoon research area is still a question worth discussing. Especially in the middle latitudes of northern China, which are located in both the monsoon boundary area and the westerly control area, the climate types are very complex (Figure 9). The impact of these two circulation systems on the evolution of climate and environment in the region is still under debate [79–85]. Some scholars have proposed that there are two patterns of climate change on the millennium scale in northwestern China since the late Pleistocene, namely the "monsoon pattern" and the "westerly pattern," and in this context, the Xinjiang area of northwestern China follows the westerly pattern, while the Gansu, Qinghai, and other regions of northwestern China are mainly affected by the monsoon pattern [86]. Other scholars suggest that since the last glacial period, there have been two evolutionary modes in the arid regions of East Asia: the relatively high lake water level (humid climate) in the early and middle Holocene and the high lake water level in the LGM and the early Holocene [84], and in this context, the southern part of the Alashan Plateau (such as the Shiyang River Basin) is jointly affected by the Asian monsoon and the westerly circulation on the millennium scale [83]. Regardless of the controversy, many scholars agree that their influence range and intensity will change with the changes in the forcing sources of the two atmospheric circulation systems [87], such as global climate change, changes in meridional thermodynamic differences between different latitudes, changes in land-sea thermodynamic differences, etc. That is, they are mainly controlled by the thermal and dynamic connection between the atmospheric circulation and the oceanic circulation in the NH on a large scale. For example, the climate change in the East Asian monsoon region is caused by the sea-land temperature contrast and the seasonal changes in the circulation between the largest ocean (the Pacific) and the largest continent (the Eurasian continent) in the world, while the climate change in the westerly belt, the planetary wind system-controlled area, is closely related to the Atlantic circulation. The westerly system originating from the Atlantic Ocean and the monsoon system originating from the Pacific Ocean have complex and diverse circulation patterns in the mid-latitude regions of Eurasia. In general, the atmospheric circulation in the middle latitudes is affected by the remote ocean circulations, which are mainly represented by the mean latitudinal circulation, the mean horizontal circulation, and the mean meridian circulation [88].

The zonal circulation near the ground in the middle latitudes is mainly characterized by the circulation of the westerly winds from the ground up to the high altitudes, which is the so-called prevailing westerlies or westerly jet. The north-south movement of the westerlies is influenced by the north-south movement of the low-latitude subtropical high. The high-pressure system, the north-south movement of the subtropical high, and the surface water temperature of the Pacific Ocean have a direct effect on the changes of the EASM [88]. Both the monsoon system and the westerly system are affected by the north-south movement of the subtropical high system, so there must be a thermodynamic connection between the two circulation systems from the two oceans, which reflects the interaction and interrelationship between the mid-latitude and low-latitude atmospheric circulations, which are complex.

The mean horizontal circulation of the atmosphere refers to the average horizontal circulation of the pressure trough, pressure ridge, and high- and low-pressure circulations developed after external disturbances at different heights and in different regions (Atlantic and Pacific) of the troposphere. Their circulation patterns are different from each other. The mean horizontal circulation in the upper troposphere is in the form of large-scale pressure troughs and pressure ridges in the westerly belt, such as the East Asian Trough (belonging to the Pacific system) and the European Shallow Trough (belonging to the Atlantic system). The patterns of horizontal circulation in the lower troposphere are mainly represented by huge high- and low-pressure systems in the monthly mean pressure map, such as the Iceland Low and the Azores High (belonging to the Atlantic system), the Aleutian Low and the Siberian High (belonging to the Pacific system), etc. Therefore, the two major circulation systems, the westerlies and the Asian monsoon, have different performances at different heights and different regions of the troposphere, and their interaction modes must also be different.

In the mean meridional circulation, Eurasia is mainly affected by the North Atlantic oscillation. The North Atlantic Oscillation (NAO) is mainly represented by two activity centers of the atmospheric pressure in the North Atlantic (the Iceland Low and the Azores High), and their changes are negatively correlated. When the barometric pressure difference between the two is large, the NAO is in a positive phase [89,90]. At this time, the direction of atmospheric movement is from high pressure to low pressure, and the maximum water transport axis shifts across the Atlantic to a more southwest-to-northeast direction, which is manifested as the enhancement of the Atlantic Meridional Overturning Circulation (AMOC) and the northward shift and weakening of the westerlies (climatically manifested as a drier environment in the areas of southern and central Europe, the Mediterranean region, and even the Middle East and Central Asia). The change of the AMOC leads to the intensification and northward shift of the subtropical high, which further promotes the northward movement of the westerlies. At the same time, the northerly position of the westerly jet will lead to the intensification of the EASM. The changes of the latter will greatly change the position of the barometric trough and barometric ridge, that is, the East Asian trough will move eastward into the sea (becoming shallower and weaker), resulting in the weakening of the Siberian High and the Aleutian Low (Pacific system) and thus the weakening of the winter monsoon. On the contrary, at this time, the warm anomaly of surface water temperature in the North Atlantic (caused by the enhanced heat transfer from low latitudes to the polar region) transports more warm water to the polar region. This ocean current activity corresponds to the enhancement of ocean current activity in the middle and low latitudes of the Pacific Ocean. At this time, the Walker circulation is enhanced and conducive to the occurrence of the La Niña event, which corresponds to the cold phase of the Pacific Decadal Oscillation (PDO) [91]. It can be seen that the Pacific circulation anomalies are closely related to the North Atlantic circulation anomalies, and the anomalies of the two major ocean circulations will both lead to changes in the westerly and monsoon circulations. There are clear temporal and spatial correlations and complexity between the two.

The relationship between the two oceanic circulation anomalies shows that the anomalies lead to the northward shift of the wind belt of the summer pressure belt, and the EASM prevails at this time. This series of changes can well explain the weakening of the AMOC, the greater probability of the occurrence of the negative phase of the NAO, and the opposite change trend of the intensity between the summer monsoon and the westerlies during the cold climate period, that is, the intensity of the westerlies increases when the intensity of the summer monsoon becomes weaker. It also reveals the "seesaw" pattern between the Icelandic low in the Atlantic Ocean and the Aleutian low in the North Pacific Ocean. At present, a large number of studies support the conclusion that there is interaction between the above-mentioned atmospheric activities of the two oceans, such as the impact of the NAO on climate change in the middle and high latitudes [9,14,90,92], the PDO and the Aleutian Low Pressure [91,93–96], the NAO and the La Niña [90], the AMOC and the EASM [97], as well as the related atmospheric activities between the East Asian Barometric Trough [98,99], the westerly jet [100–102] and the East Asian monsoon [87,103,104].

Based on the above analysis, the environmental changes of the Alashan Plateau since the last glacial period can be understood from the relationship between the three factors at different time periods, namely the intensity changes of the westerly and monsoon circulation systems and the amount of solar radiation in the northern hemisphere (Figure 7). Overall, the climate change in the first stage of the last glacial period (40~30 ka) on the Alashan Plateau should be mainly affected by the westerlies because the EASM was weak and the winter monsoon was strong during the glacial period. However, the climate effect of the winter monsoon is weaker than that of the westerlies because the winter monsoon climate is mainly characterized by being cold and dry, while the westerly climate is relatively cold and wet, and the amount of solar radiation at this time is small, so the temperature of the Alashan Plateau is relatively low and the climate is relatively cold and wet. During the second stage of the last glacial period (about 21~13 ka from the LGM to the deglaciation), the temperature showed an increasing trend. At this time, the solar insolation also increased, the intensities of the westerlies and the Asian winter monsoon weakened, and the intensity of the EASM increased. However, the effect of the winter monsoon was still dominant, so the Alsahan Plateau had little water vapor during this period and the climate was relatively dry. During the early Holocene, the insolation intensity was relatively high (Figure 7), so the humid climate of the plateau should be mainly caused by the strengthening of the EASM, while the increase in temperature was mainly caused by the high intensity of solar radiation. Therefore, the plateau climate was warm and humid during this period. During the middle Holocene, the intensity of the westerlies increased and was much larger than that of the winter monsoon, while the summer monsoon was relatively weakened. However, the intensity of the summer monsoon on the plateau was still high due to the large amount of solar insolation (Figure 7). At this stage, the westerlies will also transmit some water vapor to the plateau, but due to geographical constraints, the amount of water vapor reaching this area is not much, so the warm and humid climate of the plateau is still mainly affected by the summer monsoon. In the late Holocene, the solar insolation continued to decrease (Figure 7), the summer monsoon continued to weaken, and the winter monsoon and the westerlies continued to strengthen. However, the influence of the winter monsoon in this region was greater than that of the westerlies, resulting in a dry climate on the plateau.

In addition, the changes of lake hydrological environment and lake water levels in different periods on the Alashan Plateau and its surrounding area can also be understood from the water vapor transport effect of the two major circulation systems.

According to the modern climate records and climate simulations of the Alashan Plateau (Figure 10), the westerlies bring moisture to the Alashan Plateau mainly in winter, the precipitation in summer mainly comes from the EASM and is lower than the evaporation, and the remote water from the mountain ice after spring breeds the rivers in the western Alashan Plateau and flows into the lakes at the end of the northern plateau [14]. Alternatively, the location of the Alashan Plateau is relatively far away from the control area of the EASM (Figure 9), so it is difficult for the moisture of the EASM to reach the western and northern parts of the Alashan Plateau (such as the Juyanhai Lake area) in summer. This indicates that the winter precipitation is the major source of moisture on the Alashan Plateau, and it mainly comes from the westerlies rather than the EASM or Arctic Ocean.

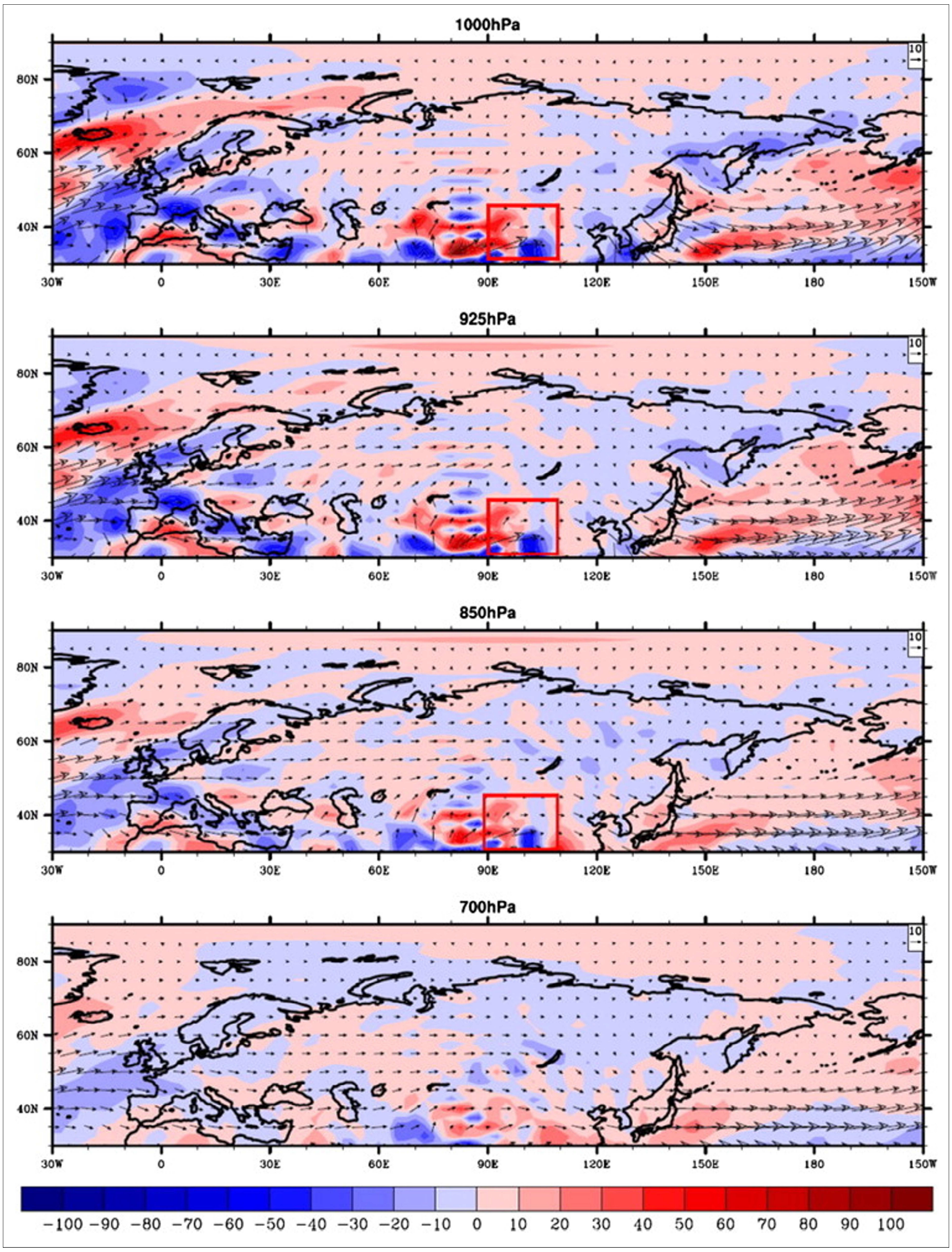

Figure 10. The modeling of moisture supplement on the Alashan Plateau (the red box in the figure) during winter (November, December, January, and February) from AD 1948 to 2009 based on the NCEP (National Centers for Environmental Prediction) (revised from [14]). The arrows in the figures represent moisture delivery capacity, and the negative blue color represents the convergence current and the positive red color represents the divergence current. The air pressures of 100, 925, 850, and 700 hPa represent the altitudes of near ground at 600, 1500, and 3000 m, respectively. Moisture is mainly supplied from the southwest red area in the Qilian Mountains below an altitude of 3000 m.

It can be seen that the climate of Central Asia is coupled not only with the monsoon system but also with the climate of the North Atlantic through the changes in the intensity and location of the westerlies. This connection may have become particularly important in the late Holocene after the Asian summer monsoon retreated southward. According to Seager et al. (2007) [89], the location and intensity of the westerlies are affected by the positive change of the North Atlantic Oscillation (NAO) and the Siberian High (Figure 11). A positive NAO is caused by a stronger than usual subtropical high-pressure center and a deeper than normal Icelandic low [105].

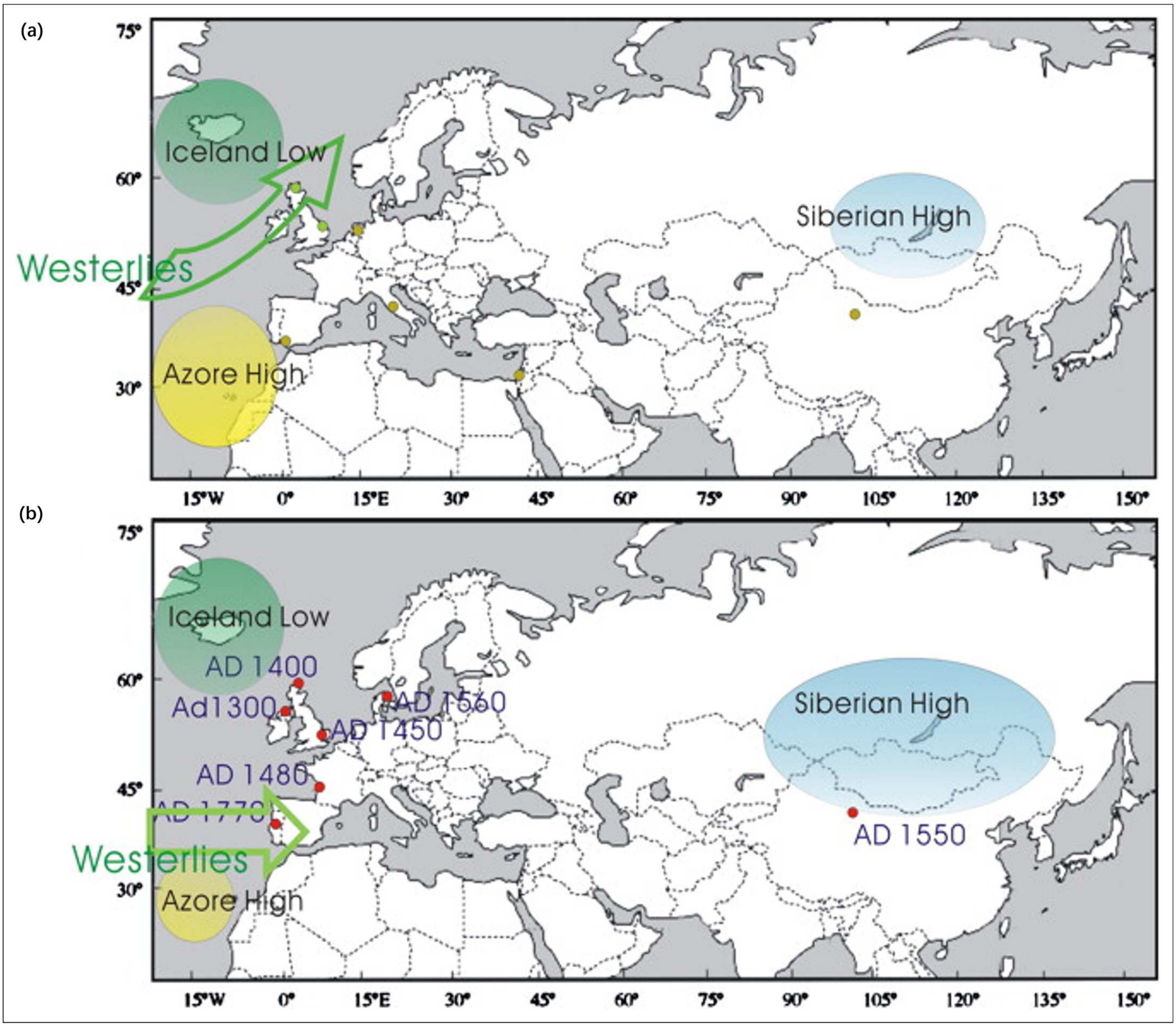

Figure 11. The movement of westerlies controlled by the NAO influence and Siberian High during the Medieval Warm Period (**a**) and Little Ice Age (**b**) (revised from [14,89]). (**a**) the brown dots are dry records and the green ones are wet records during the Medieval Warm Period; (**b**) the red dots are the onsets of the sand invasion event in Europe and drying of Central Asia during the Little Ice Age.

During the LGM period (such as 21 ka BP), high lake levels generally appeared on the plateau and its surrounding areas. This can be attributed to the relatively strong continental ice sheets in the high-altitude areas of the Asian continent during this period, which forced the westerly belt to migrate southward, reduced the temperature gradient between sea and land, shrank the EASM, and induced the westerlies to be strong all year round. Meanwhile, the low temperature in the glacial period caused lower evaporation, resulting in less water loss and higher lake water levels [56]. In other words, westerly precipitation and low evaporation were the main reasons for the high lake levels during the LGM. During the middle Holocene, the lake water level on the Alashan Plateau was also high, but this should have been caused by the intensification of the summer monsoon circulation and the increase in monsoon precipitation during this period. In contrast, the lake water level of the plateau in the middle Holocene was higher than that of the lakes during the LGM because the westerlies during the LGM had less rainfall and less evaporation (that is, less water vapor output), while there was more monsoon rainfall (more input) during the middle Holocene. It should be the main difference between the two periods. This also shows that the water vapor effect of the westerly circulation system on the Alashan Plateau is smaller than that of the monsoon circulation.

Spatially, from the Alashan Plateau westward to the adjacent inland areas of Xinjiang in northwest China and the arid region of Central Asia, the monsoon water vapor effect on the lake water levels in these mid-latitude arid regions decreases with the increase in distance from the source area, and the water vapor effect of the westerlies is enhanced, resulting in that the water vapor in these regions mainly comes from the westerly circulation system. Different from the monsoon water vapor from the Pacific source region in summer, the water vapor sources of the westerlies are the Atlantic Ocean, the Arctic Ocean, the Mediterranean Sea, and the Black Sea [106], and the winter precipitation accounts for a very large proportion of the annual precipitation. That is to say, the water vapor of the monsoon circulation is greatly affected by the solar radiation in summer, while the water vapor of the westerlies is greatly affected by the solar radiation in winter. From a global perspective, although the total solar radiation in the northern hemisphere has been decreasing from the early Holocene to the PI (Pre-Industrial, 1800 AD) period (Figure 7), the solar radiation in winter has been increasing from the early Holocene to the PI [107], which has increased the winter rainfall in this region from the early Holocene to the late Holocene. That is, the water vapor effect of the westerlies has increased and the monsoon water vapor effect has weakened. Therefore, in the arid regions of Central Asia, the low lake water levels during the early Holocene were mainly caused by less precipitation (winter precipitation, low westerly water vapor effect, and strong evaporation), while the high lake levels during the middle Holocene were mainly caused by an increase in precipitation (both summer and winter precipitation increased, that is, both the monsoon and westerly water vapor effects increased).

3.6. Role of Holocene Insolation and ITCZ on a Global Scale

At present, there are few studies focused on the response of environmental evolution on the Alashan Plateau to global climate change since the last glacial period, so the correlation between regional and global climate changes is still unclear at a global scale. However, the academic community generally agrees that the climate changes between the two are consistent on orbital, suborbital, and millennium time scales, such as the cold climate during the last glacial period and the warm climate during the Holocene. For the mechanism driving temperature change since the last glacial period, the forcing factors of global temperature change should be dominant on the Alashan Plateau, such as the change of solar radiation driven by the orbital scale [18]. However, for the change in rainfall in the middle latitudes of NH, the reasons may be much more complex. In addition to the global insolation change, the consequent changes in ocean activities at the suborbital scale are also crucial, such as changes in the north AMOC [108,109]. Events on smaller time scales, such as the NAO, the PDO, and changes in ENSO and ITCZ [109–111], all directly or indirectly affect the rainfall oscillation of the middle latitudes of NH, including the Alashan Plateau in central Asia.

Paleoclimate records and climate model simulations show that the change in the orbital forcing of solar radiation is the main factor leading to long-term climate changes in the Holocene [112,113]. The summer insolation intensity in the NP has gradually decreased since the early Holocene (Figure 7). Emerging empirical evidence shows that the intensity of the EMSA has also decreased from the early Holocene (when the monsoon intensity was the strongest) to today, along with the variational trend of the boreal summer insolation [114,115]. Therefore, the change of insolation is considered to be the key factor controlling the change of the Holocene ASM [111]. Other geological records and model simulations have also observed this correlation between rainfall anomalies and insolation change at the hemispherical and millennia scales [116–118]. However, marine core records from the Arabian Sea show that the intensity of the Indian summer monsoon (ISM) during the Holocene did not change with the change in solar radiation [119]. This indicates that the spatiotemporal pattern of the ASM precipitation responds inconsistently to the insolation variation in the Holocene. It means that the intensity of the ASM rainfall is controlled by factors other than the monotonously declining global insolation in the Holocene.

On the interannual and interdecadal scales, nearly periodic changes in precipitation have been observed around the world [109]. There are two main reasons for the periodic changes in this rainfall oscillation, namely, the El Niño Southern Oscillation (ENSO) and the sea surface temperature (SST) anomaly of subtropical gyres [120]. Compared with interannual and interdecadal variations of precipitation and ENSO events, rainfall oscillations on longer time scales (e.g., the Holocene period) have been observed in all latitudes of the world [109]. On the centennial, millennial, and 10,000-year time scales, the change of ENSO activity has a monotonic trend consistent with the change of solar radiation in the Holocene, which has continued to weaken since the middle Holocene [121]. Therefore, it seems that variations in solar radiation and ENSO on the planetary scale and on the millennial scale are still the controlling mechanisms of rainfall oscillation in the Holocene.

ENSO events originate in the tropical Pacific Ocean. Although ENSO causes global changes in temperature and rainfall, it mainly affects the tropics rather than the middle latitudes [122,123]. Secondly, both insolation and ENSO changes have shown a monotonic trend with a small variation range in the Holocene (Figure 7). The observed rainfall oscillation differences between the EASM and the ISM in the Holocene cannot be interpreted as a simple linear response to the above factors.

Environmental proxy records and model simulations show that not only between the EASM and ISM control areas but also the Holocene rainfall oscillation, there are regional differences on a larger scale. For example, significant variability of the Holocene precipitation can be observed in South America and Asia, while it is relatively stable in Europe [109], which forms a sharp contrast in the long-term trend of global rainfall oscillations. This difference further suggests that the control mechanism of rainfall oscillations in Asia is different from that in Europe (which is controlled by ENSO activities) on centennial and millennial scales, and there are other potential mechanisms driving such climate change in Asia.

The differentiated responses of regional scale to global climate change necessarily mean the amplification of solar radiation and orbital forces [109]. Both environmental proxy records and model simulations have confirmed that the regional differences of long-term rainfall oscillations on millennial scales seem to be mainly related to the latitudinal migration of the summer ITCZ in the near-equatorial region, and the area most affected by it is the area near the Hadley cell, namely the mid-latitude [109,111].

For example, stable oxygen isotopic compositions ($\delta^{18}O$) of speleothems from low latitudes in Asia indicate that the extension of the polar caps in the early Holocene increased the thermal gradient between the high and low latitudes of the subtropical gyres due to the influence of solar radiation changes since the late Pleistocene and thus increased the amplitude of the subtropical Gypes Rossby Waves [124]. Thus, the increase in the thermal gradient and GRWs favors the poleward migration of the summer ITCZ as well as the subtropical gyres due to the poleward displacement of trade winds (westerlies) and the wind-driven currents. This is the amplification effect of the subtropical gyres of NH on solar radiation through the GRWs. The hydrological processes caused by the friction between the North Equatorial Current (NEC) and the North Equatorial Countercurrent (NECC) due to the strengthening of the above subtropical gyres can explain the weakening of ENSO activity in the middle Holocene and the southward migration of the summer ITCZ during the Holocene [125].

This indicates that at mid-latitudes, the rainfall oscillation mainly results from SST anomalies where the western boundary currents (westerlies and westerly-forced currents) leave the continents to reenter the tropical gyres [125]. One-half, 1-, 4-, and 8-year periods of westward propagating Rossby waves embedded in the wind-driven current of the gyres are paced according to the warm water amount transferred by the western boundary currents from the low to the high latitudes of the gyres [125]—a powerful feedback that results from the difference in temperature between the low and high latitudes of the gyres causes the westerlies and western boundary currents to accelerate/decelerate, which deepens or raises the thermocline around the gyres. In turn, the oscillation of the thermocline reinforces the modulation of the polar and radial currents of the gyres. This proves that the spatiotemporal variation of rainfall oscillations over Asia during the Holocene is related to both the acceleration/deceleration phase of the westerlies (including western boundary currents) and the contraction of the Hadley cell, both of which are related to the latitudinal migration of the ITCZ in response to the thermal gradient change in the summer NH.

In addition to the ASM history, some paleoenvironmental records have also reconstructed the intensity variation of the Asian winter monsoon [126–128]. These records show that the AWM intensity was stronger before the Bøling–Allerød warming, during the Younger Dryas event, and in the middle and late Holocene when the ASM intensity was weaker, as indicated by speleothem records. The inverse correlation between the ASW and AWM can also be explained by the southward migration of the ITCZ (Yancheva et al., 2007) [110]. During periods of warming in the NH (such as the Bøling–Allerød events and the early Holocene), the ITCZ moved northward, and at this time the ASM was strong and the AWM was weak. This driving mechanism and interpretation model of the ITCZ can also well explain the paleoclimate records of Tropical America [129,130]. It indicates that the effect of the ITCZ migration can cross the Pacific Ocean and influence climate change in the middle and high latitudes of the NH on centennial and millennial timescales.

To sum up, the changes in solar radiation and the latitudinal transition of the summer ITCZ in response to the changes in the thermal gradient of gyres during the Holocene are the important mechanisms influencing the Holocene rainfall oscillations and environmental changes in the mid-latitudes of Asia, especially the arid areas in northern China. Inevitably, they are also important reasons for the evolution of desert landscapes in the mid-latitudes of the NH, including the three large deserts on the Aalshan Plateau. Based on this understanding and in the context of current global warming, these mechanisms have important implications for predicting the dynamic changes of mid-latitude landscapes caused by anthropogenic global warming in the future.

4. Aeolian Landforms Evolution and Climate Change of the Alashan Plateau

The sandy desert landform composed of widespread aeolian dunes is one of the main landforms of the Alashan Plateau, especially the Badanjilin Desert, which is composed of many tall sandy mountains and is unique to the arid regions of the world. Similar aeolian landforms exist only on the terrestrial planet Mars. The above-mentioned records of paleoenvironmental changes on the Alashan Plateau, especially the high-resolution and continuous records, are mostly from the paleohydrological deposits such as paleolakes on the plateau, but less from aeolian landforms. From the perspective of climate geomorphology, the desert itself is the product of climate change and contains the records of past climate change [3,17,18,39], such as the composite sedimentary strata of aeolian sedimentation and aqueous/hydrodynamic (alluvial, diluvial, fluvial, and lacustrine) sedimentation widely existing in the hinterland of the desert [17,18,58]. Here we try to trace and summarize the existing documents on the relationship between the formation of plateau desert landforms and environmental changes.

4.1. Provenance of Desert Sands

From the perspective of geomorphological causes, the formation of a sandy desert requires three basic elements: a sand source, a transportation medium (climatic circulation conditions and geomorphic forces of wind and water dynamics), and the underlying surface conditions of sediment accumulation sites (topographical, geomorphological, and vegetation conditions, etc.) [3,4,109]. Sand sediment state and sand source are the first and key elements for the formation of dunes and sandy desert landforms [131], which mainly include three important aspects, namely sand sediment supply, transport capacity, and sand sediment availability (Figure 12). The amount of sand sediments available fundamentally determines the size of the sandy desert [4].

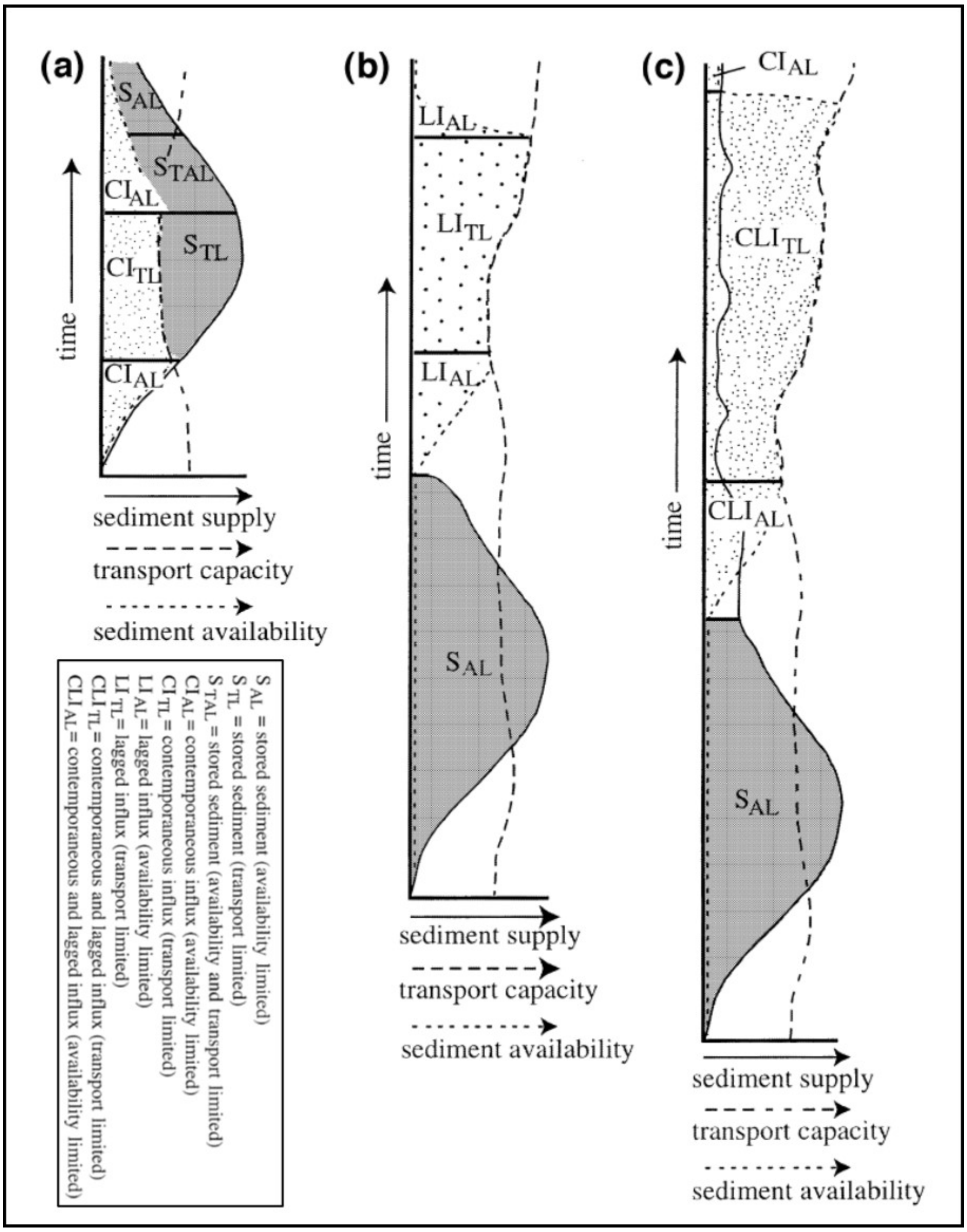

Figure 12. Sand sediment state determined by the plotting of sand sediment supply, sand sediment availability, and the transport capacity of the wind against time (revised [131]). (**a**) Aeolian construction is contemporaneous with the generation of the sand sediment supply. (**b**) Aeolian construction separated in time from an earlier period when the sand sediment supply was generated. (**c**) Aeolian construction sourced by both contemporaneous sand sediment supply and erosion of previously stored sand sediment.

The current research on the source of desert sand on the Alashan Plateau shows that the source of sand here is relatively complex. There are not only local, near-source, and distant sources depending on the distance of the source area, but also diversity in sediment types, including lacustrine sediments, hydraulic sediments associated with rivers (alluvial fans, proluvial sediments, playa sediments), surrounding gobi sediments, mutual sources of different sandy deserts (desert sand mixing), bedrock weathering products, weathered crusts (Figure 13), etc.

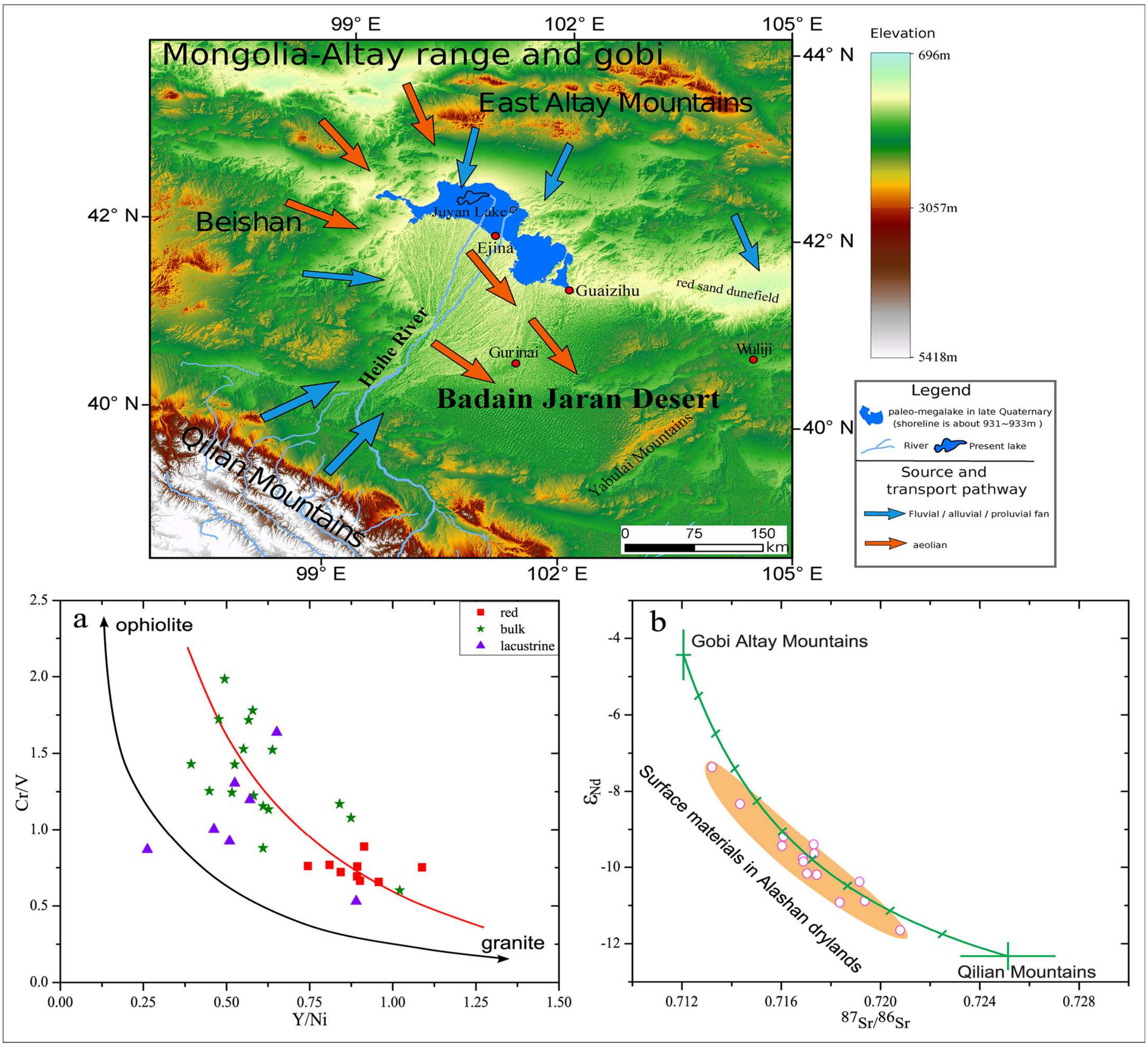

Figure 13. Source areas and source materials of dune sand in sandy deserts of the Alashan Plateau (revised from [24]). Schematic graph of source and transport pathways of sands in the Badanjilin Desert showing source contribution from Qilian Mountains and Gobi Altay Mountains via fluvial-alluvial and aeolian processes (**upper figure**). Dried palaeo-megalake beds (blue-shaded areas) are potentially direct sediment sources for aeolian transportation. Binary plots of (**a**) Y/Ni vs. Cr/V for different samples, mixing line between ophiolite and granite end-members indicating relative proportion of ultramafic and felsic rocks in the source regions. The plot of Y/Ni vs. Cr/V showing source materials from the Qilian Mountains tend to have higher ultramafic components than from Gobi Altay Mountains and implying a mixture of binary sources from Qilian Mountains and Gobi Altay Mountains for the Badanjilin Desert sands; (**b**) $^{87}Sr/^{86}Sr$ vs. ε_{Nd} (modified from [132,133]), mixing line between Qilian Mountains and Gobi Altay Mountains end-members.

Based on the analysis of the mineralogical composition of sand, ref. [54] suggested that the sand particles of sand dunes in the Badanjilin Desert mainly come from the local lake sediments (between the sand dunes or the desert periphery), because their mineralogical compositions are similar to those of the active dunes and residual dunes on the tall sand mountains. Yan M et al. (2001) [134] proposed that the Badanjilin desert sand was derived from a large number of lake sediments in its western and northwestern dry lakebeds. Yang X et al. (2003) [10] believed that the detrital sediments of the Badanjilin Desert were derived from the fluvial deposits of the Ruoshui River and the lake deposits around the desert, while Wang F et al. (2015) [23] proposed that the alluvial fans formed by the Heihe River, originating from the Qilian Mountains, were also one of the sand sources in the Badanjilin Desert. Through the major- and trace-element geochemical analysis of aeolian sand and lake sediments, Hu and Yang (2016) [24] suggested that the dune sand in the Badanjilin Desert mainly came from the Qilian Mountains and was transported by rivers, while the red dunes in the northern part of the desert originated from the Altai Mountains and the Mongolian Gobi (Figure 13). Secondly, the supply of aeolian sand in the peripheral deserts may also be an important source (Figure 14), such as the supply of a large amount of aeolian sand from the Badanjilin Desert to the Tenggeli Desert [21,135]. In addition, the weathering of bedrock also plays an important role in the material supply for sand dune formation [54].

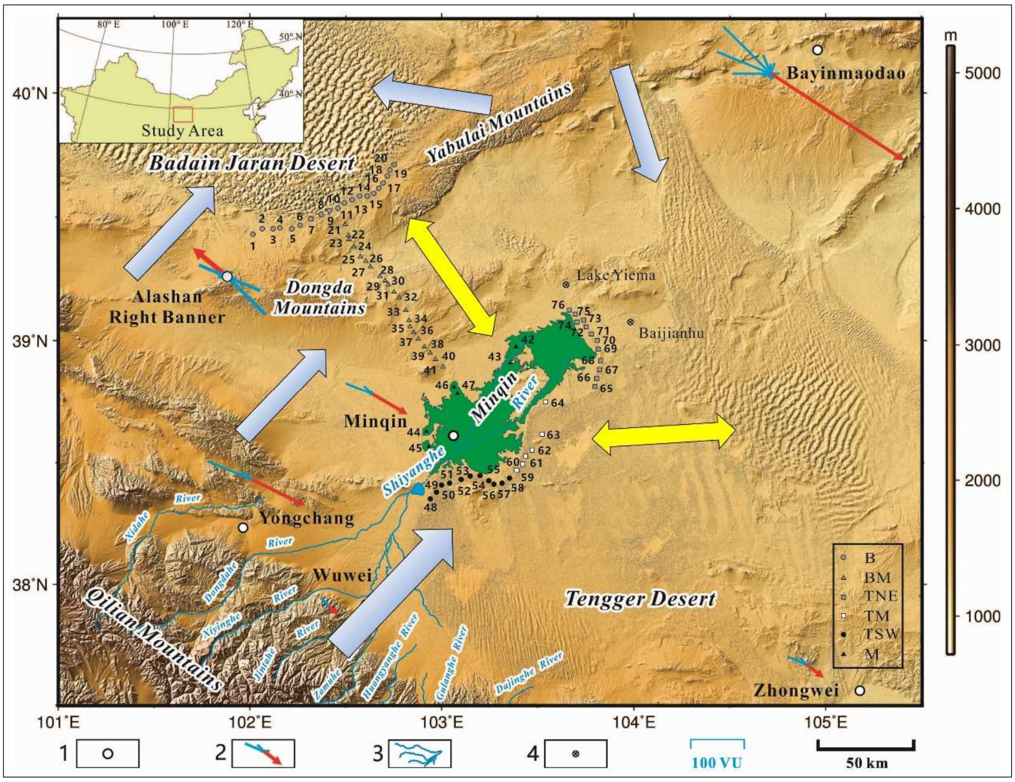

Figure 14. Potential source areas of desert sands on the Alashan Plateau indicated by different arrows (revised from Ren et al., 2014) [21]. B, Sampling sites in the Badanjilin Desert. BM, Sampling sites along dune belt from the Badanjilin to the Minqin Oasis. TNE, Sampling sites at the northeastern edge of the Minqin Oasis. TM, Sampling sites at the southeastern edge of the Minqin Oasis. TSW, Sampling sites at the southern edge of the Minqin Oasis. M, Sampling sites in the area of the Minqin Oasis. 1, Weather stations. 2, Sand rose. 3, River. 4, Sedimentary sequence sites. Sand roses for each of the five surrounding weather stations, with blue lines showing winds capable of transporting sand from various directions (DP) and red arrows indicating the resultant sand transport trends (RDP). For interpretation of the references to color in this figure legend, the reader is referred to the web version of the paper by Ren et al. (2014) [21].

It can be seen from the above that there are inconsistencies between the existing research results, indicating that there is no unified conclusion on the understanding of the source of desert sand on the Alashan Plateau. The existence of this problem may have the following reasons: Firstly, regarding the selection of the study area, a large number of studies are concentrated in the Badanjilin Desert, while there are fewer studies in the Tenggeli and Wulanbuhe Deserts and even fewer studies on the detrital materials from the periphery of the deserts. Secondly, many studies lack definite kinetic evidence on the material transportation modes, pathways, and cycles of detrital sediments. Due to the complexity and variability of geomorphic processes (such as wind, water, and glacier forces, etc.) and the uncertainty of some factors, such as the migration paths, differentiation processes, and exotic material interferences in the process of material transportation, the recycling, mixing, and post-depositional processes, and so on, it brings many difficulties to the qualitative and quantitative analysis of desert sand sources. For example, even if the mineral compositions or the ratios of elemental compositions of aeolian sands in the two regions are similar, it is difficult to explain the mother-child relationship or affinity between each other because both may originate from the third region, use the same intermediate source product, experience a similar degree of mixing, etc. In addition, many studies on the provenance of aeolian sand lack the collection and direct comparative analysis of samples from potential source areas in surrounding or distant areas, and some conclusions are still "indirect" or hypothetical. The provenance study of aeolian sand should do systematic work on material recycling, sediment transformation, sediment sorting, compositional variation, and source-to-sink analysis of clastic sediments between possible source areas and the dune land, which includes the collection of large-scale, uninterrupted typical detritus samples and the "gene" analysis of diverse compositions of the samples. Potential parent materials may involve gobi clastic sediments, weathered rock clastic materials, river sediments, lake sediments, alluvial-proluvial fan sediments, and even distant glacier or periglacial materials [29]. At the same time, the study of provenance also needs to consider the topographical and geomorphological gradients on the migration route of sediments, the characteristics of geological agents, lithology changes, and dynamic changes of climatic parameters (such as wind direction, wind speed, etc.) and their impact on the variation of debris material compositions. Therefore, the study of desert sand provenance is almost a complex work involving the integrated interaction of multiple systems and processes, which clearly needs more research in the future.

4.2. Forces Driving the Transportation of Aeolian Sand on the Alashan Plateau

In addition to the overall consideration of the above-mentioned potential source areas, the complexity and dynamic characteristics of the aeolian sand transport medium on the Alashan Plateau are also important issues to be considered. Based on the analysis of environmental parameters and geomorphoclimatic forces, the geomorphic forces of the Alashan Plateau are mainly from running water, wind, solar radiation, and weathering processes (such as drying denudation, insolation weathering, and salt weathering) [53,136,137]. Among them, running water and wind are not only the main transport media of desert sand, but their combined effect has become a hot issue in the study of landform evolution in non-glacial environments [138–145]. This compound effect is especially important for the emergence of aeolian sand and even the formation and development of dunes [131,146]. From the analysis of aeolian sand physics, the wind direction determines the type and direction of dune formation. For example, the Alashan Plateau is under the control of the northwesterly wind and its corresponding sand transport potential all year round (Figure 2e), so the desert sand is mainly transported from the northwest to the southeast and the dunes move to the southeast [11,54,147]. In turn, according to the distribution characteristics of the windward and leeward slopes of the dunes and the direction of the dune ridge line, the regional dominant wind direction and the direction of the atmospheric circulation can be judged, and the role of the circulation and even climate change on the formation of the dunes can be further reflected. Yang X (2001) [54] speculated that the original direction of the sand dunes was north-east through the observation of the Gurinai Basin, indicating that the north wind was stronger than the current during the dune formation period, and several ancient dunes in the tall sand mountain area were formed by the northeast wind, which can infer the direction of the prevailing wind in the past, with the northerly wind leading to a drier climate. Yang Y et al. (2014) [135] judge the properties of the sand-transporting wind attributes on the plateau and their contribution to the sand material on the main plateau based on the wind field data at the junction of the Badanjilin and Tenggeli Deserts (the Yamalik Desert) and found that there are three prevailing directions of sand-transporting wind on the plateau (NW, WNW, and NNW), which account for 62% of the total frequency of the sand-transporting wind. The frequency of the prevailing wind is highest in the spring. The percentages of sediment transport in the three directions of NW, WNW, and NNW are 36%, 35%, and 6%, respectively, accounting for 77% of the total amount of the sediments transported in the study area. The amount of sand sediment transported by the sand-transporting wind in spring and winter accounts for 99.8% of the annual average. These studies show that the construction period of the dune landform on the Alashan Plateau mainly occurs in the relatively arid environment in winter and spring rather than in summer, and the winter monsoon system plays a dominant role in the formation of aeolian landforms on the plateau. In addition, regarding the role of wind intensity/wind energy in the formation of plateau deserts, some studies have found that the appearance of tall dunes at the local scale and the appearance of sand deserts at the regional scale have lower wind energy than the appearance of sandy land in a stable environment [2,11,17]. This shows that although the formation of sand dunes and even sand deserts is related to the intensity of wind, the low wind energy environment is more conducive to the accumulation of sand and the construction of high sand dunes, while the high wind energy environment is more conducive to the transport and erosion of sand but is not conducive to the accumulation of aeolian sand and the formation of sand dunes. However, a low-wind environment is also not conducive to the establishment of sand dunes.

4.3. Formation of Tall Sand Mountains

The tall, sandy mountains have become a geomorphological symbol that distinguishes the Alashan Plateau from other deserts in the world. It is mainly distributed in the Badanjilin Desert, in the middle of the plateau. Research on the origins of these tall sand dunes has a long history, and the dispute is the most intense. Judging from the topographical and geomorphological characteristics of aeolian landforms and their accumulation areas, the sandy deserts in China include three terraces [148], which are mainly distributed in low-lying basins and plateau platforms. This landscape does not appear in the mountain area because it is too steep to accumulate materials [1]. Ancient sand dunes were mainly fixed by calcareous cementation [8,102], the formation of which requires specific environmental conditions, such as moderate rainfall [39]. The influence of underlying landforms on the formation of tall sand dunes is still controversial. Early studies believe that the pattern of high sand dunes is controlled by the underlying landforms; however, later studies suggest that the underlying landforms do not determine the overall pattern of tall sand dunes [11,17,146], but ancient dunes are a major factor in maintaining high tall dunes, and modern dunes are formed by the accumulation of mobile sand covering these ancient fixed dunes [17].

In addition to the above-mentioned effects of wind forces and underlying landforms, Chen J et al. (2004) [149] suggested that the tall sand dunes were maintained by groundwater derived from the northeastern mountains of the Qinghai–Tibet Plateau. Yan M et al. (2001) [134] proposed that the formation of tall sand mountains depended on diverse factors such as sand supply, wind conditions, underlying landforms, and shrub vegetation. Yang X et al. (2011) [17] based on a comprehensive study of geochronology and geophysical methods, considered that the bedrock landform of sand mountains, the massive sediment supply generated by the fluvial process at the edge of the desert, complex wind conditions, cementation of ancient dunes, and alternating wet and dry climates had all played an important role in the formation of the tallest sand dunes on the earth.

Based on the existing studies, it can be considered that the formation factors of the tall sand mountains on the Alashan Plateau are consistent with those of other parts of the world under the influence of a typical climate and environment. Firstly, the abundant supply of sand sources is the primary factor that determines the potential material basis for the formation of tall dunes. Secondly, ancient dunes are the key to the establishment of tall dunes, and the multi-stage construction process of ancient dunes is not only related to the sand source but also to the environmental conditions and climate changes (such as changes in precipitation or effective humidity) in the past, which include the maintenance of tall dunes requiring a relatively humid environment, the formation of calcareous cement, or the blocking of vegetation against external interference, as well as the role of abundant groundwater and interdune lakes. Thirdly, the heights of tall dunes are affected by wind strength (erosive force). As mentioned above, the wind energy is relatively low when the tall sand mountains are formed, but the standard of this "low" is still unknown. Finally, the underlying landform is also another important factor affecting the height of sand mountains. The bedrock topography and geology of the underlying sand mountains are relatively more conducive to the establishment and maintenance of early dunes and the formation of the maximum height of the dunes, as if the dunes here were formed by "standing on the shoulders of giants." In addition, the stability of the regional atmospheric circulation boundary layer and its turbulence height (the height of the wind erosion surface) may also be potential factors affecting the tall sand mountains in the Badanjilin Desert, because these are important factors affecting the height of the largest sand mountains on Mars [150–152].

4.4. Desertification and Environmental Change

On a global scale, the formation of sand dunes is related to the traditional glacial drought; that is, the aeolian process is strong in periods of cold and arid climate, which is conducive to the establishment and development of sand dunes. On the contrary, aeolian activity is weak in periods of warm climate, which is conducive to the stability of sand dunes and the formation of cemented surfaces. From the above-mentioned transportation medium of aeolian sand and the trend and distribution characteristics of sand dunes on the Alashan Plateau, it can be seen that the prevailing period of the winter monsoon is more conducive to the formation and expansion of the plateau desert, and the climate is generally cold and dry at this time. Paleoclimate records also show that during the last glacial period and the early Holocene, an aeolian environment prevailed in the northern Wulanbuhe Desert and the Jilantai area [20,153], and the ancient lakes in the desert region shrank and separated after 6.5 ka BP [36], that is, the modern desert occurred around 6.5 ka BP. The transition from a relatively humid alluvial/fluvial environment to an arid desert environment reflects that the Badanjilin Desert was formed at least 1.1 Ma ago [23]. Although the initial formation time of deserts on the Alashan Plateau is still debated and the evolutional processes of the deserts are accompanied by the alternation and transformation of humid environments (emergence of lakes, calcareous cements, etc.) and desert landscapes, from the perspective of climate change on a global scale, the formation of sandy deserts generally corresponds to the ice age or the cold climate period. For example, the research of An Z et al. (2012) [60] pointed out that the influence of the westerlies in the last glacial period was dominant and manifested as a significant sandstorm-enriched period related to the Heinrich events, reflecting the strengthening of the westerlies associated with the climate at high latitudes in the northern hemisphere. The study by Zheng M et al. (2007) [154] also pointed out that the core sedimentary records of the Zabuye Salt Lake are well consistent with the cold event records in the ice cores of the Arctic and the Qinghai–Tibet Plateau. Compared with the cold climate of the last glacial period, the Holocene climate was generally warm. It can be seen from the above discussion that the lakes in the study area were generally expanded, the water level was raised, and the desert was developing weakly during the Holocene period.

5. Conclusions

By reviewing the existing domestic and foreign literature and research results, this paper has reached the following conclusions and identified the following prospects for the climate changes and desertification of the Alashan Plateau since the last 40 ka of the last glacial period:

(1) The climate change of the Alashan Plateau since the last glacial period has a good correspondence with global climate change on the orbital, suborbital, and millennium scales, but there is a relative lack of records and evidence of typical climate events.

(2) From about 40 ka of the last glacial period to the end of the last glacial maximum, the climate was wetter than at present, which was not conducive to further desertification on the plateau. The climate was then generally arid, and desertification strengthened until the end of the Pleistocene. However, the climate in the Wulanbuhe Desert was still wet during this period, and the reason remains unclear.

(3) The temperature during the Holocene was higher on the plateau. The climate was generally humid in the early and middle Holocene; the lakes were further developed, and the desertification was weak in these stages. In the late Holocene, the climate was arid, and desertification was strong. Among them, the climate change of the Tenggeli Desert in the early Holocene is opposite the overall trend of climate change on the plateau. As for the drought event in the middle Holocene, it is still controversial whether the spatial scale is local or regional on the plateau, which needs to be further discovered.

(4) In terms of the causes of climate change, it is generally believed that the climate changes of the study area are affected by the two major circulation systems of the westerlies and the East Asian monsoon, and the two have different effects in different periods. Although great achievements have been made on the evolution of the East Asian monsoon in geology, the specific mechanism and degree of the influences of the two need to be confirmed and improved by more climatological and meteorological evidence. In addition, the impacts of the Qinghai–Tibet Plateau and the Yellow River cannot be ignored, and the influence of human activities should also be considered on different time scales. Although this effect is relatively small on the millennium scale, the recent effect on the local or regional scale cannot be negligible.

(5) In terms of desertification, the landscape of the Alashan Plateau is distinctive because of the existence of tall, sandy mountains, but there is no unified conclusion on the source of desert sand. In particular, the geomorphic coexistence phenomenon of tall sand dunes and permanent lakes is difficult to explain by the traditional theory of climatic geomorphology. The explanation of its formation mechanism and evolution process requires more geoscientific evidence, such as geophysics and geochronology. The wind direction and wind energy indicated by the shifting-trend and distribution characteristics of sand dunes and the attributes of sand-transporting wind and its contribution to the provenance of desert dunes reflected in the wind field data further confirm that desertification generally corresponds to periods of cold and arid climate. As one of the desert landscapes, the establishment of sand dunes requires appropriate wind energy, and the defined range of this "appropriate" energy needs further study.

(6) In our future work, since the climate change of the Alashan Plateau is dominated by the patterns of the cold dry and cold wet (or warm humid) modes, it will be more helpful for us to compare and analyze the trend of regional-scale climate change against the background of a warming climate and to further clarify the relationship of climate change between the Alashan Plateau and the global. A key to answering this question may be the need to integrate the earth system sciences such as the westerlies, the EASM, the effect of the Atlantic–Pacific Ocean Circulation Anomaly, the third polar environmental effect of the Qinghai–Tibet Plateau, the hydrological effect of the Yellow River, etc. It also needs to integrate more cooperative research between climatologists, hydrologists, oceanographers, geologists, geomorphologists, geophysicists, and paleoclimatologists. In addition, due to the complexity of the

desertification with aeolian sediments from source to sink, the research on the provenance of desert sand on the Alashan Plateau needs to combine more environmental elements and try to conduct comprehensive sampling and experimental analysis in as large a range as possible between the potential source areas of clastic materials (such as plateaus and mountains), transition zones (such as Piedmont and planation terrains, alluvial/proluvial fans, gobi deserts, river deltas, terminal lakes, etc.), and depositional zones (such as dune fields).

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