Dear editor,

Thank you for your letter and for the reviewer's comments concerning our manuscript entitled "Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Maximum and its implication for hydrological change in Central Asia" (Manuscript No.: cp-2020-53). Thanks very much for your hard work to this paper. Those comments and suggestions are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We appreciated the comments and suggestions very much. According to the comments from the reviewers, we completely revised the paper. Particularly, we highlighted the study area and supplemented the relevant results of PI period or the late Holocene, as well as reworked the structure of the "results and discussion" sections in the revised version. A point-by-point reply to the comments, a list of all relevant changes made in the manuscript, and a marked-up manuscript version are listed below this letter. We look forward to your satisfaction with this revision.

Yours sincerely,
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A point-by-point response to the reviews

Response to Referee #1

General responses:

Reviewer 1 concerned that the title of the article does not highlight the main research area and climate change in the late Holocene or PI period has been less discussed. In the revised version, we modified the title of this article and supplemented relevant contents about climate change in the late Holocene or PI period. Also, she/he has provided some specific comments on the manuscript, and we revised the manuscript as he/she suggests. A detailed list of changes against each point which is being raised was in below.

General comments The study presents an interesting way of separate the influence of westerlies and monsoon on

mid-latitude closed basins by complementing paleoclimates records and climate models. However, minor changes should be made before final publication.

1. Most of the work and its conclusions are applicable to the Northern Hemisphere (NH); in my opinion this should be represented in the title of the work.

Response: Thank you very much for your suggestion. Our study regarded global closed basins with prominent water resources problem and explored synergy of the westerly winds and monsoons in lake evolution since the LGM. We first discovered that there is a significant differentiation between the monsoon regions and the westerlies in the evolution of water balance over the global closed basins, especially the Northern Hemisphere. Then we focused on the climate change in closed basins of the Northern Hemisphere which is affected both by low-latitude monsoons and mid-latitude westerly winds. Further, we emphatically investigated the millennial scale evolution characteristics and mechanisms of East Asian summer monsoon and westerly winds in closed basins of the Asian continent since the LGM. Following your comments, we revised the title to "Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Maximum and its implication for hydrological change in Central Asia" in the revised version.

2. In Material and Methods section, authors consider three periods (LGM, MH and PI); however, in most of the analyses only LGM and Holocene are studied, having only a few mentions about the late Holocene or PI period.

Response: Thank you very much for your suggestion. We supplemented the analyses of climate characteristics in the PI period or the late Holocene in the revised version.

3. I am little confused, in P7, L144 said "Whereas, effective moisture increases since the LGM over the global Tropics". However, one the main conclusions of this work is that monsoon areas were characterized by dry conditions during the LGM (and late Holocene), and humid conditions during the early-mid Holocene. Please could you explain that?

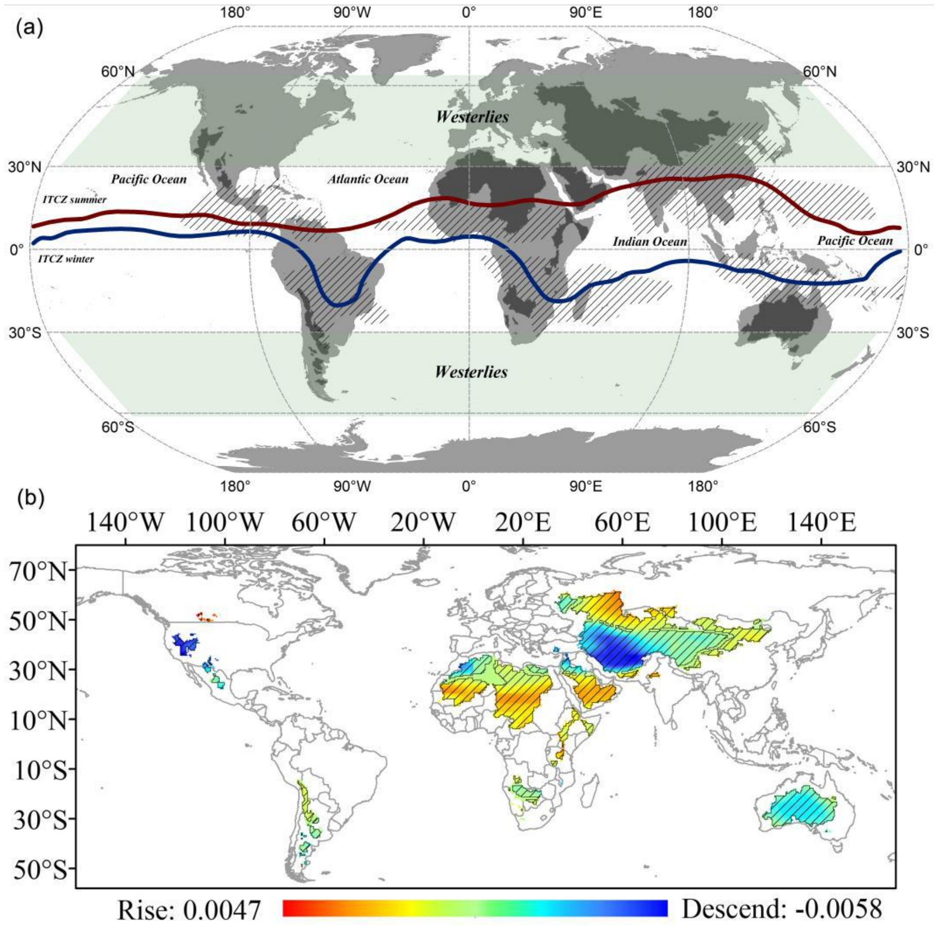
Response: Yes, of course. Based on the time series of the effective moisture change in the monsoon dominated closed basins of the Northern Hemisphere, we draw a conclusion that humid climate prevails in the early-to-mid Holocene and relative dry climate appears in the LGM and late Holocene. However, according to the trend analysis of continuous simulation in effective moisture change, effective moisture increases since the LGM over the global Tropics. Even effective moisture is relatively low in the LGM and late Holocene, and relatively high in the early-to-mid Holocene, the fluctuation of effective moisture is dominated by rising trend. Trend analysis is used to judge whether the fluctuation of the time series is mainly rising or falling, and we added this mathematical method in section 2.3. The updated contents are reproduced below.

"**2.3 Mathematical methods**

Linear tendency estimation is a common trend analysis method, which was chosen to measure the variation degree of simulated water balance in this paper. Besides, we also used the Empirical orthogonal function (EOF), a method of analyzing the structural features in matrix data and extracting the feature vector of main data, to examine spatially and temporally variability of simulated water balance. The spatial distribution of EOF first (second) mode is denoted by EOF1 (EOF2), and the time series of first (second) mode is denoted by PCA1 (PCA2)."

4. Figure 2: What are the dark areas in the map? Letters (a) and (b) are missing.

Response: Thank you for pointing this out, the dark areas are global closed basins. And we supplemented the caption and letters (a) and (b) of Figure 2 in the revised version. The updated contents are reproduced below.



“**Figure 2.** (a) Distribution of global closed basins and circulation system: The dark areas are global closed basins; summer and winter of the ITCZ are in accordance with the Northern Hemisphere; the shadows present the six monsoon areas according to Wang (2009), and (b) Trend analysis of continuous simulation in water balance change: The shadows indicate that the trends are statistically significant at 5% level.”

5. Figures 3 and 4: Improve figure caption, is not totally representative of the figure.

Response: Thank you very much for your suggestion. We improved figure caption of Figures 3 and 4. The updated contents are reproduced below.

“**Figure 3.** (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite

records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978).

Figure 4. Comparison between simulated water balance change and reconstructed moisture index in the mid-latitude closed basins of the Northern Hemisphere during the Holocene. Triangles indicate locations of paleoclimate records (Table 3)."

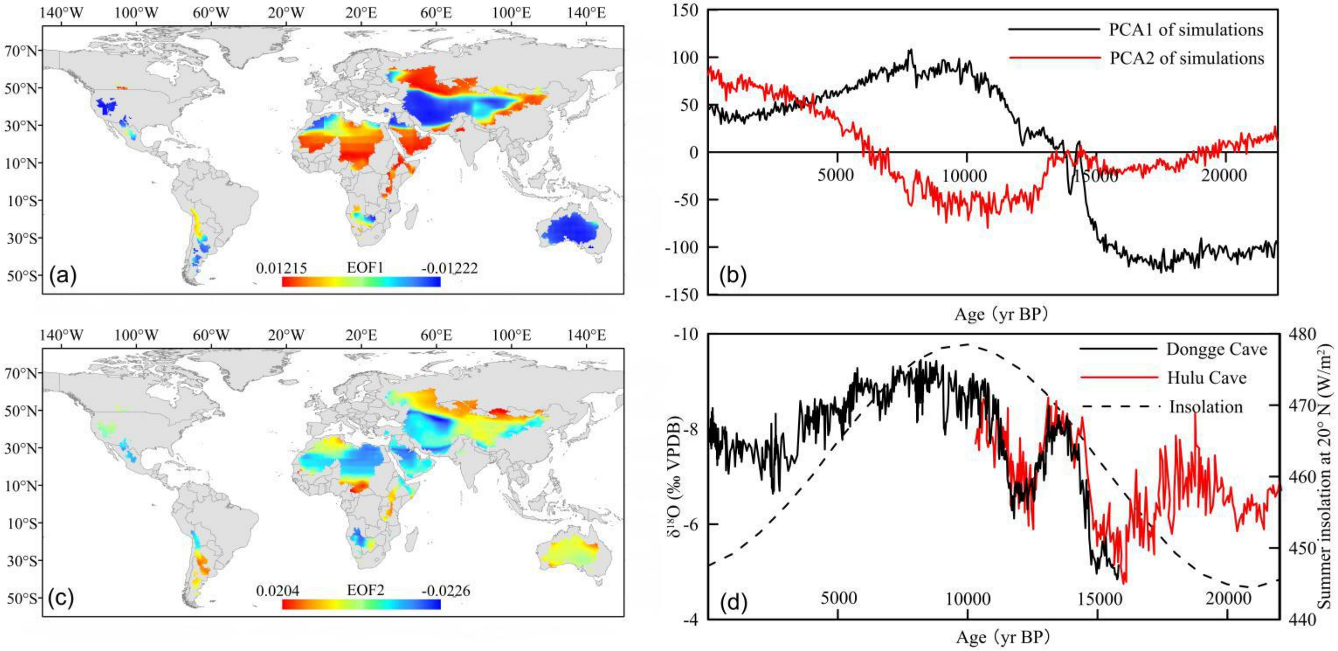
6. In P9, L177 text indicate that a moisture index was reconstructed from early Holocene to late Holocene. However, in methodology that fact is not totally explained.

Response: Thank you very much for your suggestion. We explained this in the revised version. The updated contents are reproduced below.

"Due to the different time scales of the collected continuous paleoclimate records, we can only reconstruct the regional moisture change from the early to late Holocene after unifying the time scales, but the purpose of this part is only to check the simulation results."

Specific comments 1. Figure 3: For reduce unnecessary information on Figure 3, only include latitude at one side of the map.

Response: Thank you very much for your suggestion. We modified the Figure 3 in the revised version. The updated contents are reproduced below.



"**Figure 3.** (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978)."

2. Figure caption on figure 6: I think that letters "(a)", "(b)" and "(c)" must go at the beginning of each description.

Response: Thank you very much for your suggestion. We modified figure caption on Figure 6. The updated contents are reproduced below.

"**Figure 6.** (a) Simulated water balance change between westerly dominated regions and monsoon regions in the Asian closed basins since the LGM, (b) General climate changing patterns during the Holocene in monsoon Asia and westerly Central Asia come from Chen et al. (2006), and (c) Extracted westerly dominated regions and monsoon regions in the Asian closed basins."

3. P4, L93, 96 and 100: It must be Equation (1) instead of Eq (2).

Response: Thank you very much for your careful examination of the manuscript. We modified this in the revised version.

4. P4, L101: It must be Equation (2) instead of Eq. (3).

Response: Thank you very much for your careful examination of the manuscript. We modified this in the revised version.

5. P13, L231: Text is confusing: “Major trend of moisture conditions revealed by the (. . .) is a gradual decrease since the early Holocene, and reaches the wettest status between 8 and 6 kyr in the East Asian monsoon region”. It describes a decrease in moisture but ends with wettest conditions. Please reword the sentence in order to avoid confusion.

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

“By comprehensively analyzing a variety of paleoclimate proxies, Wang et al. (2017) suggested that moisture change revealed by the Australian monsoon, the East African monsoon and the Indian monsoon regions reaches the wettest status in the early Holocene, while the wettest condition in the East Asian summer monsoon regions occurs between 8 and 6 kyr.”

Technical corrections P2, L50: “Simulate” instead of “simulating”. Include (precipitation minus evaporation) after P-E.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P2, L51: delete space before Pre-Industrial.

Response: Thank you very much for your careful examination of the manuscript. We deleted space before Pre-Industrial.

P2, L51-58: The sentence is too long, needs to be rephrased.

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

“The prominent spatial differentiation of monsoons and westerly winds revealed by simulations leads us to focus on the Northern Hemisphere mid-latitude closed basins which are simultaneously influenced by mid-latitude westerly winds and low-latitude monsoons. In the mid-latitude closed basins of the Northern Hemisphere, the good match between water balance simulation and reconstructed moisture index from 27 paleoclimate records verifies the reliability of the simulation results. Further, we disaggregated the Northern Hemisphere mid-latitude closed basins into the areas dominated by monsoons and westerly winds respectively, and emphatically explored the temporal evolution of the East Asian summer monsoon and westerly winds since the LGM. According to the climate records, we comprehensively considered the determinants that control the trend of climate change in the Northern Hemisphere westerlies and East Asian summer monsoon regions since the LGM."

P2, L53: "which" instead of "where".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P2, L57: add a "s" at the end of monsoon (= monsoons).

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P2, L58: "Last" instead of "last" (capital letter).

Response: Thank you very much for your careful examination of the manuscript. We deleted this.

P2, L58-61: I think that the phrase "(..) according to records of Quaternary ice sheets, low-mid latitudes summer insolation and winter insolation, δ18 O of Greenland ice core, etc." could be summarized.

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

"According to the climate records, we comprehensively considered the determinants that control the trend of climate change in the Northern Hemisphere westerlies and East Asian summer monsoon regions since the LGM."

P3, L67: delete space before 3 in CCSM3.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P3, L69: delete space before 4 in CCSM4.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P3, L84: Hostetler and Bartlein (1990)'s model.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P4, L90: Add parenthesis to the referenced cited (= Morrill (2004) and Li and Morrill (2010)).

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P4, L94: Add a space after AB.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P4, L95: Add space before parenthesis "lake(m year-1)".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P4, L104: Add parenthesis to the referenced cited (= Li and Morrill (2010)). Replace Eq. (2) by (1) and (3) by (2).

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P4, L108: Delete "and" and replace phrase "and lake status information sorted by latitudes are shown in Table 2" by "Lake status information sorted by latitudes are shown in Table 2".

Response: Thank you very much for your careful examination of the manuscript. We modified this. The updated contents are reproduced below.

"Lake status information sorted by latitudes is shown in Table 2."

P6, Fig. 1: In figure caption replace "mm/year" by "mm year-1".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P7, L138: Replace "that lakes with" by "in which lakes with"or "where lakes with". It is not clear to me if Qinghai Lake, Hala Lake and Zhabuye are examples of lake with relative high-level during MH or PI.

P7, L139: "and Zhabuye Lake. . ."

Response: Thank you very much for your careful examination of the manuscript. We deleted this sentence.

P9, Fig. 3: In figure caption add ", respectively." After "Wang et al. (2008)".

Response: Thank you very much for your careful examination of the manuscript. We reworded this figure caption. The updated contents are reproduced below.

"**Figure 3.** (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978)."

P10, L185: Add "that" before "a humid climate".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P10, L186: Delete "And" at the beginning of the phrase.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P10, L187: Delete "the" before "paleoclimate modelling".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P10, L188: Text is confusing, needs rewording ". . .resulting in the loss of lake water reduces and the high lake level sustains."

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

"Using paleoclimate modelling, Yu et al. (2000) mentioned that the low temperature during the glacial period causes a decrease of evaporation and a reduction of lake water loss, resulting in the appearance of high lake level."

P10, L190: replace "to increase" by "increasing".

Response: Thank you very much for your careful examination of the manuscript. We modified this.

P11, L201: include "and late Holocene" after "prevailed in the early Holocene".

Response: Thank you very much for your suggestion. We modified this.

Line 232: The phrase could be written as "The longest and highest-resolution drill core from Lake Qinghai (An et al. 2012) indicate that summer monsoon record generally(. . .).

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

"The longest and highest-resolution drill core from Lake Qinghai (An et al., 2012) indicates that the summer monsoon record generally resembles the changing trends of Asian summer monsoon records derived from Dongge and Hulu speleothems over the last 20 kyr, and the mid-latitude westerlies climate dominates the Lake Qinghai area in glacial times."

P14, L255: Change sentence by "In these regions, winter precipitation accounts for a large proportion of annual precipitation (Li et al., 2008)".

Response: Thank you very much for your careful examination of the manuscript. We modified this. The updated contents are reproduced below.

"Winter precipitation accounts for a large proportion of annual precipitations in these regions (Li et al., 2008)."

Response to Referee #2

General responses:

Reviewer 2 focused on the the title of the article and details of paleoclimate records, as well as the structure of the results and discussion sections. In the revised version, we modified the title of this article, supplemented details of paleoclimate records, reworked the results and discussion sections and added some new contents in different sections of this paper. Also, she/he has provided some specific comments on the manuscript, and we revised the manuscript as he/she suggests. A detailed list of changes against each point which is being raised was in below.

General comments The study combines simulated water balance in closed lake basins and paleoclimate records to distinguish the influence and temporal evolution of monsoon and mid-latitude westerlies on moisture levels. This study is an interesting approach to the influence of both the westerly winds and monsoon on climate changes since the Last Glacial Maximum. While as a whole the study is of good quality and fits within the scope of the journal, there are a number of issues with the manuscript, that I think will need to be taken care of prior to publication.

1. The authors present the study as global, but mainly focus on Central and East Asia.

Response: Thank you very much for your suggestion. Our study regarded global closed basins with prominent water resources problem and explored synergy of the westerly winds and monsoons in lake evolution since the LGM. We first discovered that there is a significant differentiation between the monsoon regions and the westerlies in the evolution of water balance over the global closed basins, especially the Northern Hemisphere. Then we focused on the climate change in closed basins of the Northern Hemisphere which is affected both by low-latitude monsoons and mid-latitude westerly winds. Further, we emphatically investigated the millennial scale evolution characteristics and mechanisms of East Asian summer monsoon and westerly winds in closed basins of the Asian continent since the LGM. We made some detailed interpretations in the revised version.

2. Some changes in the structure of the manuscript are needed, especially in the results and discussion sections.

Response: Thank you very much for your suggestion. As you mentioned in Specific comments 6, we combined the original result sections with the original discussion sections to create a “results and discussion” section with four parts.

3. More details on the method of selection of the paleorecords is needed.

Response: Thank you very much for your suggestion. As you mentioned in Specific comments 4, we supplemented the number of dating samples and resolution of paleoclimate records in Table 3.

4. I think the manuscript would greatly benefit from a thorough review of the English. While, the manuscript is comprehensible, there are many sentences that are not properly structured. The verb tense should be standardized, as they are sometimes changing even within a single sentence.

Response: Thank you very much for your careful examination of the manuscript. We checked each sentence carefully.

Specific comments 1. Title I have issues with the title where the authors present the study as global, while in fact it is focusing on the Northern Hemisphere. The authors even provide the reasoning behind the focusing on the Northern Hemisphere in the last paragraph of the introduction. Actually, the study largely focuses on Central Asia and China (17/25 (68%) records from China). I think the title should be modified accordingly.

Response: Thank you very much for your suggestion. Our study regarded global closed basins with prominent water resources problem and explored synergy of the westerly winds and monsoons in lake evolution since the LGM. We first discovered that there is a significant differentiation between the monsoon regions and the westerlies in the evolution of water balance over the global closed basins, especially the Northern Hemisphere. Then we focused on the climate change in closed basins of the Northern Hemisphere which is affected both by low-latitude monsoons and mid-latitude westerly winds. Further, we emphatically investigated the millennial scale evolution characteristics and mechanisms of East Asian summer monsoon and westerly winds in closed basins of the Asian continent since the LGM. Following your comments, we revised the title to “Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Maximum and its implication for hydrological change in Central Asia” in the revised version.

2. Introduction There is no clearly defined objective. Please clearly state the purpose of the study. What scientific question was this study intended to answer?

Response: Thank you very much for your suggestion. We modified the introduction for clearly stating the purpose of the study. The updated contents are reproduced below.

“As important components of atmospheric circulation systems, the mid-latitude westerly winds and low-latitude monsoon systems play key roles in global climate change. Whether on the decadal or the millennial scale, researches about this aspect always attract widespread attention from scientists. Examination of global monsoon precipitation changes in land suggests an overall weakening over the recent half-century (1950-2000) (Zhou et al., 2008). Individual monsoon indexes reconstructed by Wang et al. (2017) indicate the moisture in the tropical Australian, the East Africa, and the Indian monsoon regions exhibits a gradual decrease since the early Holocene. It is widely accepted that the East Asian summer monsoon usually follows the variation of low-latitude summer solar radiation (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Charney (1969) and Wang (2009) also proposed that the seasonal migration of the intertropical convergence zone (ITCZ) profoundly influences the seasonality of the global monsoons. However, the global westerly winds and their associated storm tracks dominate the mid-latitude dynamics of the global atmosphere and affect the extratropical large-scale temperature and precipitation patterns (Oster et al., 2015; Voigt et al., 2015). Since the Last Glacial Maximum (LGM), climate in central and southern regions of the North American continent gradually dries out as the ice sheet melt and the westerlies move to north (Qin et al., 1997). As mentioned in the foregoing studies, millennial scale evolution in global monsoons and westerly winds probably shows different patterns as a result of complex driving mechanisms. Arguments about an asynchronous pattern of moisture variations between monsoon and westerly winds evolution underscore the importance of studying their millennial scale differentiation (Chen et al., 2006, 2008, 2019; An and Chen, 2009; Li et al., 2011; An et al., 2012).

A way to examine past climate variability is traditional methods of studying various archives which truly document the evolution of regional climate, including lake sediments (Madsen et al., 2008), stalagmites (Dykoski et al., 2005; Wang et al., 2008) and tree rings (Linderholm and Braeuning, 2006). However, due to the limited time scale of paleoclimate records, most researches on the evolution of monsoons and westerly winds are concentrated in the Holocene and lack an exploration during the LGM. With the development of paleoclimatology in recent decades, numerical simulations of paleoclimate continue to emerge and develop to a relatively mature system, which provides a useful tool for reviewing paleoclimate change over long time scales. On account of water balance system constantly responding to climatic conditions changes, a combination of numerical simulations and lake water balance models can be used to effectively track past climate change, and make up the deficiency in qualitative method of multi-proxy analysis (Qin and Yu, 1998; Xue and Yu, 2000; Morrill et al., 2001, 2004; Li and Morrill, 2010, 2013; Lowry and Morrill, 2019; Li et al., 2020). Covering one-fifth of the terrestrial surface, global closed basins distribute in both low-latitude monsoon regions and mid-latitude westerlies. Furthermore, closed basins with relative independent hydrological cycle system have a plenty of terminal lakes records that provide more evidence for retrospecting climate change (Li et al., 2017), and can be regarded as ideal regions for studying spatiotemporal difference between monsoons and westerly winds."

3. Time period partitioning What is the reasoning behind the selection of the PI period in the simulation? The authors mention that the selection of the time periods where subjective, was that 100 years period selected as a reference for the "modern/recent"? Why not choose a more climatically significant period like the Little Ice Age or the late Holocene, for which monsoon reconstruction clearly display a change? The authors mention that the division into those three periods was done to validate the water balance simulations and explore the evolution of the monsoons and westerly winds in the selected basins. Validating the water balance simulations for such a short period of time with records that are generally poorly constrained (see comment on section 2.2 below) for that period might be problematic. Furthermore, the PI period is absent from the discussion on the changes in monsoon and the westerlies.

Response: Thank you for pointing this out. In the time slice simulations, the selection of PI period which is considered as a typical period of the late Holocene, is mainly used to measure the changes in hydroclimate conditions during the LGM and MH periods relative to the late Holocene, and verify the feasibility of the lake models by comparing the lake level simulation with the lake status records among the three periods. After verification, combining lake models and continuous simulation can be used to track water balance change of the global closed basins and investigate the evolutionary differentiation of the westerly winds and monsoons since the LGM. We added relevant explanations in the revised version and supplemented the discussion on the changes in monsoon and the westerlies during the late Holocene. The updated contents are reproduced below.

"Here the PI period which is considered as a typical period of the late Holocene, is mainly used to measure the changes of hydroclimate conditions during the LGM and MH periods relative to the late Holocene, and verify the feasibility of the lake models by comparing the lake level simulations with the lake status records among three periods."

"The regions dominated by East Asian summer monsoon and westerly winds were then selected respectively based on the spatial characteristics of two modes extracted from the EOF, to explore millennial scale evolution features of two climate systems (Fig. 6). In the westerly winds dominated regions, the LGM and MH are characterized by humid climate, and relative dry climate prevails in the early and late Holocene. Whereas, the water balance in the monsoon dominated regions is generally affected by East Asian summer monsoon which brings much water vapor over the early-to-mid Holocene, and leads to relative dry climate in the LGM and late Holocene."

4. Section 2.2: Please define what is considered a reliable chronology. . . Did the authors apply a minimum number of dates per thousand years? What a about the temporal resolution for the selection of the various records? Did the authors apply a minimum number of the samples per time frame? For example, minimum one sample per 100 or 200 years? I cannot tell for other regions, but to me there are some Chinese high-resolution lake records missing from the list that would be of better quality than some of those included. On the top of my head, I would consider Gonghai lake (Chen et al., 2015 Sci Rep 5), Dali lake (Goldsmith et al., 2017 PNAS 114). They might not be within your simulated closed basins, but they are close enough and high-quality enough to be considered. Finally, for the PI period, as far as I know, many of the records in table 3 do not have any proper chronological control (210Pb or 14C bomb pulse) for the top section of the cores. The 1800-1900AD period can be difficult to narrow down chronologically as 14C is not very precise during this period and 210-Pb is at its limit.

Response: Thank you very much for your suggestion. It is our negligence not to specify the number of dating numbers and resolution of paleoclimate records in detail, and we supplemented these parts in Table 3 in the revised version. As you suggested, paleoclimate records of Gonghai lake and Dali lake were added in the revised version. In this section, our aim is to reconstruct the regional moisture change by synthesizing the paleoclimate records to verify the continuous simulation. Therefore, we do not need to pay special attention to the dry and wet changes in the PI period, but focus on the matching degree of reconstructed results and simulated results throughout the Holocene. Both reconstructed moisture change and simulated water balance fluctuation exhibit a decreased trend since the early Holocene, giving our confidence that the simulations are useful for investigating the millennial evolution of the westerly winds and monsoons.

5. In section 3.2, the authors state "Qinghai Lake, Hala Lake, Zhabuye Lake are typical lakes which are located in interactional transition zones between Asian monsoon and westerly winds, probably not following a single climate changing pattern". I would argue that many of the selected lakes in China, which they consider as being in the monsoon zones (see Fig. 6), were influenced both by the westerlies and the East Asian summer monsoon. Especially since the boundary of the monsoon was not static over time.

Response: Indeed, due to various internal and external forces, the low-latitude monsoons and the mid-latitude westerly winds produce different intensities over time. The boundary of the East Asian summer monsoon will also be adjusted accordingly with the change of monsoon strength, leading to more complex and diverse evolution of Asian lakes. We modified this sentence in the revised version. The updated contents are reproduced below.

"Since the boundary of the monsoon will be adjusted accordingly with the change of East Asian summer monsoon strength, evolution of Asian lakes on the millennial scale probably not follows a single climate changing pattern (Wu et al., 2000; Editorial Committee of China's Physical Geography, 1984; An et al., 2012)."

6. Structure of the manuscript Some parts of the result section belong to the discussion. While I understand that the authors must show that the lake simulations are valid and that, to do so, some interpretation is needed. I think that sections 3.3 and 3.4 should at the very least be moved to the discussion as they are focusing on the mechanisms driving the changes in water balance. Actually, I think that, given the nature of the data, this manuscript is a case where it would be beneficial to do a results and discussion section rather than separating them.

Response: Thank you very much for your suggestion. Your suggestion provides a new perspective for discussing our study deeply. We combined the original result sections with the original discussion sections to create a "results and discussion" section with four parts.

7. Terminology Several times in the manuscript, the authors refer to the Asian monsoon. To me it seems that what they call Asian monsoon is actually the East Asian monsoon. Especially since most of the selected records at the eastern edge of the simulated closed basins in Asia are roughly located at the northern limit of the East Asian summer monsoon (EASM). I think some precision is needed.

Response: Thank you very much for your suggestion. We modified the “Asian monsoon” mentioned in this manuscript to the “East Asian summer monsoon” in the revised version.

8. Discussion - Westerlies-monsoon interactions While studies have shown that trends in moisture changes in Westerly dominated arid Central Asia generally differ from those in EASM regions, owing to the fact that EASM rainfall does not reach this region, the opposite is not necessarily true. Records well into the region that the authors would consider as the East Asian monsoon region suggest an influence of the westerlies on moisture levels. The authors briefly discuss the interactions between the westerlies and the East Asian monsoon. However, I think the discussion would benefit from a more in-depth discussion of the relationship between the Westerly Jet and the EASM. For example, there are increasing evidence for a control of the Westerly Jet on the northward extent and timing of the EASM rainfall in East Asia (see for example: Chiang et al., 2015 QSR 108: 11-129; Herzschuh et al., 2019 Nat Comm 10; Nagashima et al., 2013 (Geochem Geophys Geosys 14: 5041-5053).

Response: Thank you very much for your suggestion. The information you provided about the influence of the orientation and position of the westerly jet on the EASM rainfall give us a lot of help. Previous studies mostly focus on the complexity of climate change in the transition zone between the westerlies and Asian monsoon, and investigate the interplay of two global atmospheric circulation on the millennial scale. However, the impact of the seasonal progression of the westerly jet on the EASM rainfall has not been thoroughly discussed. We supplemented this issue in the section 3.4. The updated contents are reproduced below.

“The Northern Hemisphere westerlies shifting northward or southward has a significant impact on global atmosphere circulation and inevitably affects the monsoon systems. Quaternary ice sheets of the Northern Hemisphere in the LGM develop to its maximum extension, and consequent existence of persisting strong glacial anticyclone leads to the southward displacement of the westerly winds (Yu et al., 2000). Many researches suggested the Northern Hemisphere westerlies in the LGM move to the southwest of the United States and the eastern Mediterranean region (Lachniet et al., 2014; Rambeau, 2010). Therefore, the narrowed temperature difference between sea and land causes the East Asian summer monsoon weaken, and may further induces the strong westerly winds throughout the year and then the precipitation increases (Yu et al., 2000). Furthermore, a growing body of evidence shows that the position and orientation of the westerly jet (WJ) probably control the Holocene East Asian summer rainfall patterns. A link between the northward seasonal progression of the WJ and the spatial pattern of East Asian summer monsoon precipitation shows that earlier northward progression of the WJ causes abundant precipitation at high-latitudes and less precipitation at low-latitudes (Nagashima et al., 2013). Especially the northward evolution of the WJ from south of the Tibetan Plateau and seasonal transition exert great influences on East Asian paleoclimate change (Chiang et al., 2015). Herzschuh et al. (2009) proposed that the position of summer monsoon rain band changes as the WJ axis shifts gradually southward, leading to the occurrence of spatiotemporal difference in Holocene China's maximum precipitation. In summary, the above views emphasize that the complex interaction between the monsoon and the westerly systems on the millennial scale should receive more attention."

9. Speleothems The close similarity of the PCA1 time series with the speleothem records from Gongge and Hulu caves suggest it is a record of the East Asian summer monsoon. There is a long-standing debate about what the δ18O speleothem records from China represents. One view interprets the oxygen isotopic record from Chinese cave deposits as reflecting real rainfall changes and hence reflecting changes in the EASM. The other main view suggests that these the oxygen records (depending where they are located) reflect changes in the moisture source (Indian monsoon vs EASM) and that they do not directly represent changes in EASM. What can the present study contribute to that debate? I think it could be an interesting addition to this manuscript.

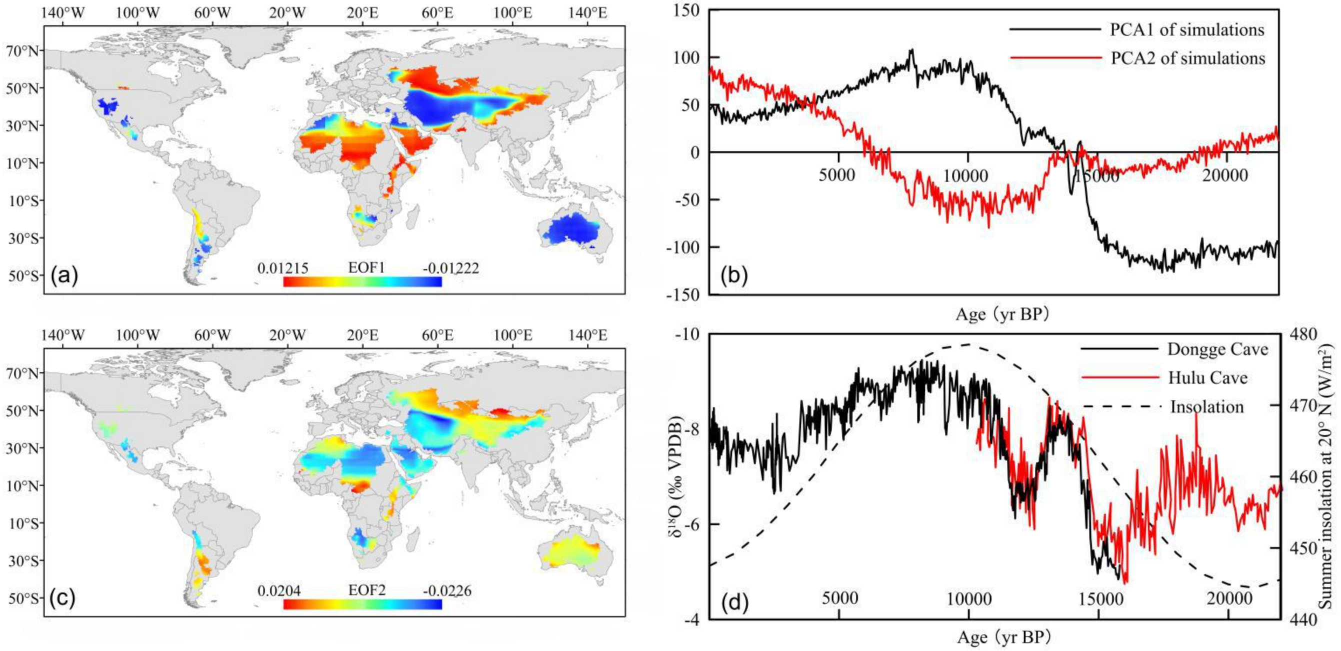
Response: Thank you very much for your suggestion. We made corresponding supplement about the contribution of our results to the paleoclimate research of Chinese stalagmites in the revised version. The updated contents are reproduced below.

"The contribution rate of PCA1 and PCA2 is 51% and 14% respectively, therefore the following discussion mainly focuses on PCA1 with the high contribution rate. The PCA1 extracted from water balance simulation tends to represent the effective moisture fluctuation of closed basins in low-latitude monsoon regions, indicating a relative humid climate during the early-to-mid Holocene. By comprehensively analyzing a variety of paleoclimate proxies, Wang et al. (2017) suggested that moisture change revealed by the Australian monsoon, the East African monsoon and the Indian monsoon regions reaches the wettest status in the early Holocene, while the wettest condition in the East Asian summer monsoon regions occurs between 8 and 6 kyr. Likewise, Qin (1997) presented that the wettest period in the African and South Asian monsoon regions is the early-to-mid Holocene, coinciding well with our results.

The climatic significance of the $\delta^{18}O$ in the Asian speleothem records is always a long-standing debate, and some influential hypotheses regard $\delta^{18}O$ of the monsoon regions as a proxy for "Asian monsoon intensity", "Indian monsoon intensity", "summer monsoon rainfall amount" and "circulation conditions" (Cheng et al., 2012; Chen et al., 2016). Although the climatic significance is controversial, it is well accepted that $\delta^{18}O$ changes should bear the imprint of variations in the oxygen isotopic composition of precipitation (Cheng et al., 2012; Chen et al., 2016). According to the close similarity of the PCA1 with the speleothem records from Dongge and Hulu caves, our simulations are more inclined to suggest that the $\delta^{18}O$ stalagmite records indicate the change in water vapor brought by the monsoons. In addition, we not only compared the PCA1 with the stalagmite records of Dongge Cave with controversial climatic significance, but also with the summer solar radiation at low-latitudes in the Northern Hemisphere. This comparison provides evidence for the view that the evolution of low-latitude monsoons is generally controlled by summer insolation in the Northern Hemisphere (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Thus, we further speculated that the water balance change in monsoon regions of global closed basins is mainly driven by mid-latitude and low-latitude summer solar radiation."

Technical/minor comments Fig 3: Please provide letters to refer to each section of the figure both in the figure caption and the figure itself. I would also suggest putting both EOF figures on the left side and the PCA curves above the speleothem records. It would make the comparison of the curve easier.

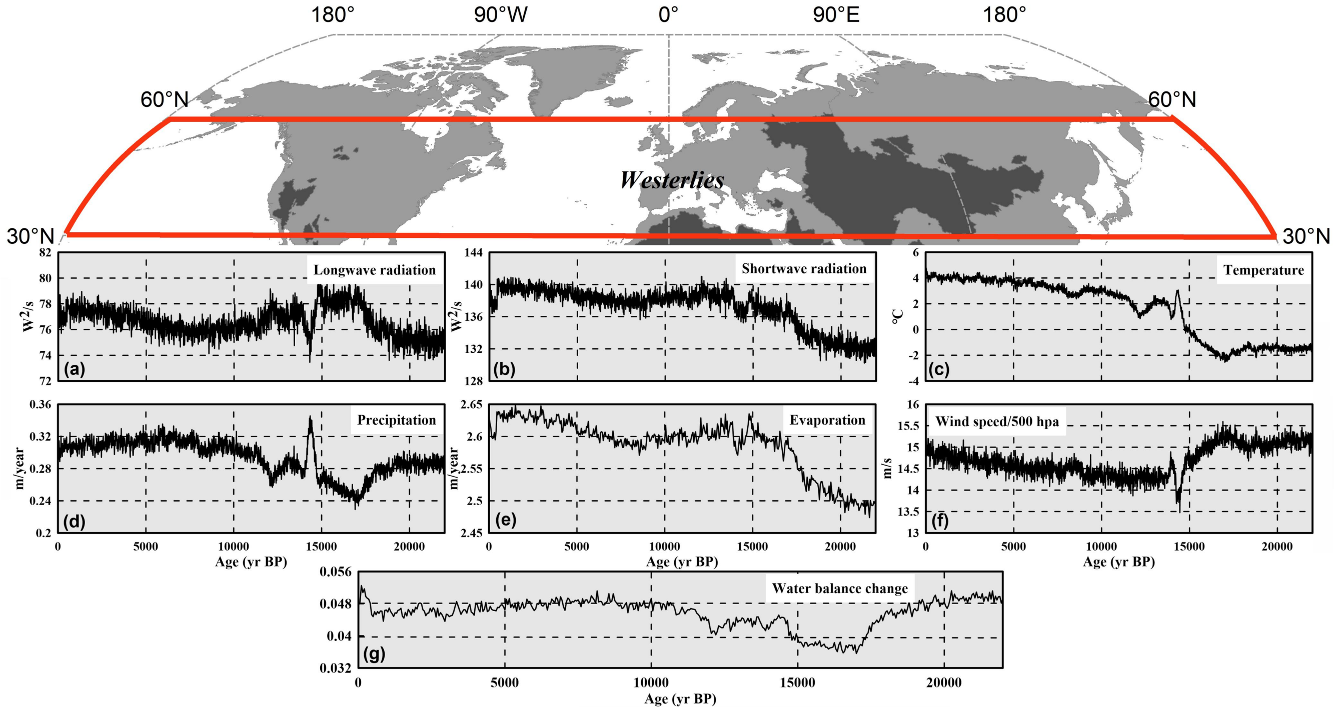
Response: Thank you very much for your suggestion. We modified the Figure 3 in the revised version. The updated contents are reproduced below.



"**Figure 3.** (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978)."

Fig 5: please provide letters the refer to each time series, especially since the font size is quite small. If possible, increase the font size of the time series.

Response: Thank you for pointing this out. We provided letters of each time series and increased the font size of the time series. The updated contents are reproduced below.



“**Figure 5.** Time series of (a) longwave radiation, (b) shortwave radiation, (c) temperature, (d) precipitation, (e) evaporation, (f) 500 hpa wind speed and (g) water balance change between 30°N and 60°N closed basins since the LGM.”

Section 3.3 and 3.4: EOF is not defined anywhere in the manuscript.

Response: Thank you for pointing this out. We added section 2.3 to describe the mathematical methods. The updated contents are reproduced below.

“**2.3 Mathematical methods**

Linear tendency estimation is a common trend analysis method, which was chosen to measure the variation degree of simulated water balance in this paper. Besides, we also used the Empirical orthogonal function (EOF), a method of analyzing the structural features in matrix data and extracting the feature vector of main data, to examine spatially and temporally variability of simulated water balance. The spatial distribution of EOF first (second) mode is denoted by EOF1 (EOF2), and the time series of first (second) mode is denoted by PCA1 (PCA2).”

Line 29: indicate rather than indicated. I would also remove monsoon after Australian and East African.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Line 30: Remove the And at the start of the sentence.

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Lines 32-33. That sentence needs to be rephrased to something like ". . . the seasonal migration of the (ITCZ) profoundly influences the seasonality of the global monsoons."

Response: Thank you very much for your suggestion. We rephrased this sentence in the revised version. The updated contents are reproduced below.

"Charney (1969) and Wang (2009) also proposed that the seasonal migration of the intertropical convergence zone (ITCZ) profoundly influences the seasonality of the global monsoons."

Line 36: Please define LGM. This is the first time you mention it in the main body of the manuscript.

Response: Thank you very much for your careful examination of the manuscript. We added the full name of LGM.

Line 36: . . . southern regions of THE North American continent. . .

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Line 51: Please define MH. This is the first time you mention it in the main body of the manuscript.

Response: Thank you very much for your careful examination of the manuscript. We added the full name of MH.

Line 51: remove one space between and and Pre-Industrial

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Line 51: remove and at the start of the sentence.

Response: Thank you very much for your suggestion. We modified this.

Line 58: Capital letter for last

Response: Thank you very much for your careful examination of the manuscript. We deleted this.

Line 70: please define P-E. It is mentioned for the first time in the manuscript.

Response: Thank you very much for your careful examination of the manuscript. We added the full name of P-E.

Line 75: either remove And at the start of the sentence or combine with the previous one by for example writing: "(Peltier, 2004), while the vegetation. . ."

Response: Thank you very much for your suggestion. We modified this. The updated contents are reproduced below.

"A remnant Laurentide ice sheet in the LGM and a modern-day ice sheet configuration in the MH and PI simulations are specified by the ICE-5G reconstruction (Peltier, 2004), while the vegetation is prescribed to modern values."

Line 82: IN each grid cell not at

Response: Thank you very much for your suggestion. We modified this.

Line91: assumed rather than supposed

Response: Thank you very much for your suggestion. We modified this.

Lines 135-136: However, there are exceptions that lakes. . . Replace that by where

Response: Thank you very much for your suggestion. We deleted this sentence.

Lines 148-149: this sentence need to be rephrased, for example: " Comparing the simulations with the records, most simulations coincide with the upward. . ."

Response: Thank you very much for your suggestion. We deleted this sentence.

Line 135 "For better validating simulated results, reviewed and summarized the millennial-scale changing patterns in lake level of the closed basins since the LGM are particularly important."

Response: Thank you very much for your careful examination of the manuscript. We deleted this sentence.

Line 164: East Asian summer monsoon not East summer Asian. . .

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Line 173: suggested change to: "According to. . . basins in the Northern Hemisphere, affected both by low-latitude monsoon and mid-latitude westerly winds, are ideal region. . ."

Response: Thank you very much for your suggestion. We modified this. The updated contents are reproduced below.

"On the basis of the spatial characteristics of the EOF analysis, closed basins in the Northern Hemisphere, affected both by low-latitude monsoons and mid-latitude westerly winds, are ideal regions for revealing synergy of the westerly winds and monsoons."

Line 179: "from A humid climate IN the early-mid Holocene to AN arid climate IN the late Holocene" not "from humid climate of the early-mid Holocene to arid climate of the late Holocene".

Response: Thank you very much for your careful examination of the manuscript. We modified this. The updated contents are reproduced below.

"Simulated mean water balance curve corresponds well with mean moisture index in the Northern Hemisphere mid-latitude closed basins, indicating a transition from a humid climate in the early-to-mid Holocene to an arid climate in the late Holocene."

Line 185: "in THE early-mid Holocene"

Response: Thank you very much for your careful examination of the manuscript. We modified this.

Lines 187-188: That sentence need to be rewritten.

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

"Using paleoclimate modelling, Yu et al. (2000) mentioned that the low temperature during the glacial period causes a decrease of evaporation and a reduction of lake water loss, resulting in the appearance of high lake level."

Lines 188-190: Do you still refer to Yu et al. (2000) there or to Fig. 5. This is not clear.

Response: Thank you for pointing this out. Lines 188-190 describe Fig. 5 and we clarified it.

Line 190: reaches A maximum not the

Response: Thank you very much for your suggestion. We modified this.

Line 221: experienced not experiences

Response: Thank you very much for your suggestion. We modified this.

Line 255-256: suggest edit: "Winter precipitations account for a large proportion of annual precipitations in these regions."

Response: Thank you very much for your suggestion. We reworded this sentence. The updated contents are reproduced below.

"Winter precipitation accounts for a large proportion of annual precipitations in these regions (Li et al., 2008)."

A list of all relevant changes made in the manuscript

Article title

Original: Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Max imum

Revised: Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Ma ximum and its implication for hydrological change in Central Asia

Section Abstract

Original: Monsoon system and westerly circulation, to which climate change responds differently, are two important components of global atmospheric circulation, interacting with each other in the mid-to-low latitudes and having synergy effect to those regions. Relevant researches on global millennial-scale climate change in monsoon and westerlies regions are mostly devoted to multi-proxy analyses of lakes, stalagmites, ice cores, marine and eolian sediments. Different responses from these proxies to long-term environmental change make understanding climate change pattern in monsoonal and westerlies regions difficult. Accordingly, we disaggregated global closed basins into areas governed by monsoon and westerly winds and unified palaeoclimate indicators, as well as combined with the lake models and paleoclimate simulations for tracking millennial-scale evolution characteristics and mechanisms of global monsoon and westerly winds since the Last Glacial Maximum (LGM). Our results concluded that the effective moisture in most closed basins of the mid-latitudes Northern Hemisphere is mainly a trend on the decrease since the LGM, and of the low-latitudes is mainly a trend on the rise. Millennial-scale water balance change exhibits an obvious boundary between global westerlies and monsoon regions in closed basins, particularly in the Northern Hemisphere. In the monsoon dominated closed basins of the Northern Hemisphere, humid climate prevails in the early-mid Holocene and relative dry climate appears in the LGM and late Holocene. While in the westerly winds dominated closed basins of the Northern Hemisphere, climate is characterized by relative humid LGM and mid-Holocene (MH) compared with the dry early Holocene, which is likely to be connected with precipitation brought by the westerly circulation. This study provides insights into long-term evolution and synergy of monsoon and westerly wind systems and basis for projection of future hydrological balance in the low-to-mid latitudes.

Revised: Monsoon system and westerly circulation, to which climate change responds differently, are two important components of global atmospheric circulation, interacting with each other in the mid-to-low latitudes. Relevant researches on global millennial scale climate change in monsoon and westerlies regions are mostly devoted to multi-proxy analyses of lakes, stalagmites, ice cores, marine and eolian sediments. Different responses from these proxies to long-term environmental change make understanding climate change pattern in monsoon and westerlies regions difficult. Accordingly, we disaggregated global closed basins into areas governed by monsoon and westerly winds, and unified paleoclimate indicators, as well as added the lake models and paleoclimate simulations for emphatically tracking millennial scale evolution characteristics and mechanisms of East Asian summer monsoon and westerly winds since the Last Glacial Maximum (LGM). Our results conclude that millennial scale water balance change exhibits an obvious boundary between global monsoon and westerlies regions in closed basins, particularly in the Northern Hemisphere. The effective moisture in most closed basins of the mid-latitudes Northern Hemisphere mainly exhibits a decreasing trend since the LGM, while of the low-latitudes shows an increasing trend. In the monsoon dominated closed basins of Asia, humid climate prevails in the early-to-mid Holocene and relative dry climate appears in the LGM and late Holocene. While in the westerly winds dominated closed basins of Asia, climate is characterized by humid LGM and mid-Holocene (MH) compared with the dry early and late Holocene, which is likely to be connected with precipitation brought by the westerly circulation. This study provides an insight into long-term evolution and synergy of westerly winds and monsoon systems and a basis for projection of future hydrological balance.

Section 1

Original: As important components of atmospheric circulation systems, the mid-latitude westerly winds and low-latitude monsoon systems play key roles in global climate change. Whether on the decadal scale or the millennial scale, researches about this aspect always attract widespread attention from scientists. Examination of global monsoon precipitation changes in land suggested an overall weakening over the recent half-century (1950-2000) (Zhou et al., 2008). Individual monsoon indexes reconstructed by Wang et al. (2017) indicated the moisture in the tropical Australian monsoon, the East African monsoon, and the Indian monsoon regions is a gradual decrease since the early Holocene. And it is widely accepted that the East Asian summer monsoon usually follows the variation of low-latitude summer solar radiation (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Charney (1969) and Wang (2009) also proposed that the seasonal migration of the intertropical convergence zone (ITCZ) profoundly influences the global monsoons which have significant seasonality. However, the global westerly winds and their associated storm tracks dominate the mid-latitude dynamics of the global atmosphere and influence the extratropical large-scale temperature and precipitation patterns (Oster et al., 2015; Voigt et al., 2015). Lake records suggested that since the LGM, climate in central and southern regions of north American continent gradually dried out as the ice sheet melted and the westerlies moved north (Qin et al., 1997).

Millennial-scale evolution in global monsoons and westerly winds probably shows different patterns as a result of complex driving mechanisms. Previous arguments about an asynchronous pattern of moisture variations between monsoon and westerly winds evolution underscore the importance for studying their millennial-scale differentiation (Chen et al., 2006, 2008, 2019; An and Chen, 2009; Li et al., 2011; An et al., 2012). Covering one-fifth of the terrestrial surface, global closed basins are mostly located in arid and semi-arid areas of global mid-low-latitudes. Furthermore, closed basins with relative independent hydrological cycle system have a plenty of terminal lakes records that provide more evidences for retrospecting climate change, and can be regarded as ideal regions for studying spatiotemporal differences between monsoons and westerly winds (Li et al., 2017). On account of lake water balance system constantly responding to climatic conditions changes, lake water balance model has become one of the common methods to track past climate change, and makes up the deficiency in qualitative method of multi-proxy analysis (Qin and Yu, 1998; Xue and Yu, 2000; Morrill et al., 2001, 2004; Li and Morrill, 2010, 2013; Lowry and Morrill, 2019).

Here we constructed virtual lakes systems and applied lake models and a transient climate evolution model to continuously simulating water balance change since the LGM in global closed basins. Meanwhile, P-E simulations and 37 lake status records in the LGM, MH and Pre-Industrial (PI) were supplemented. And based on the prominent spatial characteristics of global monsoons and westerly winds revealed by simulations, we focused on the Northern Hemisphere mid-latitude closed basins where are simultaneously influenced by mid-latitude westerly winds and low-latitude monsoons: first, due to the limited time scale of the climate records, the reconstructed moisture index from 25 paleoclimate records and water balance simulations were used to reveal and validate the climate change of the whole the Northern Hemisphere mid-latitude closed basins; second, the Northern Hemisphere mid-latitude closed basins were disaggregated into the areas dominated by monsoon and westerly winds respectively, and we emphatically explored the temporal evolution of the Northern Hemisphere monsoons and westerly winds since the LGM. last, we comprehensively considered the determinant that controls the direction of climate change in the Northern Hemisphere westerly winds and monsoons since the LGM, according to records of Quaternary ice sheets, low-mid latitudes summer insolation and winter insolation, δ 18O of Greenland ice core, etc. This study not only reveals millennial-scale climate change from the perspective of water balance, but also provides a new method for studying the synergy of the westerly winds and monsoons.

Revised: As important components of atmospheric circulation systems, the mid-latitude westerly winds and low-latitude monsoon systems play key roles in global climate change. Whether on the decadal or the millennial scale, researches about this aspect always attract widespread attention from scientists. Examination of global monsoon precipitation changes in land suggests an overall weakening over the recent half-century (1950-2000) (Zhou et al., 2008). Individual monsoon indexes reconstructed by Wang et al. (2017) indicate the moisture in the tropical Australian, the East Africa, and the Indian monsoon regions exhibits a gradual decrease since the early Holocene. It is widely accepted that the East Asian summer monsoon usually follows the variation of low-latitude summer solar radiation (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Charney (1969) and Wang (2009) also proposed that the seasonal migration of the intertropical convergence zone (ITCZ) profoundly influences the seasonality of the global monsoons. However, the global westerly winds and their associated storm tracks dominate the mid-latitude dynamics of the global atmosphere and affect the extratropical large-scale temperature and precipitation patterns (Oster et al., 2015; Voigt et al., 2015). Since the Last Glacial Maximum (LGM), climate in central and southern regions of the North American continent gradually dries out as the ice sheet melt and the westerlies move to north (Qin et al., 1997). As mentioned in the foregoing studies, millennial scale evolution in global monsoons and westerly winds probably shows different patterns as a result of complex driving mechanisms. Arguments about an asynchronous pattern of moisture variations between monsoon and westerly winds evolution underscore the importance of studying their millennial scale differentiation (Chen et al., 2006, 2008, 2019; An and Chen, 2009; Li et al., 2011; An et al., 2012).

A way to examine past climate variability is traditional methods of studying various archives which truly document the evolution of regional climate, including lake sediments (Madsen et al., 2008), stalagmites (Dykoski et al., 2005; Wang et al., 2008) and tree rings (Linderholm and Braeuning, 2006). However, due to the limited time scale of paleoclimate records, most researches on the evolution of monsoons and westerly winds are concentrated in the Holocene and lack an exploration during the LGM. With the development of paleoclimatology in recent decades, numerical simulations of paleoclimate continue to emerge and develop to a relatively mature system, which provides a useful tool for reviewing paleoclimate change over long time scales. On account of water balance system constantly responding to climatic conditions changes, a combination of numerical simulations and lake water balance models can be used to effectively track past climate change, and make up the deficiency in qualitative method of multi-proxy analysis (Qin and Yu, 1998; Xue and Yu, 2000; Morrill et al., 2001, 2004; Li and Morrill, 2010, 2013; Lowry and Morrill, 2019; Li et al., 2020). Covering one-fifth of the terrestrial surface, global closed basins distribute in both low-latitude monsoon regions and mid-latitude westerlies. Furthermore, closed basins with relative independent hydrological cycle system have a plenty of terminal lakes records that provide more evidence for retrospecting climate change (Li et al., 2017), and can be regarded as ideal regions for studying spatiotemporal difference between monsoons and westerly winds.

By constructing virtual lakes systems, here we applied lake models and a transient climate evolution model to continuously simulate water balance change since the LGM in global closed basins. Meanwhile, precipitation minus evaporation (P-E) simulations and 37 lake status records in the LGM, mid-Holocene (MH) and Pre-Industrial (PI) were supplemented for validating results of the continuous simulations. The prominent spatial differentiation of monsoons and westerly winds revealed by simulations leads us to focus on the Northern Hemisphere mid-latitude closed basins which are simultaneously influenced by mid-latitude westerly winds and low-latitude monsoons. In the mid-latitude closed basins of the Northern Hemisphere, the good match between water balance simulation and reconstructed moisture index from 27 paleoclimate records verifies the reliability of the simulation results. Further, we disaggregated the Northern Hemisphere mid-latitude closed basins into the areas dominated by monsoons and westerly winds respectively, and emphatically explored the temporal evolution of the East Asian summer monsoon and westerly winds since the LGM. According to the climate records, we comprehensively considered the determinants that control the trend of climate change in the Northern Hemisphere westerlies and East Asian summer monsoon regions since the LGM. This study not only reveals millennial scale climate change from the perspective of water balance, but also provides a new method for studying the synergy of the westerly winds and monsoons.

Section 2.1.1

Original: Transient climate evolution experiment (TraCE-21 kyr) as a synchronously coupled atmosphere-ocean circulation model simulation, is completed by the Community Climate System Model version 3 (CCSM 3) (He, 2011). We applied this model to continuously simulating effective moisture change represented by virtual water balance variation since the LGM. Likewise, CCSM 4, CNRM-CM5, FGOALS-g2, GISS-E2-R, MIROC-ESM, MPI-ESM-P and MRI-CGCM3 models participating in CMIP5/PMIP3 were also used and simulated the relative change of P-E during three particular periods (LGM, MH, PI). PMIP3 protocols define the boundary conditions of these models, with a few exceptions (Table 1). Precession, obliquity and eccentricity values are specified according to Berger (1978). CO_2, CH_4, and N_2O values are set on the basis of reconstructions from ice cores (Monnin et al., 2004; Flückiger et al., 1999, 2002). A remnant Laurentide ice sheet in the LGM and a modern-day ice sheet configuration in the MH and PI simulations were specified by the ICE-5G reconstruction (Peltier, 2004). And the vegetation is prescribed to modern values. Ice sheet configuration and vegetation distribution are used by GISS model. LGM radiative forcing changes in MIROC model and MRI model are the exceptions of the PMIP3 boundary conditions, details are shown in Licciardi et al. (1998) and Lowry and Morrill (2019).

Revised: Transient climate evolution experiment (TraCE-21 kyr) as a synchronously coupled atmosphere-ocean circulation model simulation, is completed by the Community Climate System Model version 3 (CCSM3) (He, 2011). We applied this model to continuously simulating effective moisture change represented by virtual water balance variation since the LGM. Likewise, CCSM4, CNRM-CM5, FGOALS-g2, GISS-E2-R, MIROC-ESM, MPI-ESM-P and MRI-CGCM3 models participating in CMIP5/PMIP3 were also used to simulate the relative change of P-E during three particular periods (LGM, MH, PI). Here the PI period which is considered as a typical period of the late Holocene, is mainly used to measure the changes of hydroclimate conditions during the LGM and MH periods relative to the late Holocene, and verify the feasibility of the lake models by comparing the lake level simulations with the lake status records among three periods. PMIP3 protocols define the boundary conditions of these models, with a few exceptions (Table 1). Precession, obliquity and eccentricity values are specified according to Berger (1978). CO_2, CH_4, and N_2O values are set on the basis of reconstructions from ice cores (Monnin et al., 2004; Flückiger et al., 1999, 2002). A remnant Laurentide ice sheet in the LGM and a modern-day ice sheet configuration in the MH and PI simulations are specified by the ICE-5G reconstruction (Peltier, 2004), while the vegetation is prescribed to modern values. Ice sheet configuration and vegetation distribution are used by GISS model. LGM radiative forcing changes in MIROC model and MRI model are the exceptions of the PMIP3 boundary conditions, details are shown in Licciardi et al. (1998) and Lowry and Morrill (2019).

Section 2.1.2

Original: Before calculating, we linearly interpolated different resolutions grid cells of TraCE model and multi-model ensemble into a uniform resolution of 0.5°×0.5°. For all grid cells in closed basins, we assumed that the virtual lake at each grid cell is a 1 meter deep lake with freshwater, and then the virtual lake evaporation is calculated by a lake energy balance model that is modified according to Hostetler and Bartlein's model (Hostetler and Bartlein, 1990). The evaporation of lake surface depends on the heat capacity of water, water density, lake depth, lake surface temperature, shortwave radiation and longwave radiation absorbed by the water surface, longwave radiation emitted by the water surface, latent heat flux, sensible heat flux, etc. If the surface energy balance is negative (positive), the ice forms (melts). Besides, lake depth and lake salinity are important input parameters influencing lake surface evaporation (Dickinson et al., 1965), however, only small changes appear in lake evaporation when adding lake depth to 5 and 10 m and increasing lake salinity to 10 ppt. More details of lake energy balance model were described in Morrill, 2004 and Li and Morrill, 2010.

For better assessing the relative change of water balance since the LGM, the virtual lakes were supposed in hydrological equilibrium with steady state. The lake water balance equation is shown as follows:

$$D = A_B R + A_L (P_L - E_L) \ , \qquad (2)$$

where D is discharge from the lake (m^3 $year^{-1}$), $A_B$is area of the drainage basin (m^2), R is runoff from the drainage basin (m $year^{-1}$), $A_L$is area of the lake (m^2), $P_L$is precipitation over the lake(m $year^{-1}$) and $E_L$is lake evaporation (m $year^{-1}$). Given the application of Eq. (2) requires specific values of the A_B and A_L, this equation is simplified for grid cells where $P_L - E_L \geq 0$ and grid cells where $P_L - E_L < 0$. Grid cells where $P_L - E_L \geq 0$ represent open lakes, and maintain water balance by discharging more or less water. While the runoff into the lake compensates the net water loss in grid cells where $P_L - E_L < 0$, and these regions maintain water balance by changes in the ratio of A_L to A_B, as described by setting $D = 0$ in Eq. (2):

$$\frac{A_L}{A_B} = \frac{R}{(E_L - P_L)} \ , \qquad (3)$$

where A_L/A_B represents virtual lake level. Accordingly, for grid cells with $P_L - E_L < 0$, the A_L/A_B values were calculated and compared to represent relative water balance change, and more details about lake water balance model were described in Li and Morrill, 2010. We combined the values of P_L, E_L and R with Eq. (2) and (3) and simulated the continuous water balance change since the LGM using TraCE 21 kyr model.

Revised: Before calculating, we linearly interpolated different resolutions grid cells of TraCE model and multi-model ensemble into a uniform resolution of 0.5°×0.5°. For all grid cells in closed basins, we assumed that the virtual lake in each grid cell is a 1 meter deep lake with freshwater, and then the virtual lake evaporation is calculated by a lake energy balance model that is modified according to Hostetler and Bartlein (1990)'s model. The evaporation of lake surface depends on the heat capacity of water, water density, lake depth, lake surface temperature, shortwave radiation, longwave radiation absorbed by the water surface, longwave radiation emitted by the water surface, latent heat flux, and sensible heat flux, etc. If the surface energy balance is negative (positive), the ice forms (melts). Besides, lake depth and lake salinity are important input parameters influencing lake surface evaporation (Dickinson et al., 1965), however, only small changes appear in lake evaporation when adding lake depth to 5 and 10 m and increasing lake salinity to 10 ppt. More details of lake energy balance model are described in Morrill (2004) and Li and Morrill (2010).

For better assessing the relative change of water balance since the LGM, the virtual lakes are assumed in hydrological equilibrium with steady state. The lake water balance equation is shown as follows:

$$D = A_B R + A_L (P_L - E_L) \ , \qquad (1)$$

where D is discharge from the lake (m^3 year^{-1}), A_B is area of the drainage basin (m^2), R is runoff from the drainage basin (m year^{-1}), A_L is area of the lake (m^2), P_L is precipitation over the lake (m year^{-1}) and E_L is lake evaporation (m year^{-1}). Given the application of Equation (1) requiring specific values of the A_B and A_L, this equation is simplified for grid cells where $P_L - E_L \geq 0$ and grid cells where $P_L - E_L < 0$. Grid cells where $P_L - E_L \geq 0$ represent open lakes, and maintain water balance by discharging more or less water. While the runoff into the lake compensates the net water loss in grid cells where $P_L - E_L < 0$, and these regions maintain water balance by changes in the ratio of A_L to A_B, as described by setting $D = 0$ in Equation (2):

$$\frac{A_L}{A_B} = \frac{R}{(E_L - P_L)} \ , \qquad (2)$$

where A_L/A_B represents virtual lake level. Accordingly, for grid cells with $P_L - E_L < 0$, the A_L/A_B values are calculated and compared to represent relative water balance change, and more details about lake water balance model are described in Li and Morrill (2010). We combined the values of P_L, E_L and R with Equations (1) and (2) and simulated the continuous water balance change since the LGM using TraCE 21 kyr model.

Section 2.2

Original 1: We collected 37 lake status information in or near global closed basins to compare relative changes among three characteristic periods, and lake status information sorted by latitudes are shown in Table 2. Then, 25 climate records were compiled in or near the mid-latitude closed basins of the Northern Hemisphere with reliable chronologies and successive sedimentary sequences from published literatures, which can reflect the continuous dry and wet change (Table 3). We interpolated climate data at intervals of 10 years and unified the time scale according to the chronology accuracy of the extracted data. Lastly, the data were standardized to indicate a humid climate with a relative high value and a dry climate with a relative low value, and the signals of moisture change were transformed into a range of 0 to 1 index.

Revised 1: 37 lake status information in or near global closed basins were collected to compare relative changes among three characteristic periods. Lake status information sorted by latitudes is shown in Table 2. Then, 27 climate records were compiled in or near the mid-latitude closed basins of the Northern Hemisphere with reliable chronologies and successive sedimentary sequences from published literatures, which can reflect the continuous dry and wet change (Table 3). We interpolated climate data at intervals of 10 years and unified the time scale according to the chronology accuracy of the extracted data. Finally, the data were standardized to indicate a humid climate with a relative high value and a dry climate with a relative low value, and the signals of moisture change were transformed into a range of 0 to 1 index. Due to the different time scales of the collected continuous paleoclimate records, we can only reconstruct the regional moisture change from the early to late Holocene after unifying the time scales, but the purpose of this part is only to check the simulation results.

Original 2: Table 3. Paleoclimatic records indicating dry or wet status

Lake	Location	Lat (°)	Lon (°)	Elevations (m)	Dating method	Time period (cal yr BP)	Proxies used	References
Karakul Lake	Tajikistan	39.02	73.53	3915	^{14}C	10000-0	TOC, TOC/TN, δ18Ocarb, TIC	Heinecke et al., 2017
Achit Nuur	Mongolia	49.42	90.52	1444	AMS ^{14}C	22000-0	Pollen	Sun et al., 2013
Ulungur Lake	China	46.98	87	478.6	AMS ^{14}C	10000-0	grain-size, pollen data	Liu et al., 2008
Lower Red Rock Lake	America	44.63	-111.84	2015	AMS ^{14}C	22000-0	Magnetic susceptibility, Carbonate, Organic	Mumma et al., 2012
Ulaan Nuur	Mongolia	44.51	103.65	1110	OSL	16000-0	TOC, TN, C/N, CaCO3, CIA	Lee et al., 2013
Jenny Lake	America	43.76	-110.73	2070	AMS ^{14}C	14000-0	TOC, C/N	Larsen et al., 2016
Balikun Lake	China	43.67	92.8	1580	^{14}C	10000-0	TOC, δ18Ocar	Xue et al., 2011
Lake Woods	America	43.48	-109.89	2816	^{14}C	12000-0	Sand content	Pribyl and Shuman, 2014
Blue Lake	America	40.5	-114.04	1297	AMS ^{14}C	14000-1000	Pollen	Louderback and Rhode, 2009
Yitang Lake	China	40.3	94.97	/	OSL	23000-0	TOC, C/N, δ13Corg	Zhao et al., 2015
Tiao Lake	China	40.26	99.31	1188	AMS ^{14}C	11000-1000	Rb/Sr, Fe/Mn	Li et al., 2013
Yanhaizi Lake	China	40.1	108.42	1180	^{14}C	14000-0	TOC, magnetic susceptibility, maturity index	Chen et al., 2003
Yanchi Lake	China	39.72	99.17	1200	AMS ^{14}C	18000-0	TOC, C/N, Carbonate	Li et al., 2013
Qingtu Lake	China	39.05	103.67	1309	AMS ^{14}C	11000-0	C/N, grain size	Li et al., 2012
Van Lake	Turkey	38.5	43	1649	AMS ^{14}C	25000-0	TOC, TIC, δ13C, δ18O	Öğretmen.,2012
Hala Lake	China	38.2	97.4	4078	^{14}C	24000-0	OM, Carbonate	Yan et al., 2014

Sanjiaocheng	China	39.01	103.34	1325	AMS ^{14}C	15000-0	TOC, δ13Corg	Zhang et al., 2004
Hurleg Lake	China	37.28	96.9	2817	AMS ^{14}C	10000-0	Carbonate	Zhao et al., 2010
Gahai Lake	China	37.13	97.55	2850	AMS ^{14}C	12000-0	δ13Cc, δ18Oc, CaCO3	Guo et al., 2012
Chaka Lake	China	36.63	99.03	3200	AMS ^{14}C	10000-0	TOC, TN	Liu et al., 2008
Qinghai Lake	China	36.53	99.6	3200	AMS ^{14}C	18000-0	TOC, TN, C/N, Carbonate	Shen et al., 2005
Dalianhai Lake	China	36.24	100.39	2852	^{14}C	24000-0	Rb/Sr	Wu, 2017
Zigetang Co	China	32	90.73	4560	^{14}C	10500-0	TOC, TOC/TS, HI, δ13Corg, TC, TIC	Wu et al., 2007
Bangong Co	China	33.7	79	4241	AMS ^{14}C	10000-0	δ18O	Fontes et al., 1996
Zabuye Lake	China	31.35	84.07	4421	AMS ^{14}C	30000-0	TOC, TIC, δ18Ocarb, δ13Ccarb	Wang et al., 2002

Revised 2: Table 3. Paleoclimatic records indicating dry or wet status

Lake	Location	Lat (°)	Lon (°)	Elevations (m)	Dating method	Resolution (yr)	Dates number	Time period （cal yr BP）	Proxies used	References
Karakul Lake	Tajikistan	39.02	73.53	3915	^{14}C	~200	5	10000-0	TOC, TOC/TN, δ18Ocarb, TIC	Heinecke et al., 2017
Achit Nuur	Mongolia	49.42	90.52	1444	AMS ^{14}C	~220-440	10	22000-0	Pollen	Sun et al., 2013
Ulungur Lake	China	46.98	87	478.6	AMS ^{14}C	~40	6	10000-0	grain-size, pollen data	Liu et al., 2008
Lower Red Rock Lake	America	44.63	-111.84	2015	AMS ^{14}C	~410	5	22000-0	Magnetic susceptibility, Carbonate, Organic	Mumma et al., 2012
Ulaan Nuur	Mongolia	44.51	103.65	1110	OSL	~60	12	16000-0	TOC, TN, C/N, CaCO3, CIA	Lee et al., 2013
Jenny Lake	America	43.76	-110.73	2070	AMS ^{14}C	~200	11	14000-0	TOC, C/N	Larsen et al., 2016
Balikun Lake	China	43.67	92.8	1580	^{14}C	~30	7	10000-0	TOC, δ18Ocar	Xue et al., 2011
Lake Woods	America	43.48	-109.89	2816	^{14}C	~120	17	12000-0	Sand content	Pribyl and Shuman, 2014
Blue Lake	America	40.5	-114.04	1297	AMS ^{14}C	~280	12	14000-1000	Pollen	Louderback and Rhode, 2009
Yitang Lake	China	40.3	94.97	/	OSL	~110	4	23000-0	TOC, C/N, δ13Corg	Zhao et al., 2015
Tiao Lake	China	40.26	99.31	1188	AMS ^{14}C	~195	4	11000-1000	Rb/Sr, Fe/Mn	Li et al., 2013
Yanhaizi Lake	China	40.1	108.42	1180	^{14}C	~80	17	14000-0	TOC, magnetic susceptibility, maturity index	Chen et al., 2003
Yanchi Lake	China	39.72	99.17	1200	AMS ^{14}C	~250	14	18000-0	TOC, C/N, Carbonate	Li et al., 2013
Qingtu Lake	China	39.05	103.67	1309	AMS ^{14}C	~40	11	11000-0	C/N, grain size	Li et al., 2012
Van Lake	Turkey	38.5	43	1649	AMS ^{14}C	~200	3	25000-0	TOC, TIC, δ13C, δ18O	Öğretmen.,2012
Hala Lake	China	38.2	97.4	4078	^{14}C	~150	18	24000-0	OM, Carbonate	Yan et al., 2014
Sanjiaocheng	China	39.01	103.34	1325	AMS ^{14}C	~50	11	15000-0	TOC, δ13Corg	Zhang et al., 2004
Hurleg Lake	China	37.28	96.9	2817	AMS ^{14}C	/	8	10000-0	Carbonate	Zhao et al., 2010
Gahai Lake	China	37.13	97.55	2850	AMS ^{14}C	~90	27	12000-0	δ13Cc, δ18Oc, CaCO3	Guo et al., 2012
Chaka Lake	China	36.63	99.03	3200	AMS ^{14}C	/	10	10000-0	TOC, TN	Liu et al., 2008
Qinghai Lake	China	36.53	99.6	3200	AMS ^{14}C	~30	10	18000-0	TOC, TN, C/N, Carbonate	Shen et al., 2005
Dalianhai Lake	China	36.24	100.39	2852	^{14}C	~10	28	24000-0	Rb/Sr	Wu, 2017
Zigetang Co	China	32	90.73	4560	^{14}C	/	5	10500-0	TOC, TOC/TS, HI, δ13Corg, TC, TIC	Wu et al., 2007
Bangong Co	China	33.7	79	4241	AMS ^{14}C	~80	11	10000-0	δ18O	Fontes et al., 1996
Zabuye Lake	China	31.35	84.07	4421	AMS ^{14}C	~620	17	30000-0	TOC, TIC, δ18Ocarb, δ13Ccarb	Wang et al., 2002

Gonghai Lake	China	38.9	112.23	1860	AMS ^{14}C	~15	25	14700-0	Pollen	Chen et al., 2015
Dali lake	China	43.15	116.29	1220	AMS ^{14}C	~350	27	16000-0	Lake elevation	Goldsmith et al., 2016

Section 2.3

Original: None

Revised: 2.3 Mathematical methods

Linear tendency estimation is a common trend analysis method, which was chosen to measure the variation degree of simulated water balance in this paper. Besides, we also used the Empirical orthogonal function (EOF), a method of analyzing the structural features in matrix data and extracting the feature vector of main data, to examine spatially and temporally variability of simulated water balance. The spatial distribution of EOF first (second) mode is denoted by EOF1 (EOF2), and the time series of first (second) mode is denoted by PCA1 (PCA2).

Section 3 and Section 4

Original: 3 Results

3.1 Comparison of TraCE simulation and muti-model ensemble simulation

As Fig. 1 shown, we intercepted LGM (18000-22000 yr), MH (5000-7000 yr) and PI (1800-1900 AD) periods from the TraCE 21 kyr dataset for better matching the multi-model ensemble. Differences between the time period we chosen subjectively and the time period defined by the multi-model ensemble may affect the comparison results. However, precipitation and evaporation difference of TraCE 21 kyr among three periods exhibits similar spatial pattern with P-E difference of multi-model ensemble. Because runoff anomalies are highly correlated to precipitation anomalies, it is therefore feasible to consider that the contribution of runoff on water balance is considered as the contribution of precipitation on water balance. This comparison validates the feasibility of continuous simulation, giving our confidence to track continuous water balance fluctuations on the millennial scale using TraCE 21 kyr simulations.

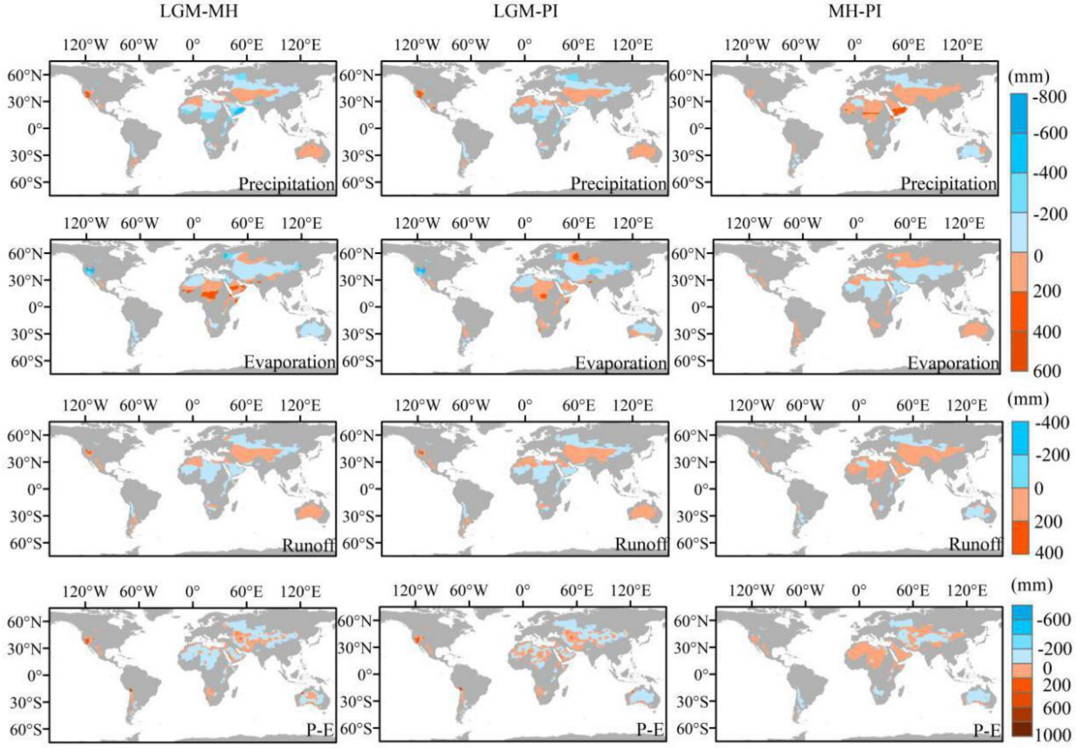


Figure 1. Annual mean precipitation, evaporation and runoff from TraCE 21 kyr simulations, and precipitation minus evaporation (P-E) from multi-model ensemble, all units mm/year; (first column) difference between LGM and MH simulations; (second column) difference between LGM and PI simulations; (third row) difference between MH and PI simulations.

3.2 Observed and modeled water balance change

For better validating simulated results, reviewed and summarized the millennial-scale changing patterns in lake level of the closed basins since the LGM are particularly important. If these models are useful in testing differentiation between global monsoons and westerly winds, the simulations must be able to reproduce the differentiation. In the global mid-latitudes, most lakes in closed basins experience relative high level in LGM, moderate high level in MH and low level in PI. However, there are exceptions that lakes with relative high level appear during the MH or PI in Central Asia mid-latitudes. Qinghai Lake, Hala Lake, Zhabuye Lake are typical lakes which are located in interactional transition zones between Asian monsoon and westerly winds, probably not following a single climate changing pattern (Wu et al., 2000; Editorial Committee of China's Physical Geography, 1984; An et al., 2012).

We partitioned continuous simulation trend map of water balance into positive and negative components to highlight the spatial patterns of water balance change (Fig. 2). In the Northern Hemisphere westerlies, simulations indicate widespread effective moisture declined since the LGM, except the northern Caspian Sea. Whereas, effective moisture increases since the LGM over the global Tropics. Due to the small area of the closed basins in the Southern Hemisphere westerlies and few lake records, it is difficult to measure and validate the direction of the water balance change. However, the trend map exactly exhibits the differentiation of millennial-scale water balance change between the global low-latitude monsoon dominated regions and the mid-latitude westerly winds dominated regions. Compared the simulations with the records, the most simulations to a great extent coincide with the upward or downward trend from LGM to PI in lake status. It's not our intent to simulate relative lake status change among three periods, but to validate continuous water balance simulations and to explore the continuous evolution of monsoon and westerly winds in the global closed basins since the LGM.

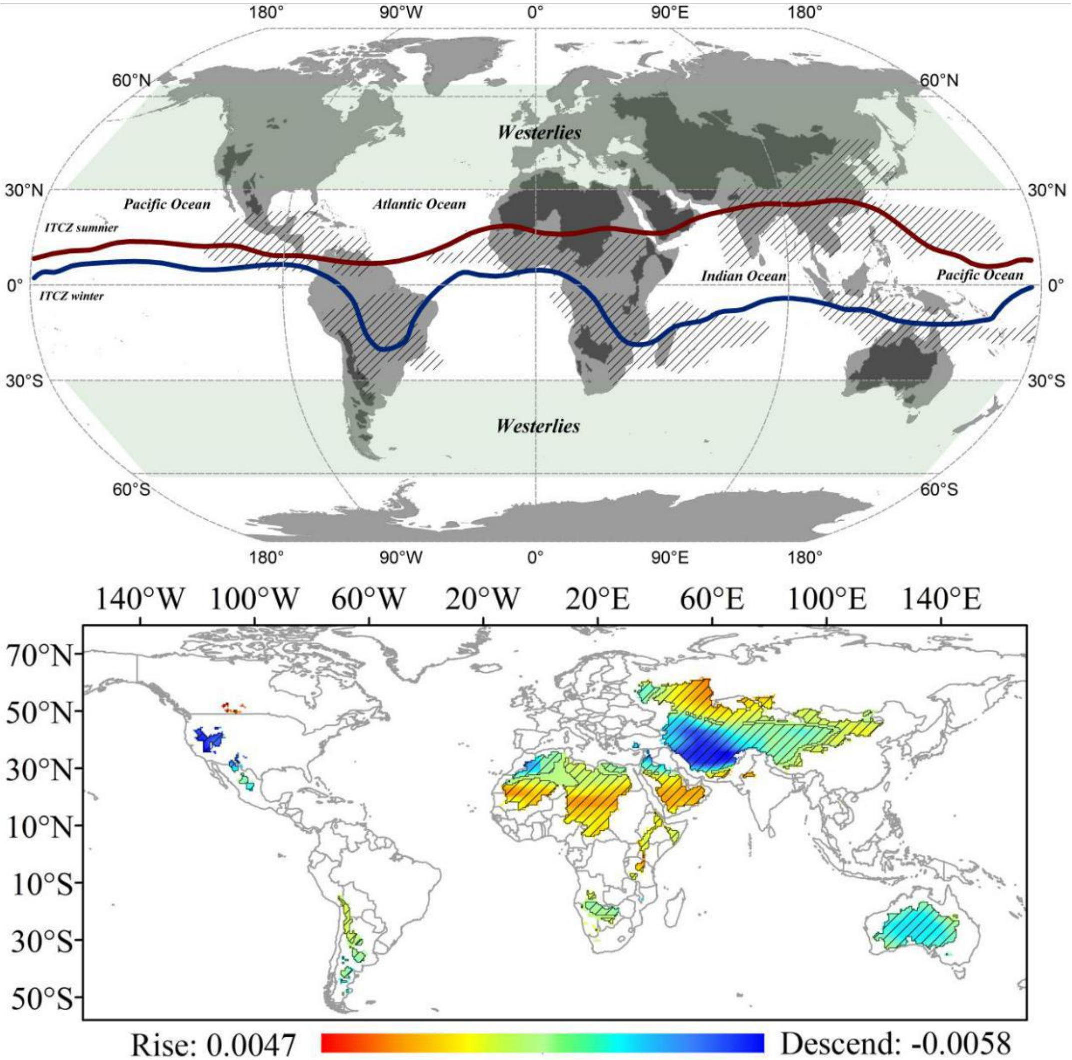


Figure 2. Distribution of global closed basins and circulation system (a): Summer and winter are in accordance with the Northern Hemisphere; the shadows present the six monsoon areas according to Wang (2009). Trend analysis of continuous

simulation in water balance change (b): The shadows indicate that the trends are statistically significant at 5% level.

3.3 Possible driving mechanisms of millennial-scale water balance change

In this section, the possible driving mechanism that affects the millennial-scale water balance change in the global closed basins was explored. The spatial-temporal decomposition was applied to obtaining the PCA1 and PCA2 with contribution rate of 51% and 14% respectively. Spatial distributions of the EOF1 and EOF2 clearly exhibit that a prominent boundary exists the interactional zones between Asian monsoon and westerly winds in Eurasia (Fig. 3). Positive signs of the EOF1 are most monsoon regions of mid-latitudes and low-latitudes, while negative signs of that are mainly located in the Northern and Southern Hemisphere westerlies, especially in the Northern Hemisphere westerlies. Spatial characteristics of the EOF2 have an opposite trend with the EOF1, except for the Caspian Sea. The PCA1 fluctuation corresponds well with stalagmite records of Dongge Cave which documents east summer Asian monsoon change. Thus, we further speculated that the water balance change in monsoon regions of global closed basins is mainly driven by mid-latitude and low-latitude summer solar radiation. The PCA2 corresponding with not obvious positive signs presents a gradual increase trend in most westerlies during the late Holocene.

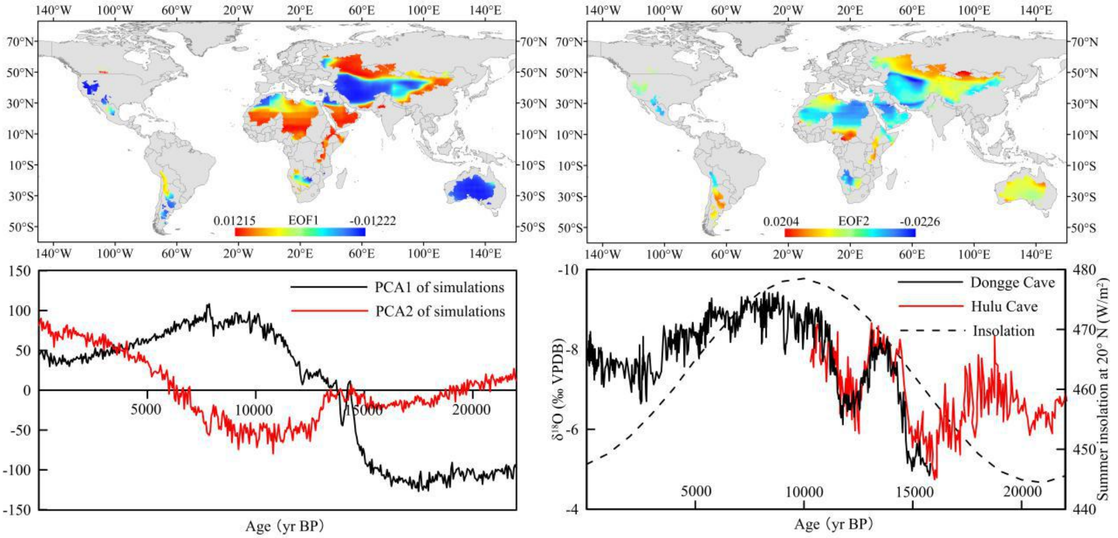


Figure 3. Spatial and temporal distribution features of EOF1 and EOF2. Stalagmite records and summer insolation come from Dykoski et al. (2005) and Wang et al. (2008).

3.4 Evolutionary differentiation of millennial-scale monsoons and westerly winds in the Northern Hemisphere mid-latitude closed basins

According to the spatial characteristics of the EOF analysis, closed basins in the Northern Hemisphere that affected by both low-latitude monsoon and mid-latitude westerly winds are ideal regions for revealing synergy of the westerly winds and monsoons. Between 30°N and 60°N, 25 paleoclimate records indicating dry or wet climate were collected from the Northern Hemisphere mid-latitude closed basins. As described in Sect. 2.2, we reconstructed moisture index from the early Holocene to late Holocene around that regions (Fig. 4). Simulated mean water balance curve corresponds well with mean moisture index in the Northern Hemisphere mid-latitude closed basins, indicating a transition from humid climate of the early-mid Holocene to arid climate of late Holocene. Therefore, continuous simulations, well validated by the paleoclimate indicators, could be better used to track climate change during the LGM.

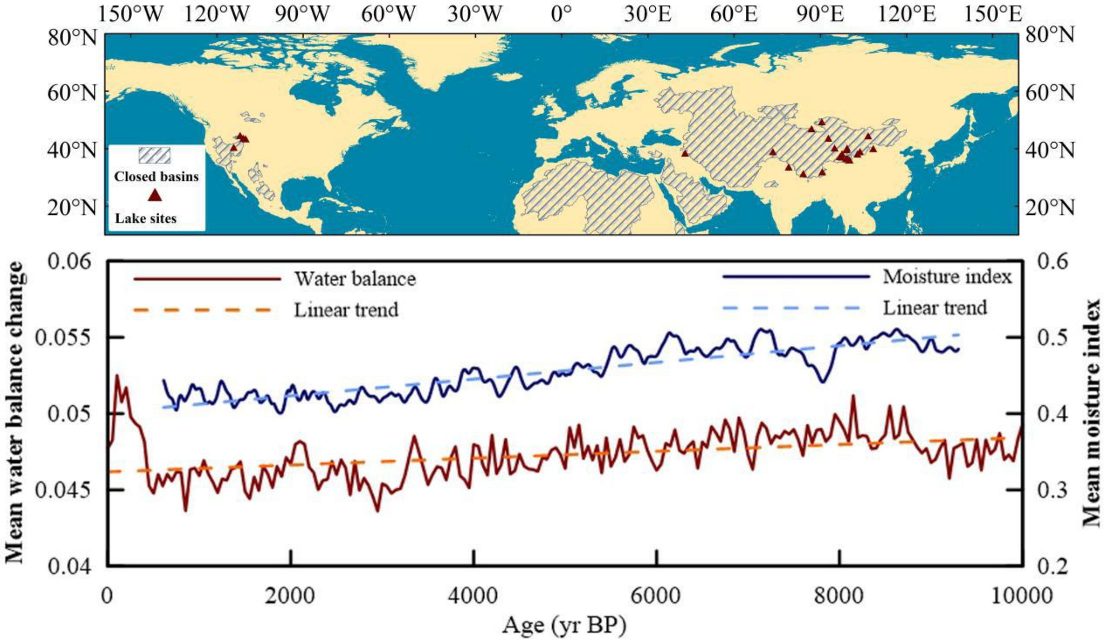


Figure 4. Comparison between simulated water balance change and reconstructed moisture index during the Holocene. Triangles indicate locations of paleoclimate records (Table 3).

Water balance simulations show a humid climate not only appears in early and mid-Holocene but also occurs during the LGM. And the maintained high moisture in the LGM is possibly influenced by low evaporation and high precipitation (Fig. 5). Using the paleoclimate modelling, Yu et al. (2000) mentioned that the low temperature during the glacial period causes a decrease in evaporation, resulting in the loss of lake water reduces and the high lake level sustains. Afterward, solar radiation, atmosphere radiation, temperature, evaporation and precipitation simulations gradually increase during the Last Glacial. When entering the warm Holocene, precipitation continues to increase and reaches the maximum in the mid-Holocene, while solar radiation, atmosphere radiation and evaporation decrease during the early-mid Holocene and then increase around the late Holocene. Low evaporation and high precipitation are responsible for the mid-Holocene relative humid climate (Fig. 5).

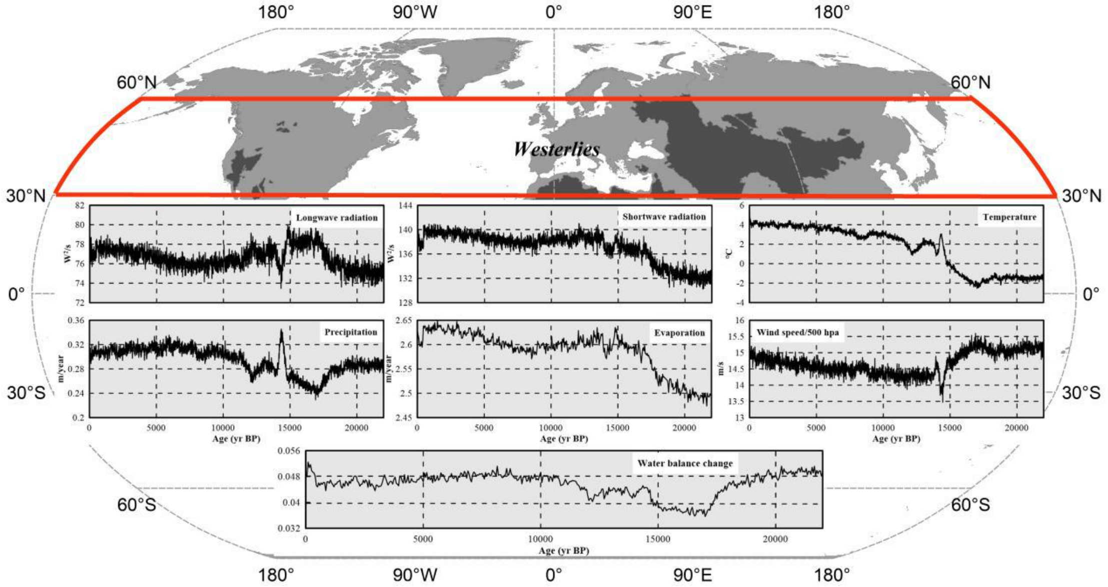


Figure 5. Time series of longwave radiation, shortwave radiation, temperature, precipitation, evaporation and 500hpa wind speed between 30°N and 60°N closed basins since the LGM.

The regions dominated by monsoons and westerly winds were then selected respectively on the basis of spatial characteristics of two mode extracted from the EOF, to explore millennial-scale evolution features of two climate systems (Fig. 6). In the westerly winds dominated regions, the LGM and mid-Holocene were characterized by humid climate, and relative dry climate prevailed in the early Holocene. Whereas, the water balance in the monsoon dominated regions was generally affected by Asian summer monsoon which brings more water vapor over the early-mid Holocene, and relative dry climate occurred in the LGM. Different climate changing patterns between arid central Asia and monsoonal Asia were demonstrated by numerous paleoclimate records (Chen et al., 2006). Li (1990) first proposed the “monsoon” and “westerly” modes on the millennial scale since the late Pleistocene in northwest China. Millennial-scale Asian summer monsoon change is possibly driven by summer insolation change in low-latitudes (Yuan et al., 2004; Dykoski et al., 2005; Hu et al., 2008; Fleitmann et al., 2003). However, Chen et al. (2008) manifested that the sea-surface temperatures (SSTs) of North Atlantic and air temperatures of high-latitudes are responsible for the Holocene effective moisture evolution of arid Central Asia which is dominated by the westerly winds.

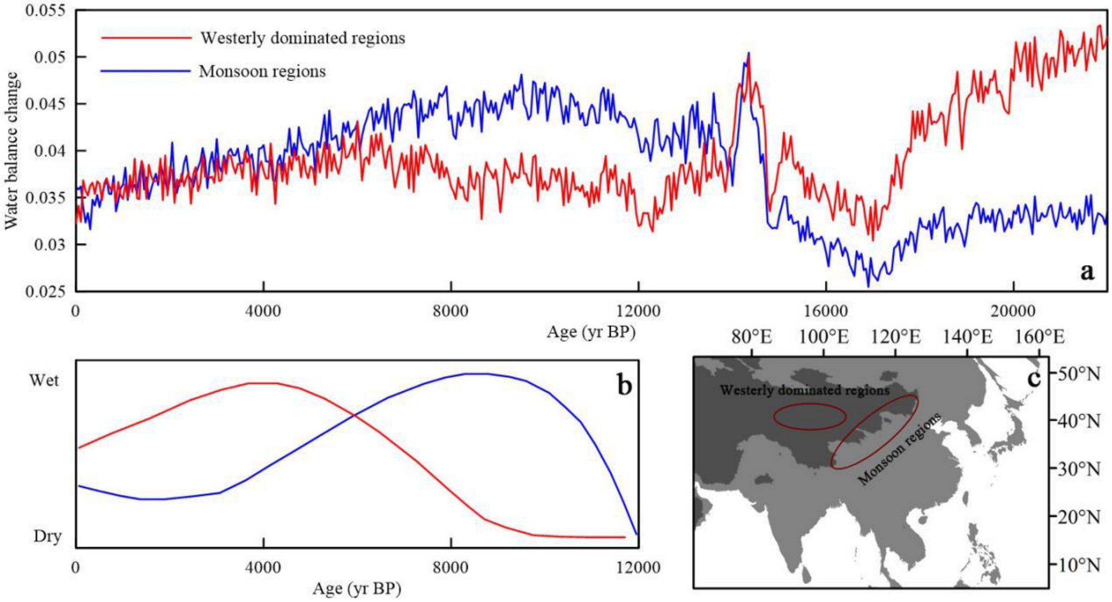


Figure 6. Simulated water balance change between westerly dominated regions and monsoon regions in the Asian closed basin since the LGM (a), general climate changing patterns during the Holocene in monsoon Asia and westerly Central Asia (b) come from Chen et al. (2006), and extracted westerly dominated regions and monsoon regions in the Asian closed basins (c).

4 Discussion

The global low-latitudes and mid-latitudes are mainly controlled by the global monsoon and westerly winds systems. As a result of different driving mechanisms, millennial-scale climate change in global low-latitudes and mid-latitudes probably exhibits diverse variations. Qin (1997) made a large-scale spatial analysis and presented that lake levels in south-central North America range from high to low since the LGM and reach the lowest in early-mid Holocene, while the wettest period in the African and South Asian monsoon regions is the early and mid-Holocene. The LGM proxies indicated the southwestern America experiences a climate that was wetter than present, and the Pacific Northwest through the Rockies experiences a climate that was drier than present, as well as a transition from wetter to drier conditions happened along a northwest-southeast trending band across the northern Great Basin (Oster et al., 2015). For the African and Asian tropics in the Northern Hemisphere, the increase summer solar radiation from 12000 to 6000 yr induced the enhancement of thermal contrast between land and sea, and further caused the strengthening of summer monsoons, so that more water vapor was brought (COHMAP Members, 1988).

Collected records in the Northern Hemisphere indicate evolution of westerly winds and monsoons system (Fig. 7). Speleothem records from central and southern China confirmed that the periods of weak East Asian summer monsoons are coincided with the cold periods of the North Atlantic (Yuan et al., 2004, Dykoski et al., 2005; Wang et al., 2008). Major trend of moisture conditions revealed by the Australian monsoon, the east African monsoon and the Indian monsoon regions is a gradual decrease since the early Holocene, and reaches the wettest status between 8 and 6 kyr in the East Asian monsoon region (Wang et al., 2017). According to the longest and highest-resolution drill core from Lake Qinghai, An et al. (2012) presented that the Lake Qinghai summer monsoon record generally resembles the changing trends of Asian summer monsoon records derived from Dongge and Hulu speleothems over the last 20 kyr, and the mid-latitude Westerlies climate dominates the Lake Qinghai area in glacial times. Low-latitude summer insolation is broadly recognized as a major control on low-latitudes monsoon systems, as a result, the tropical monsoons are weak during the LGM and strong monsoons prevail in the early-mid Holocene (Fig. 7).

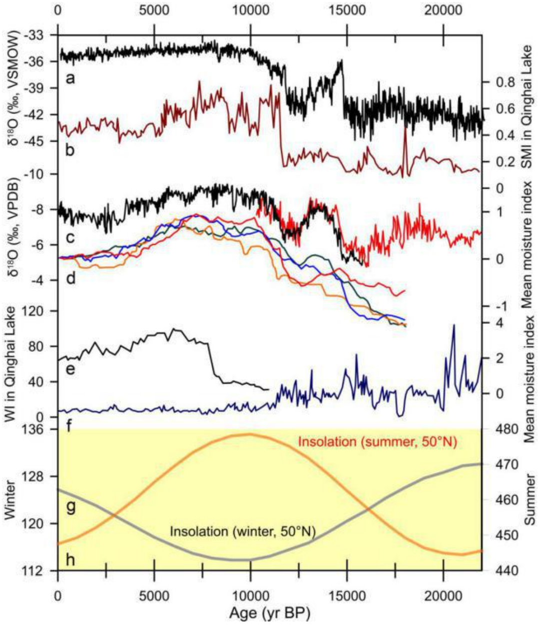


Figure 7. Comparison of records between the westerly and monsoon regions of the Northern Hemisphere. (a) NGRIP $\delta^{18}O$ (Rasmussen et al., 2006); (b) Lake Qinghai Westerlies climate index (An et al., 2012); (c) Dongge and Hulu cave speleothem $\delta^{18}O$ records (Dykoski et al., 2005; Wang et al., 2008); (d) moisture indexes in East Asian Monsoon (red line), East African Monsoon (green line), Indian Monsoon (blue line) and Australian Monsoon (orange line) regions (Wang et al., 2017); (e) The average moisture index for arid central Asian region as a whole during the Holocene (An and Chen, 2009); (f) Lake Qinghai Asian summer monsoon index (An et al., 2012); (g) and (h) are summer 50°N insolation and winter 50°N insolation, respectively.

The Northern Hemisphere westerlies shifting northward or southward influences global atmosphere circulation significantly. Quaternary ice sheets of the Northern Hemisphere in the LGM develop to its maximum extension and consequent existence of persisting strong glacial anticyclone leads to the southward displacement of the westerly winds (Yu et al., 2000). Many researches suggested the Northern Hemisphere westerlies in the LGM moves south to the southwest of the United States and the eastern Mediterranean region (Lachniet et al., 2014; Rambeau, 2010). Therefore, the narrowed temperature difference between sea and land causes the East Asian summer monsoon weaken, and may further induces the strong westerly winds throughout the year and the precipitation increases (Yu et al., 2000). The moisture transport in the arid central Asia mainly comes from the Northern Hemisphere westerlies of which the moisture source derives from the Black Sea, the Mediterranean Sea, the Arctic Ocean and the Atlantic Ocean. In these regions, winter precipitation in this region accounts for a large proportion of annual precipitation (Li et al., 2008).

The above views emphasize the complexity of climate change in the interactional zones between mid-latitude westerlies and Asian summer monsoon. Our results separated the climate systems of the monsoon and westerly dominated regions, revealing humid climate characterized the LGM and mid-Holocene in the westerly winds dominated regions, and drier climate prevailed during the LGM in the monsoon dominated regions. Besides, lots of evidences about Holocene different moisture evolution features between Asian monsoon regions and westerlies dominated arid central Asia were provided by scholars (Chen et al., 2006, 2008; An and Chen, 2009; Li et al., 2011; Chen et al., 2019). However, the intensity of monsoon system and westerly winds varies in different periods so that the main control system in the interactional regions depends largely on which system was much stronger during that period.

Revised: 3 Results and discussion

3.1 Observed and simulated water balance change in global closed basins

As Fig. 1 shown, we intercepted LGM (18000-22000 yr), MH (5000-7000 yr) and PI (1800-1900 AD) periods from the TraCE 21 kyr dataset for better matching the multi-model ensemble. Because runoff anomalies are highly correlated to precipitation anomalies, it is therefore feasible to consider that the contribution of runoff on water balance is considered as the contribution of precipitation on water balance. Difference between the time period we chosen subjectively and the time periods defined by the multi-model ensemble may affect the comparison results. However, precipitation and evaporation difference of TraCE 21 kyr among three periods exhibits similar spatial pattern with P-E difference of multi-model ensemble. The simulations and lake status records of the mid-latitude westerlies (low-latitude monsoon regions) show that LGM is humid (dry) relative to MH and PI, which generally corresponds to the hydroclimate patterns of previous researches (Street and Grove, 1979; Qin et al., 1997; Quade and Broecker, 2009; Lowry and Morrill, 2019). It’s not our intent to simulate relative lake status change among three periods, but to validate continuous water balance simulations and to track continuous water balance fluctuations on the millennial scale using TraCE 21 kyr simulations.

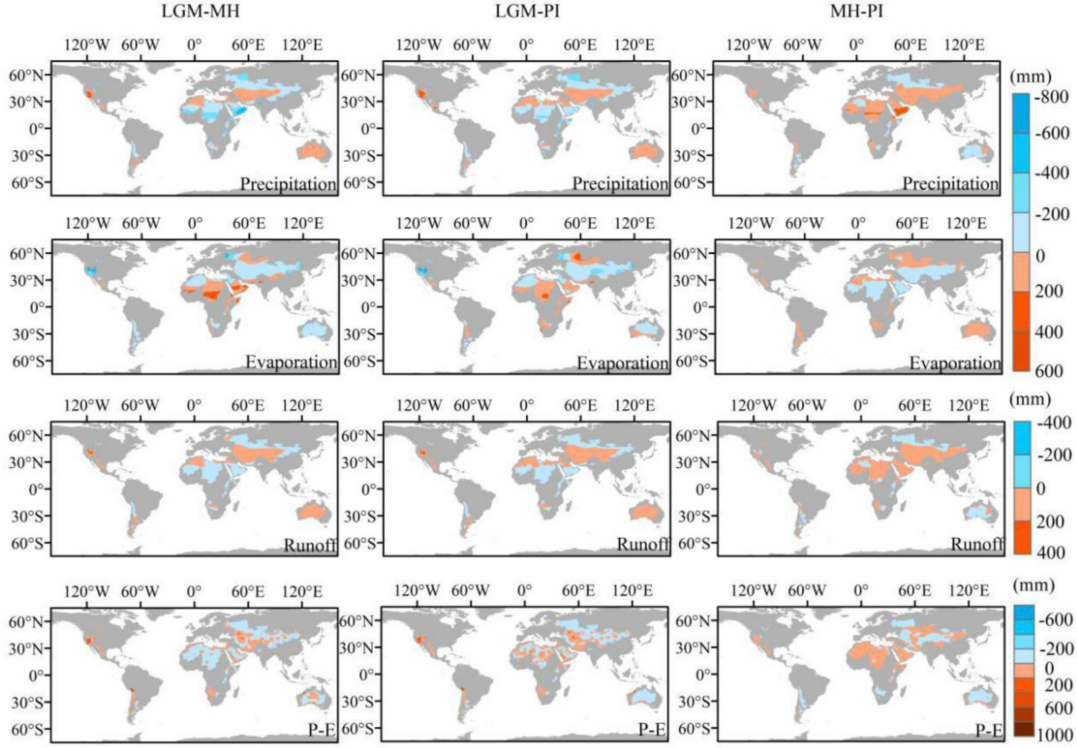


Figure 1. Annual mean precipitation, evaporation and runoff from TraCE 21 kyr simulations, and precipitation minus evaporation (P-E) from multi-model ensemble, all units mm year^{-1}; (first column) difference between LGM and MH simulations; (second column) difference between LGM and PI simulations; (third row) difference between MH and PI simulations.

In continuous simulations, we partitioned the trend map of water balance into positive and negative components to highlight the spatial patterns of water balance change (Fig. 2). In the global mid-latitude westerlies, simulations indicate widespread effective moisture declines since the LGM except the northern Caspian Sea, whereas, effective moisture increases since the LGM over the global Tropics. Meanwhile, the trend map exactly exhibits the spatial differentiation of the millennial scale water balance change between the global low-latitude monsoon dominated regions and the mid-latitude westerly winds dominated regions. This differentiation provides the basis to explore the continuous evolution of monsoons and westerly winds in the closed basins since the LGM.

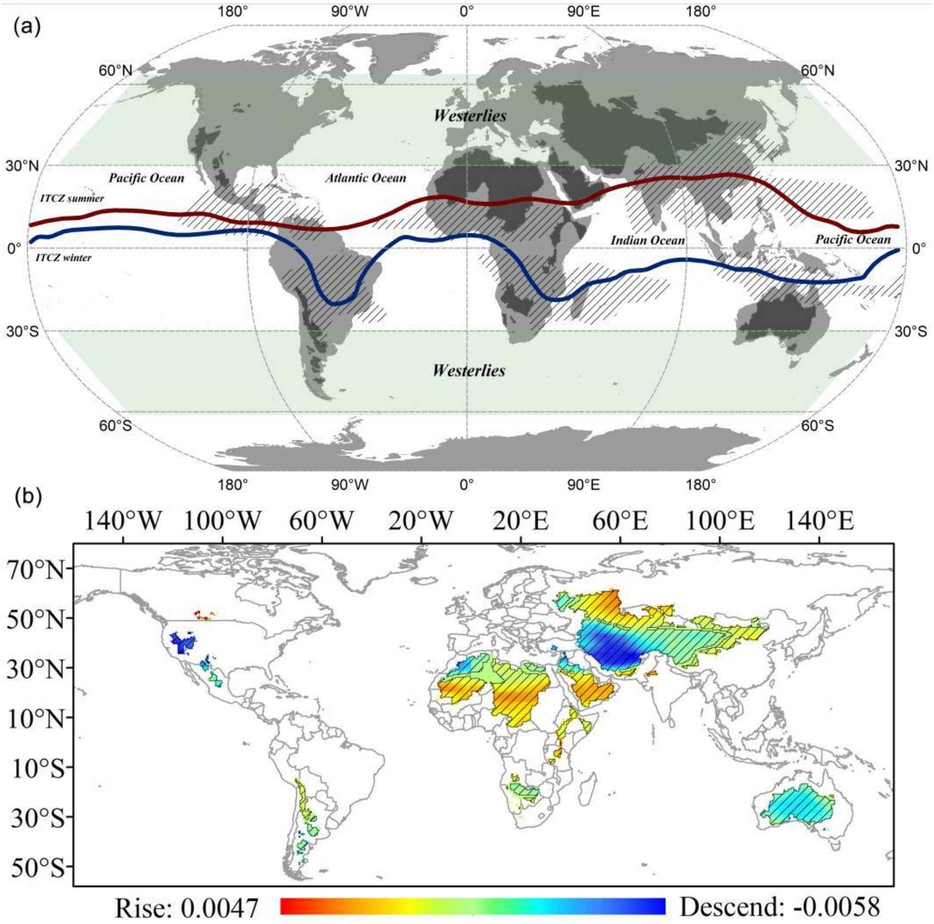


Figure 2. (a) Distribution of global closed basins and circulation system: The dark areas are global closed basins; summer and winter of the ITCZ are in accordance with the Northern Hemisphere; the shadows present the six monsoon areas according to Wang (2009), and (b) Trend analysis of continuous simulation in water balance change: The shadows indicate that the trends are statistically significant at 5% level.

3.2 Possible driving mechanisms of millennial scale water balance change

In this section, the possible driving mechanism that affects the millennial scale water balance change in the global closed basins is explored. Positive signs of the EOF1 represent most monsoon regions of mid-latitudes and low-latitudes, while negative signs of that are mainly located in the Northern and Southern Hemisphere westerlies. Spatial characteristics of the EOF2 have an opposite trend with the EOF1, except for the Caspian Sea. The contribution rate of PCA1 and PCA2 is 51% and 14% respectively, therefore the following discussion mainly focuses on PCA1 with the high contribution rate. The PCA1 extracted from water balance simulation tends to represent the effective moisture fluctuation of closed basins in low-latitude monsoon regions, indicating a relative humid climate during the early-to-mid Holocene. By comprehensively analyzing a variety of paleoclimate proxies, Wang et al. (2017) suggested that moisture change revealed by the Australian monsoon, the East African monsoon and the Indian monsoon regions reaches the wettest status in the early Holocene, while the wettest condition in the East Asian summer monsoon regions occurs between 8 and 6 kyr. Likewise, Qin (1997) presented that the wettest period in the African and South Asian monsoon regions is the early-to-mid Holocene, coinciding well with our results.

The climatic significance of the $\delta^{18}O$ in the Asian speleothem records is always a long-standing debate, and some influential hypotheses regard $\delta^{18}O$ of the monsoon regions as a proxy for “Asian monsoon intensity”, “Indian monsoon intensity”, “summer monsoon rainfall amount” and “circulation conditions” (Cheng et al., 2012; Chen et al., 2016). Although the climatic significance is controversial, it is well accepted that $\delta^{18}O$ changes should bear the imprint of variations in the oxygen isotopic composition of precipitation (Cheng et al., 2012; Chen et al., 2016). According to the close similarity of the PCA1 with the speleothem records from Dongge and Hulu caves, our simulations are more inclined to suggest that the $\delta^{18}O$ stalagmite records indicate the change in water vapor brought by the monsoons. In addition, we not only compared the PCA1 with the stalagmite records of Dongge Cave with controversial climatic significance, but also with the summer solar radiation at low-latitudes in the Northern Hemisphere. This comparison provides evidence for the view that the evolution of low-latitude monsoons is generally controlled by summer insolation in the Northern Hemisphere (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Thus, we further speculated that the water balance change in monsoon regions of global closed basins is mainly driven by mid-latitude and low-latitude summer solar radiation.

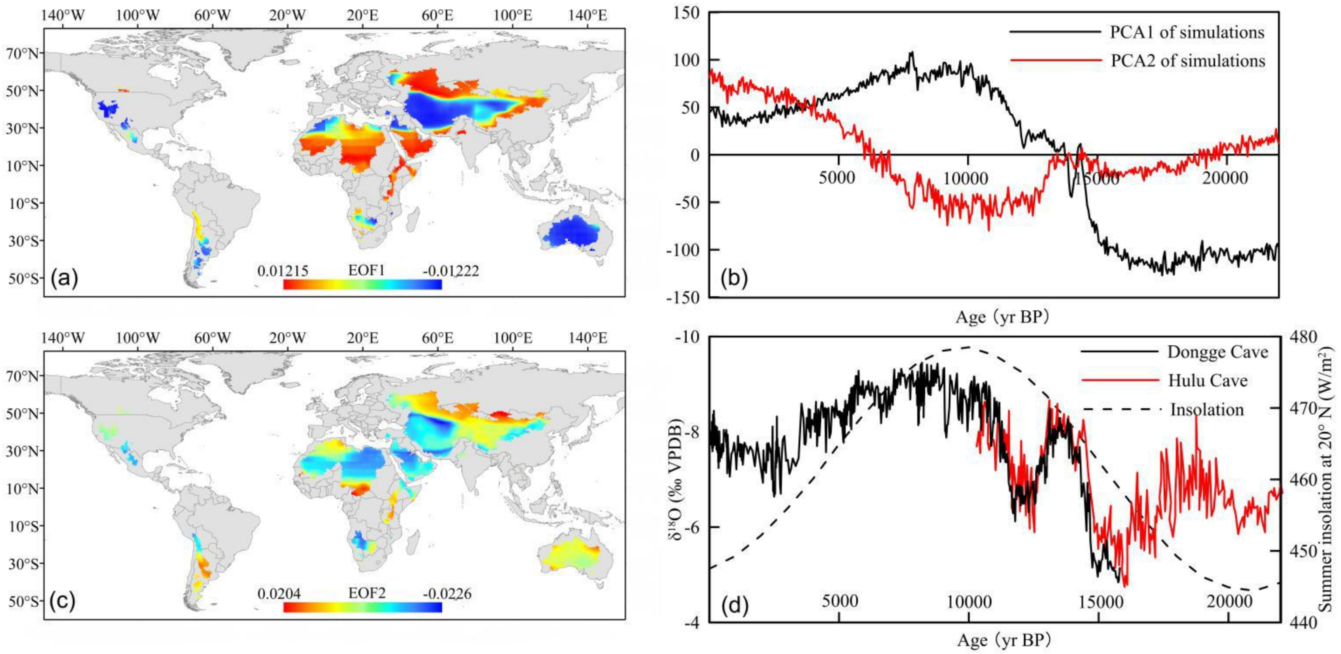


Figure 3. (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite

records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978).

3.3 Evolutionary characteristics and causing factors of millennial scale hydroclimate change in the Northern Hemisphere mid-latitude closed basins

On the basis of the spatial characteristics of the EOF analysis, closed basins in the Northern Hemisphere, affected both by low-latitude monsoons and mid-latitude westerly winds, are ideal regions for revealing synergy of the westerly winds and monsoons. Between 30°N and 60°N, 27 paleoclimate records indicating dry or wet climate were collected from the Northern Hemisphere mid-latitude closed basins. As described in Sect. 2.2, we reconstructed moisture index from the early to late Holocene around that regions (Fig. 4). Simulated mean water balance curve corresponds well with mean moisture index in the Northern Hemisphere mid-latitude closed basins, indicating a transition from a humid climate in the early-to-mid Holocene to an arid climate in the late Holocene. Therefore, continuous simulations, well validated by the paleoclimate indicators, could be better used to track climate change during the LGM.

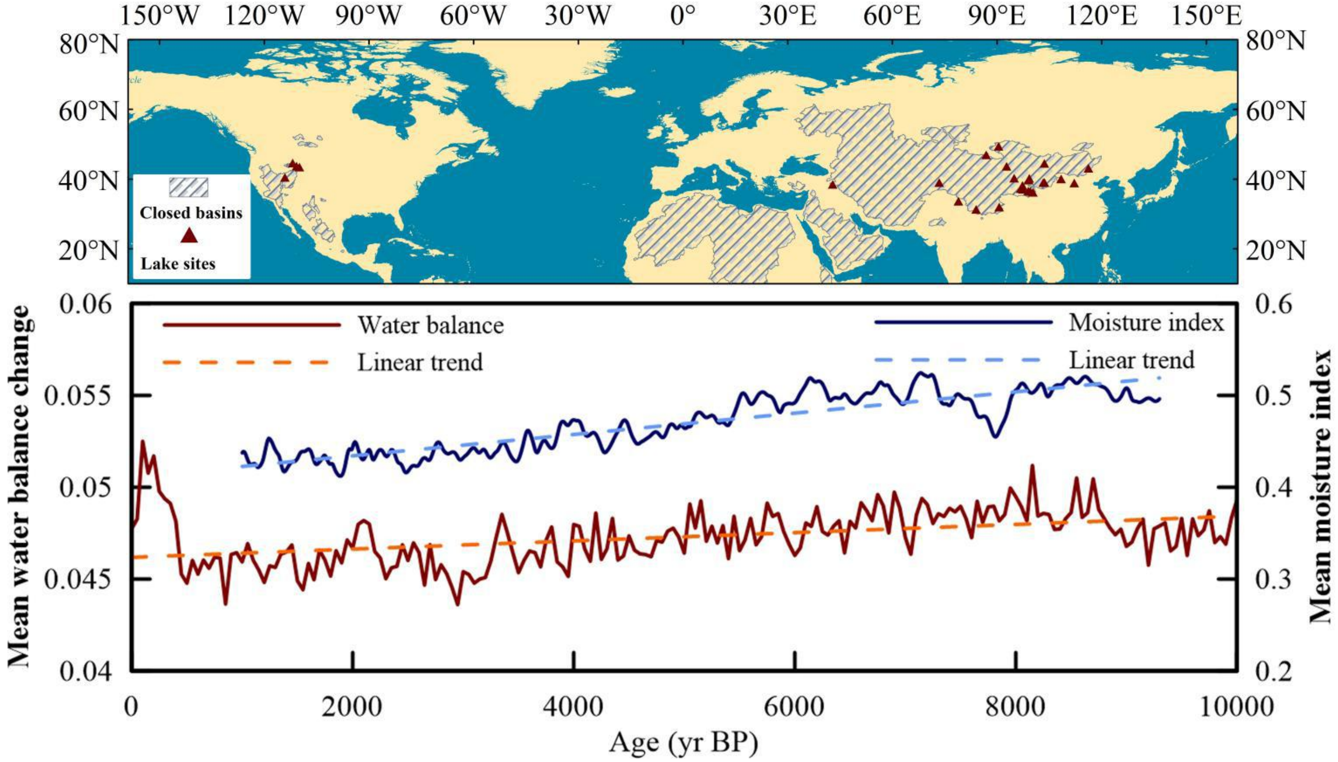


Figure 4. Comparison between simulated water balance change and reconstructed moisture index in the mid-latitude closed basins of the Northern Hemisphere during the Holocene. Triangles indicate locations of paleoclimate records (Table 3).

Water balance simulations since the LGM show that a humid climate not only appears in the early-to-mid Holocene but also occurs during the LGM, while the climate is relatively dry in the late Holocene. The maintained high moisture in the

LGM is possibly influenced by low evaporation and high precipitation (Fig. 5). Using paleoclimate modelling, Yu et al. (2000) mentioned that the low temperature during the glacial period causes a decrease of evaporation and a reduction of lake water loss, resulting in the appearance of high lake level. Afterward, solar radiation, atmosphere radiation, temperature, evaporation and precipitation simulations gradually increase (Fig. 5). When entering the warm Holocene, precipitation continues increasing and reaches a maximum in the MH, while solar radiation, atmosphere radiation and evaporation decrease during the early-to-mid Holocene and then increase around the late Holocene. Low (high) evaporation and high (low) precipitation are responsible for the MH (late-Holocene) relative humid (dry) climate (Fig. 5).

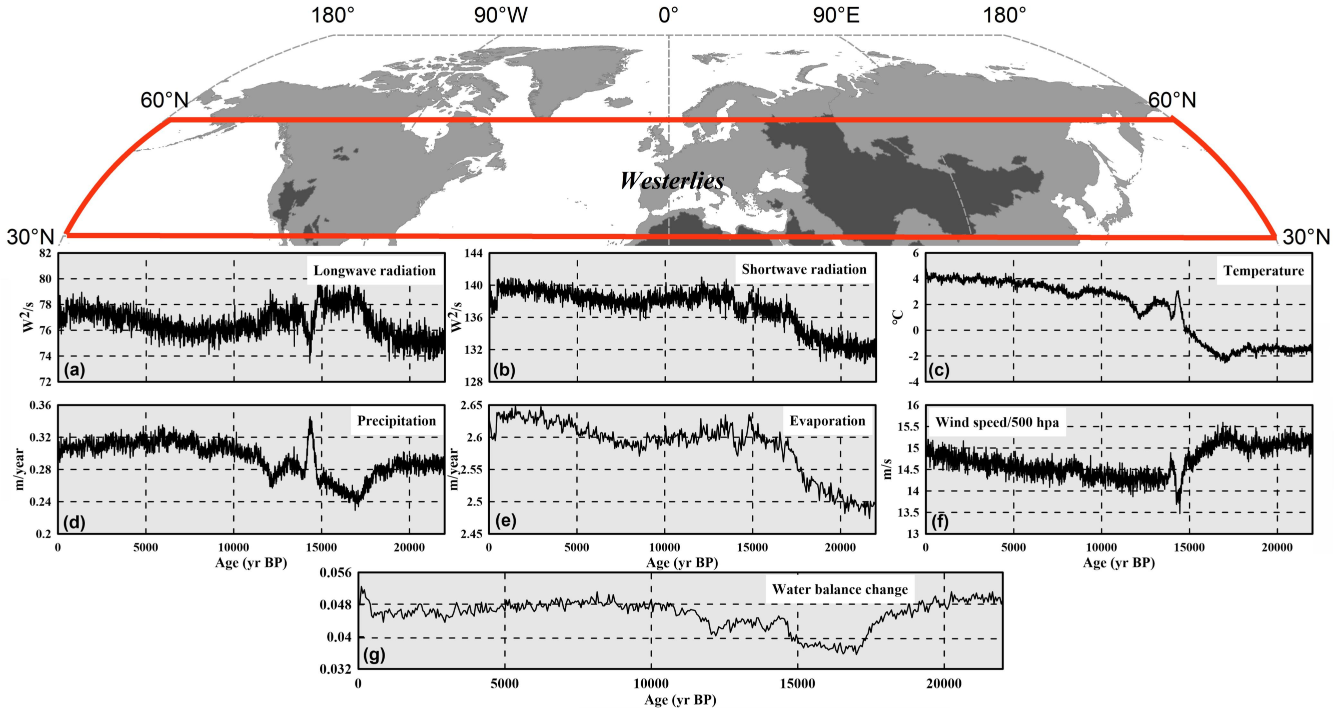


Figure 5. Time series of (a) longwave radiation, (b) shortwave radiation, (c) temperature, (d) precipitation, (e) evaporation, (f) 500 hpa wind speed and (g) water balance change between 30°N and 60°N closed basins since the LGM.

3.4 Evolutionary differentiation of millennial scale monsoons and westerly winds in Asian closed basins

Spatial distributions of the EOF1 and EOF2 clearly exhibit that a prominent boundary exists in the interactional zones between East Asian summer monsoon and westerly winds in Asia. Since the boundary of the monsoon will be adjusted accordingly with the change of East Asian summer monsoon strength, evolution of Asian lakes on the millennial scale probably not follows a single climate changing pattern (Wu et al., 2000; Editorial Committee of China's Physical Geography, 1984; An et al., 2012). The regions dominated by East Asian summer monsoon and westerly winds were then selected respectively based on the spatial characteristics of two modes extracted from the EOF, to explore millennial scale evolution features of two climate systems (Fig. 6). In the westerly winds dominated regions, the LGM and MH are characterized by humid climate, and relative dry climate prevails in the early and late Holocene. Whereas, the water balance in the monsoon dominated regions is generally affected by East Asian summer monsoon which brings much water vapor over the early-to-mid Holocene, and leads to relative dry climate in the LGM and late Holocene. Li (1990) first proposed the “monsoon” and “westerly” modes on the millennial scale since the late Pleistocene in northwest China, then different climate changing patterns between arid central Asia and monsoonal Asia were demonstrated by numerous paleoclimate records (Chen et al., 2006, 2008; An and Chen, 2009; Li et al., 2011; Chen et al., 2019). Thereinto, a viewpoint that millennial scale East Asian summer monsoon change is possibly driven by summer insolation change in low-latitudes is the most widely accepted (Yuan et al., 2004; Dykoski et al., 2005; Hu et al., 2008; Fleitmann et al., 2003). And the sea-surface temperatures (SSTs) of North Atlantic and air temperatures of high-latitudes are responsible for the Holocene effective moisture evolution of arid Central Asia which is dominated by the westerly winds (Chen et al., 2008). The moisture transport in the arid Central Asia mainly comes from the Northern Hemisphere westerlies of which the moisture source derives from the Black Sea, the Mediterranean Sea, the Arctic Ocean and the Atlantic Ocean. Winter precipitation accounts for a large proportion of annual precipitations in these regions (Li et al., 2008).

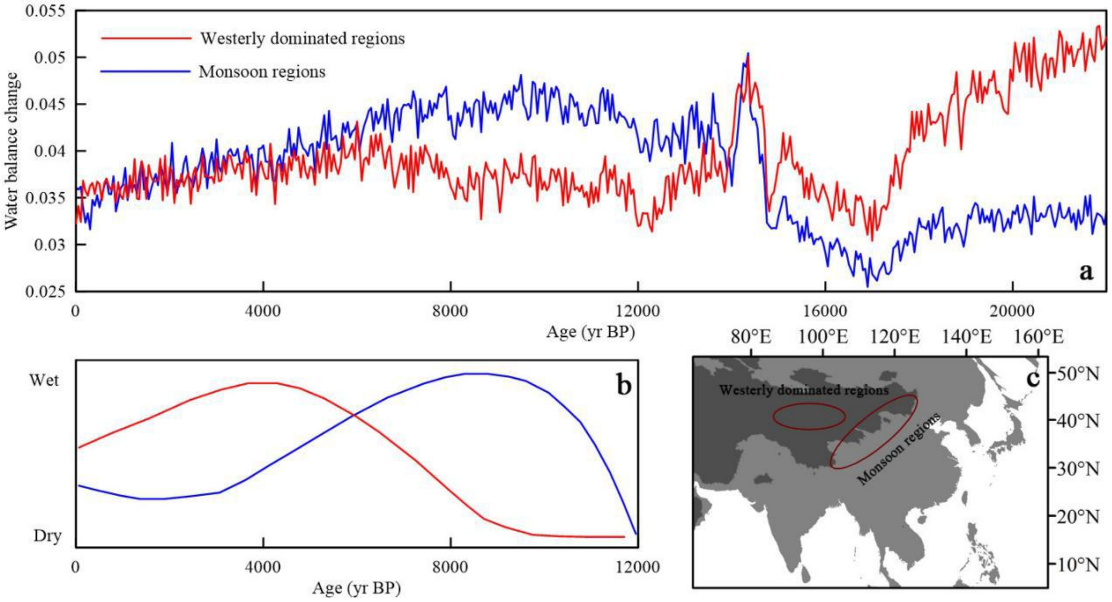


Figure 6. (a) Simulated water balance change between westerly dominated regions and monsoon regions in the Asian closed basins since the LGM, (b) General climate changing patterns during the Holocene in monsoon Asia and westerly Central Asia come from Chen et al. (2006), and (c) Extracted westerly dominated regions and monsoon regions in the Asian closed basins.

The water balance change in the Asian monsoon regions we extracted largely represents the hydroclimate variation in East Asian summer monsoon dominated regions since the LGM, while the water balance change in the westerly regions in

Central Asia can represent the hydroclimate variation in the entire Northern Hemisphere westerlies. Qin (1997) made a large-scale spatial analysis and presented that lake levels in south-central North America change from high to low since the LGM and reach the lowest in early-to-mid Holocene. The LGM proxies indicate the southwestern America experienced a climate that was wetter than present, and the Pacific Northwest through the Rockies experienced a climate that was drier than present, as well as a transition from wetter to drier conditions happened along a northwest-southeast trending band across the northern Great Basin (Oster et al., 2015). Our results generally reflect that the climate of westerlies is relatively wet at the LGM and relatively dry at the MH. For the Asian tropics in the Northern Hemisphere, the increased summer solar radiation from 12000 to 6000 yr induces the enhancement of thermal contrast between land and sea, and further causes the strengthening of summer monsoons, so that more water vapor is brought (COHMAP Members, 1988). Collected records in the Northern Hemisphere indicate evolution of westerly winds and monsoon systems (Fig. 7). Speleothem records from central and southern China confirm that the periods of weak East Asian summer monsoons are coincided with the cold periods of the North Atlantic (Yuan et al., 2004, Dykoski et al., 2005; Wang et al., 2008). The longest and highest-resolution drill core from Lake Qinghai (An et al., 2012) indicates that the summer monsoon record generally resembles the changing trends of Asian summer monsoon records derived from Dongge and Hulu speleothems over the last 20 kyr, and the mid-latitude westerlies climate dominates the Lake Qinghai area in glacial times. Low-latitude summer insolation is broadly recognized as a major control on low-latitudes monsoon systems, as a result, the tropical monsoons are weak during the LGM and late Holocene, and strong monsoons prevail in the early-to-mid Holocene (Fig. 7). Accordingly, the intensity of monsoon systems and westerly winds varies in different periods so that the main control system in the interactional regions depends largely on which system is much stronger during that period.

The Northern Hemisphere westerlies shifting northward or southward has a significant impact on global atmosphere circulation and inevitably affects the monsoon systems. Quaternary ice sheets of the Northern Hemisphere in the LGM develop to its maximum extension, and consequent existence of persisting strong glacial anticyclone leads to the southward displacement of the westerly winds (Yu et al., 2000). Many researches suggested the Northern Hemisphere westerlies in the LGM move to the southwest of the United States and the eastern Mediterranean region (Lachniet et al., 2014; Rambeau, 2010). Therefore, the narrowed temperature difference between sea and land causes the East Asian summer monsoon weaken, and may further induces the strong westerly winds throughout the year and then the precipitation increases (Yu et al., 2000). Furthermore, a growing body of evidence shows that the position and orientation of the westerly jet (WJ) probably control the Holocene East Asian summer rainfall patterns. A link between the northward seasonal progression of the WJ and the spatial pattern of East Asian summer monsoon precipitation shows that earlier northward progression of the WJ causes abundant precipitation at high-latitudes and less precipitation at low-latitudes (Nagashima et al., 2013). Especially the northward evolution of the WJ from south of the Tibetan Plateau and seasonal transition exert great influences on East Asian paleoclimate change (Chiang et al., 2015). Herzschuh et al. (2009) proposed that the position of summer monsoon rain band changes as the WJ axis shifts gradually southward, leading to the occurrence of spatiotemporal difference in Holocene China's maximum precipitation. In summary, the above views emphasize that the complex interaction between the monsoon and the westerly systems on the millennial scale should receive more attention.

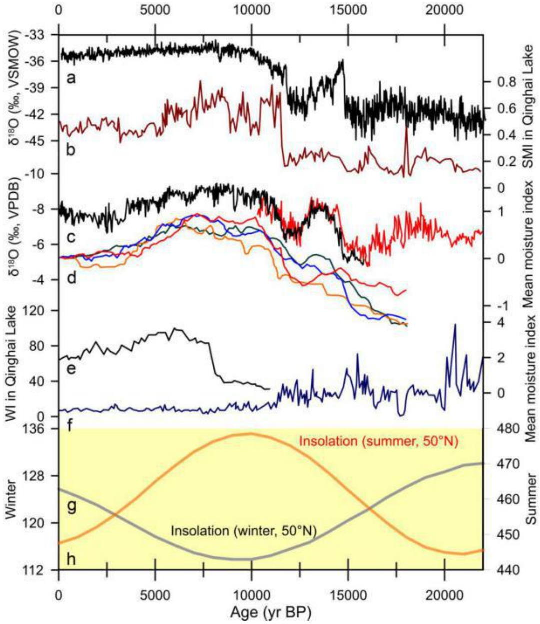


Figure 7. Comparison of records between the westerly and monsoon regions of the Northern Hemisphere. (a) NGRIP δ^{18}O (Rasmussen et al., 2006); (b) Lake Qinghai Westerlies climate index (An et al., 2012); (c) Dongge and Hulu cave speleothem δ^{18}O records (Dykoski et al., 2005; Wang et al., 2008); (d) moisture indexes in East Asian Monsoon (red line), East African Monsoon (green line), Indian Monsoon (blue line) and Australian Monsoon (orange line) regions (Wang et al., 2017); (e) The average moisture index for arid central Asian region as a whole during the Holocene (An and Chen, 2009); (f) Lake Qinghai Asian summer monsoon index (An et al., 2012); (g) and (h) are summer 50°N insolation and winter 50°N insolation, respectively (Berger, 1978).

Section 5

Original: 5 Conclusion

On the basis of 37 lake status records near global closed basins and 25 paleoclimatic records near mid-latitude closed basins of the Northern Hemisphere, we applied a lake energy balance model, a lake water balance model and paleoclimate simulations to exploring the millennial-scale differentiation between global monsoons and westerly winds. Water balance simulation showed that the effective moisture in most closed basins of the mid-latitudes Northern Hemisphere gradually decreases since the LGM, which matches well with reconstructed moisture index. Effective moisture change in most closed basins of the low-latitudes (monsoon regions) presents an opposite changing trend with that in the mid-latitudes. In the

Northern Hemisphere mid-latitude closed basins, climate change in regions dominated by westerly winds exhibits a relative humid climate in the LGM and MH, and a relative dry climate in early Holocene, whereas, Asian summer monsoon generally influences the climate change in regions dominated by monsoons, which brings more water vapor over the early-mid Holocene but less water vapor in the LGM and late Holocene.

Revised: 4 Conclusion

On the basis of 37 lake status records near global closed basins and 27 paleoclimatic records near mid-latitude closed basins of the Northern Hemisphere, we applied a lake energy balance model, a lake water balance model and paleoclimate simulations to exploring the millennial scale differentiation between global monsoons and westerly winds. Water balance simulation shows that the effective moisture in most closed basins of the Northern Hemisphere mid-latitudes gradually decreases since the LGM, which matches well with reconstructed moisture index. Effective moisture change in most closed basins of the low-latitudes (monsoon regions) presents an opposite changing trend with that in the mid-latitudes. In the Asian mid-latitude closed basins, climate change in regions dominated by westerly winds exhibits a relative humid climate in the LGM and MH, and a relative dry climate in early and late Holocene. Whereas, East Asian summer monsoon generally influences the climate change in closed basins dominated by monsoons, which brings more water vapor over the early-to-mid Holocene but less water vapor in the LGM and late Holocene.

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Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Maximum and its implication for hydrological change in Central Asia

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Abstract. Monsoon system and westerly circulation, to which climate change responds differently, are two important components of global atmospheric circulation, interacting with each other in the mid-to-low latitudes. Relevant researches on global millennial scale climate change in monsoon and westerlies regions are mostly devoted to multi-proxy analyses of lakes, stalagmites, ice cores, marine and eolian sediments. Different responses from these proxies to long-term environmental change make understanding climate change pattern in monsoon and westerlies regions difficult. Accordingly, we disaggregated global closed basins into areas governed by monsoon and westerly winds, and unified paleoclimate indicators, as well as added the lake models and paleoclimate simulations for emphatically tracking millennial scale evolution characteristics and mechanisms of East Asian summer monsoon and westerly winds since the Last Glacial Maximum (LGM). Our results conclude that millennial scale water balance change exhibits an obvious boundary between global monsoon and westerlies regions in closed basins, particularly in the Northern Hemisphere. The effective moisture in most closed basins of the mid-latitudes Northern Hemisphere mainly exhibits a decreasing trend since the LGM, while of the low-latitudes shows an increasing trend. In the monsoon dominated closed basins of Asia, humid climate prevails in the early-to-mid Holocene and relative dry climate appears in the LGM and late Holocene. While in the westerly winds dominated closed basins of Asia, climate is characterized by humid LGM and mid-Holocene (MH) compared with the dry early and late Holocene, which is likely to be connected with precipitation brought by the westerly circulation. This study provides an insight into long-term evolution and synergy of westerly winds and monsoon systems and a basis for projection of future hydrological balance.

1 Introduction

As important components of atmospheric circulation systems, the mid-latitude westerly winds and low-latitude monsoon systems play key roles in global climate change. Whether on the decadal or the millennial scale, researches about this aspect always attract widespread attention from scientists. Examination of global monsoon precipitation changes in land suggests an overall weakening over the recent half-century (1950-2000) (Zhou et al., 2008). Individual monsoon indexes reconstructed by Wang et al. (2017) indicate the moisture in the tropical Australian, the East Africa, and the Indian monsoon regions exhibits a gradual decrease since the early Holocene. It is widely accepted that the East Asian summer monsoon usually follows the variation of low-latitude summer solar radiation (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Charney (1969) and Wang (2009) also proposed that the seasonal migration of the intertropical convergence zone (ITCZ) profoundly influences the seasonality of the global monsoons. However, the global westerly winds and their associated storm tracks dominate the mid-latitude dynamics of the global atmosphere and affect the extratropical large-scale temperature and precipitation patterns (Oster et al., 2015; Voigt et al., 2015). Since the Last Glacial Maximum (LGM), climate in central and southern regions of the North American continent gradually dries out as the ice sheet melt and the westerlies move to north (Qin et al., 1997). As mentioned in the foregoing studies, millennial scale evolution in global monsoons and westerly winds probably shows different patterns as a result of complex driving mechanisms. Arguments about an asynchronous pattern of moisture variations between monsoon and westerly winds evolution underscore the importance of studying their millennial scale differentiation (Chen et al., 2006, 2008, 2019; An and Chen, 2009; Li et al., 2011; An et al., 2012).

A way to examine past climate variability is traditional methods of studying various archives which truly document the evolution of regional climate, including lake sediments (Madsen et al., 2008), stalagmites (Dykoski et al., 2005; Wang et al., 2008) and tree rings (Linderholm and Braeuning, 2006). However, due to the limited time scale of paleoclimate records, most researches on the evolution of monsoons and westerly winds are concentrated in the Holocene and lack an exploration during the LGM. With the development of paleoclimatology in recent decades, numerical simulations of paleoclimate continue to emerge and develop to a relatively mature system, which provides a useful tool for reviewing paleoclimate change over long time scales. On account of water balance system constantly responding to climatic conditions changes, a combination of numerical simulations and lake water balance models can be used to effectively track past climate change, and make up the deficiency in qualitative method of multi-proxy analysis (Qin and Yu, 1998; Xue and Yu, 2000; Morrill et al., 2001, 2004; Li and Morrill, 2010, 2013; Lowry and Morrill, 2019; Li et al., 2020). Covering one-fifth of the terrestrial surface, global closed basins distribute in both low-latitude monsoon regions and mid-latitude westerlies. Furthermore, closed basins with relative independent hydrological cycle system have a plenty of terminal lakes records that provide more evidence for retrospecting climate change (Li et al., 2017), and can be regarded as ideal regions for studying spatiotemporal difference between monsoons and westerly winds.

By constructing virtual lakes systems, here we applied lake models and a transient climate evolution model to continuously simulate water balance change since the LGM in global closed basins. Meanwhile, precipitation minus evaporation (P-E) simulations and 37 lake status records in the LGM, mid-Holocene (MH) and Pre-Industrial (PI) were supplemented for validating results of the continuous simulations. The prominent spatial differentiation of monsoons and westerly winds revealed by simulations leads us to focus on the Northern Hemisphere mid-latitude closed basins which are simultaneously influenced by mid-latitude westerly winds and low-latitude monsoons. In the mid-latitude closed basins of the Northern Hemisphere, the good match between water balance simulation and reconstructed moisture index from 27 paleoclimate records verifies the reliability of the simulation results. Further, we disaggregated the Northern Hemisphere mid-latitude closed basins into the areas dominated by monsoons and westerly winds respectively, and emphatically explored the temporal evolution of the East Asian summer monsoon and westerly winds since the LGM. According to the climate records, we comprehensively considered the determinants that control the trend of climate change in the Northern Hemisphere westerlies and East Asian summer monsoon regions since the LGM. This study not only reveals millennial scale climate change from the perspective of water balance, but also provides a new method for studying the synergy of the westerly winds and monsoons.

2 Material and Methods

2.1 Experimental design

2.1.1 Transient climate evolution experiment and CMIP5/PMIP3 multi-model ensemble

Transient climate evolution experiment (TraCE-21 kyr) as a synchronously coupled atmosphere-ocean circulation model simulation, is completed by the Community Climate System Model version 3 (CCSM3) (He, 2011). We applied this model to continuously simulating effective moisture change represented by virtual water balance variation since the LGM. Likewise, CCSM4, CNRM-CM5, FGOALS-g2, GISS-E2-R, MIROC-ESM, MPI-ESM-P and MRI-CGCM3 models participating in CMIP5/PMIP3 were also used to simulate the relative change of P-E during three particular periods (LGM, MH, PI). Here the PI period which is considered as a typical period of the late Holocene, is mainly used to measure the changes of hydroclimate conditions during the LGM and MH periods relative to the late Holocene, and verify the feasibility of the lake models by comparing the lake level simulations with the lake status records among three periods. PMIP3 protocols define the boundary conditions of these models, with a few exceptions (Table 1). Precession, obliquity and eccentricity values are specified according to Berger (1978). CO_2, CH_4, and N_2O values are set on the basis of reconstructions from ice cores (Monnin et al., 2004; Flückiger et al., 1999, 2002). A remnant Laurentide ice sheet in the LGM and a modern-day ice sheet configuration in the MH and PI simulations are specified by the ICE-5G reconstruction (Peltier, 2004), while the vegetation is prescribed to modern values. Ice sheet configuration and vegetation distribution are used by GISS model. LGM radiative forcing changes in MIROC model and MRI model are the exceptions of the PMIP3 boundary conditions, details are shown in Licciardi et al. (1998) and Lowry and Morrill (2019).

Table 1. Boundary conditions in CMIP5/PMIP3 simulations at PI, MH and LGM

	Pre-industrial	Mid-Holocene	Last Glacial Maximum
Eccentricity	0.016724	0.018682	0.018994
Obliquity (°)	23.446°	24.105°	22.949°
Longitude of perihelion (°)	102.04°	0.87°	114.42°
CO_2 (ppm)	280	280	185
CH_4 (ppb)	760	650	350
N_2O (ppb)	270	270	200
Ice sheet	Peltier (2004) 0 ka	Peltier (2004) 0 ka	Peltier (2004) 21 ka
Vegetation	Present-day	Present-day	Present-day

2.1.2 Lake energy balance model and lake water balance model

Before calculating, we linearly interpolated different resolutions grid cells of TraCE model and multi-model ensemble into a uniform resolution of 0.5°×0.5°. For all grid cells in closed basins, we assumed that the virtual lake in each grid cell is a 1 meter deep lake with freshwater, and then the virtual lake evaporation is calculated by a lake energy balance model that is modified according to Hostetler and Bartlein (1990)'s model. The evaporation of lake surface depends on the heat capacity of water, water density, lake depth, lake surface temperature, shortwave radiation, longwave radiation absorbed by the water surface, longwave radiation emitted by the water surface, latent heat flux, and sensible heat flux, etc. If the surface energy balance is negative (positive), the ice forms (melts). Besides, lake depth and lake salinity are important input parameters influencing lake surface evaporation (Dickinson et al., 1965), however, only small changes appear in lake evaporation when adding lake depth to 5 and 10 m and increasing lake salinity to 10 ppt. More details of lake energy balance model are described in Morrill (2004) and Li and Morrill (2010).

For better assessing the relative change of water balance since the LGM, the virtual lakes are assumed in hydrological equilibrium with steady state. The lake water balance equation is shown as follows:

$$D = A_B R + A_L (P_L - E_L) \ , \qquad (1)$$

where D is discharge from the lake (m^3 $year^{-1}$), A_B is area of the drainage basin (m^2), R is runoff from the drainage basin (m $year^{-1}$), A_L is area of the lake (m^2), P_L is precipitation over the lake (m $year^{-1}$) and E_L is lake evaporation (m $year^{-1}$). Given the application of Equation (1) requiring specific values of the A_B and A_L, this equation is simplified for grid cells where $P_L - E_L \geq 0$ and grid cells where $P_L - E_L < 0$. Grid cells where $P_L - E_L \geq 0$ represent open lakes, and maintain water balance by discharging more or less water. While the runoff into the lake compensates the net water loss in grid cells where $P_L - E_L < 0$, and these regions maintain water balance by changes in the ratio of A_L to A_B, as described by setting $D = 0$ in Equation (2):

$$\frac{A_L}{A_B} = \frac{R}{(E_L - P_L)} \ , \qquad (2)$$

where A_L/A_B represents virtual lake level. Accordingly, for grid cells with $P_L - E_L < 0$, the A_L/A_B values are calculated and compared to represent relative water balance change, and more details about lake water balance model are described in Li and Morrill (2010). We combined the values of P_L, E_L and R with Equations (1) and (2) and simulated the continuous water balance change since the LGM using TraCE 21 kyr model.

2.2 Records selection and moisture index inference

37 lake status information in or near global closed basins were collected to compare relative changes among three characteristic periods. Lake status information sorted by latitudes is shown in Table 2. Then, 27 climate records were compiled in or near the mid-latitude closed basins of the Northern Hemisphere with reliable chronologies and successive sedimentary sequences from published literatures, which can reflect the continuous dry and wet change (Table 3). We interpolated climate data at intervals of 10 years and unified the time scale according to the chronology accuracy of the

extracted data. Finally, the data were standardized to indicate a humid climate with a relative high value and a dry climate with a relative low value, and the signals of moisture change were transformed into a range of 0 to 1 index. Due to the different time scales of the collected continuous paleoclimate records, we can only reconstruct the regional moisture change from the early to late Holocene after unifying the time scales, but the purpose of this part is only to check the simulation results.

Table 2. Summary of lake level change in or near global closed basins

Lake	Location	Lat(°)	Lon(°)	Materials and dating methods	LGM relative to MH	LGM relative to PI	MH relative to PI	References
Achit Nuur	Mongolia	49.42	90.52	Sediments and AMS ^{14}C	High	High	High	Sun et al., 2013
Ulungur Lake	China	46.98	87	Sediments and AMS ^{14}C	Low	Low	High	Mischke et al., 2011
Manas Lake	China	45.75	86	Sediments and AMS ^{14}C	Low	Low	Low	Rhodes et al., 1996
Ebinur Lake	China	44.9	82.7	Sediments and OSL dating	High	High	High	Wu et al., 1995; Jin et al., 2013
Lower Red Rock Lake	America	44.63	-111.84	Sediments and AMS ^{14}C	High	High	High	Mumma et al., 2012
Balikun Lake	China	43.67	92.8	Sediments and U–Th dating	High	High	High	Ma et al., 2004; Lu et al., 2015
Bosten Lake	China	42	87	Sediments and AMS ^{14}C	Low	Low	High	Wünnemann et al., 2006; Huang et al., 2009
Surprise Lake	America	41.5	-120.1	Sediments and U–Th dating	High	High	Similar	Ibarra et al., 2014
Bonneville Lake	America	40.5	-113	Terraces and ^{14}C	High	High	Low	Oviatt, 2015; Hart et al.,2004
Yitang Lake	China	40.3	94.97	Sediments and OSL dating	Low	Low	High	Zhao et al., 2015
Lop Nur Lake	China	40.29	90.8	Sediments and U–Th dating	High	High	High	Yan et al., 2000
Yanhaizi Lake	China	40.1	108.42	Sediments and AMS ^{14}C	High	High	Similar	Chen et al., 2003
Lahontan Lake	America	40	-119.5	Terraces and ^{14}C	High	High	High	Lyle et al., 2012
Qingtu Lake	China	39.05	103.67	Terraces and AMS ^{14}C	High	High	Similar	Zhang et al., 2004
Karakul Lake	Tajikistan	39.02	73.53	Sediments and AMS ^{14}C	Low	High	High	Heinecke et al., 2017
Van Lake	Turkey	38.5	43	Sediments and AMS ^{14}C	High	High	High	Çağatay et al., 2014
Hala Lake	China	38.2	97.4	Sediments and AMS ^{14}C	Low	Low	Low	Yan and Wünnemann, 2014
Owens Lake	America	38	-119	Terraces and ^{14}C	High	High	/	Bacon et al., 2006
Qinghai Lake	China	36.53	99.6	Terraces and AMS ^{14}C	Low	Low	Similar	Madsen et al., 2008
Bangong Co	China	33.7	79	Sediments and AMS ^{14}C	Similar	High	High	Rossit et al., 1996; Li et al., 1991
Cochise Lake	America	32.1	-109.8	Sediments and ^{14}C	High	High	High	Waters, 1989
Cloverdale Lake	America	31.5	-109	Terraces and ^{14}C	High	High	/	Krider, 1998
Zabuye Lake	China	31.35	84.07	Sediments and AMS ^{14}C	High	High	High	Wang et al.,2002
Nam Co	China	30.65	90.5	Sediments and AMS ^{14}C	Low	Low	High	Witt et al., 2016
Babicora Lake	Mexico	29	-108	Sediments and U–Th dating	High	High	/	Metcalfe et al., 2002
Chen Co	China	28.93	90.6	Sediments and AMS ^{14}C	High	Similar	High	Zhu et al., 2009
La Piscina de Yuriria Lake	Mexico	20.22	-100.13	Sediments and ^{14}C	Low	Low	High	Davies, 1995
Chignahuapan Lake	Mexico	19.16	-99.53	Sediments and ^{14}C	High	High	/	Caballero et al., 2002
Pátzcuaro Lake	Mexico	19.5	-101.5	Sediments and AMS ^{14}C	High	High	Low	Bradbury, 2000

Malawi Lake	Malawi	-10.02	34.19	Sediments and OSL dating	Low	Low	High	Konecky et al., 2011
Titicaca Lake	Peru/Bolivia	-16	-69.4	Sediments and AMS ^{14}C	High	High	Low	Rowe et al., 2002
Makgadikgadi Lake	Botswana	-20	24.76	Terraces and ^{14}C	High	High	High	Riedel et al., 2014
Uyuni Lake	Bolivia	-20.2	-67.5	Sediments and U–Th dating	High	High	High	Baker et al., 2001
Mega-Frome Lake	Australia	-31	140	Terraces and AMS ^{14}C	High	High	High	Cohen et al., 2011
Cari Laufquen Lake	Argentina	-41.4	-69.6	Sediments and ^{14}C	/	High	/	Cartwright et al., 2011
Huelmo Lake	Chile	-41.5	-73	Sediments and AMS ^{14}C	High	High	/	Moreno and León, 2003
Potrok Aike Lake	Argentina	-52	-70.4	Sediments and OSL dating	High	High	/	Kliem et al., 2013

Table 3. Paleoclimatic records indicating dry or wet status

Lake	Location	Lat (°)	Lon (°)	Elevations (m)	Dating method	Resolution (yr)	Dates number	Time period (cal yr BP)	Proxies used	References
Karakul Lake	Tajikistan	39.02	73.53	3915	^{14}C	~200	5	10000-0	TOC, TOC/TN, δ18Ocarb, TIC	Heinecke et al., 2017
Achit Nuur	Mongolia	49.42	90.52	1444	AMS ^{14}C	~220-440	10	22000-0	Pollen	Sun et al., 2013
Ulungur Lake	China	46.98	87	478.6	AMS ^{14}C	~40	6	10000-0	grain-size, pollen data	Liu et al., 2008
Lower Red Rock Lake	America	44.63	-111.84	2015	AMS ^{14}C	~410	5	22000-0	Magnetic susceptibility, Carbonate, Organic	Mumma et al., 2012
Ulaan Nuur	Mongolia	44.51	103.65	1110	OSL	~60	12	16000-0	TOC, TN, C/N, CaCO3, CIA	Lee et al., 2013
Jenny Lake	America	43.76	-110.73	2070	AMS ^{14}C	~200	11	14000-0	TOC, C/N	Larsen et al., 2016
Balikun Lake	China	43.67	92.8	1580	^{14}C	~30	7	10000-0	TOC, δ18Ocar	Xue et al., 2011
Lake Woods	America	43.48	-109.89	2816	^{14}C	~120	17	12000-0	Sand content	Pribyl and Shuman, 2014
Blue Lake	America	40.5	-114.04	1297	AMS ^{14}C	~280	12	14000-1000	Pollen	Louderback and Rhode, 2009
Yitang Lake	China	40.3	94.97	/	OSL	~110	4	23000-0	TOC, C/N, δ13Corg	Zhao et al., 2015
Tiao Lake	China	40.26	99.31	1188	AMS ^{14}C	~195	4	11000-1000	Rb/Sr, Fe/Mn	Li et al., 2013
Yanhaizi Lake	China	40.1	108.42	1180	^{14}C	~80	17	14000-0	TOC, magnetic susceptibility, maturity index	Chen et al., 2003
Yanchi Lake	China	39.72	99.17	1200	AMS ^{14}C	~250	14	18000-0	TOC, C/N, Carbonate	Li et al., 2013
Qingtu Lake	China	39.05	103.67	1309	AMS ^{14}C	~40	11	11000-0	C/N, grain size	Li et al., 2012
Van Lake	Turkey	38.5	43	1649	AMS ^{14}C	~200	3	25000-0	TOC, TIC, δ13C, δ18O	Öğretmen.,2012
Hala Lake	China	38.2	97.4	4078	^{14}C	~150	18	24000-0	OM, Carbonate	Yan et al., 2014
Sanjiaocheng	China	39.01	103.34	1325	AMS ^{14}C	~50	11	15000-0	TOC, δ13Corg	Zhang et al., 2004
Hurleg Lake	China	37.28	96.9	2817	AMS ^{14}C	/	8	10000-0	Carbonate	Zhao et al., 2010
Gahai Lake	China	37.13	97.55	2850	AMS ^{14}C	~90	27	12000-0	δ13Cc, δ18Oc, CaCO3	Guo et al., 2012
Chaka Lake	China	36.63	99.03	3200	AMS ^{14}C	/	10	10000-0	TOC, TN	Liu et al., 2008
Qinghai Lake	China	36.53	99.6	3200	AMS ^{14}C	~30	10	18000-0	TOC, TN, C/N, Carbonate	Shen et al., 2005
Dalianhai Lake	China	36.24	100.39	2852	^{14}C	~10	28	24000-0	Rb/Sr	Wu, 2017
Zigetang Co	China	32	90.73	4560	^{14}C	/	5	10500-0	TOC, TOC/TS, HI, δ13Corg, TC, TIC	Wu et al., 2007
Bangong Co	China	33.7	79	4241	AMS ^{14}C	~80	11	10000-0	δ18O	Fontes et al., 1996
Zabuye Lake	China	31.35	84.07	4421	AMS ^{14}C	~620	17	30000-0	TOC, TIC, δ18Ocarb, δ13Ccarb	Wang et al., 2002
Gonghai Lake	China	38.9	112.23	1860	AMS ^{14}C	~15	25	14700-0	Pollen	Chen et al., 2015
Dali lake	China	43.15	116.29	1220	AMS ^{14}C	~350	27	16000-0	Lake elevation	Goldsmith et al., 2016

2.3 Mathematical methods

Linear tendency estimation is a common trend analysis method, which was chosen to measure the variation degree of simulated water balance in this paper. Besides, we also used the Empirical orthogonal function (EOF), a method of analyzing the structural features in matrix data and extracting the feature vector of main data, to examine spatially and temporally variability of simulated water balance. The spatial distribution of EOF first (second) mode is denoted by EOF1 (EOF2), and the time series of first (second) mode is denoted by PCA1 (PCA2).

3 Results and discussion

3.1 Observed and simulated water balance change in global closed basins

As Fig. 1 shown, we intercepted LGM (18000-22000 yr), MH (5000-7000 yr) and PI (1800-1900 AD) periods from the TraCE 21 kyr dataset for better matching the multi-model ensemble. Because runoff anomalies are highly correlated to precipitation anomalies, it is therefore feasible to consider that the contribution of runoff on water balance is considered as the contribution of precipitation on water balance. Difference between the time period we chosen subjectively and the time periods defined by the multi-model ensemble may affect the comparison results. However, precipitation and evaporation difference of TraCE 21 kyr among three periods exhibits similar spatial pattern with P-E difference of multi-model ensemble. The simulations and lake status records of the mid-latitude westerlies (low-latitude monsoon regions) show that LGM is humid (dry) relative to MH and PI, which generally corresponds to the hydroclimate patterns of previous researches (Street and Grove, 1979; Qin et al., 1997; Quade and Broecker, 2009; Lowry and Morrill, 2019). It's not our intent to simulate relative lake status change among three periods, but to validate continuous water balance simulations and to track continuous water balance fluctuations on the millennial scale using TraCE 21 kyr simulations.

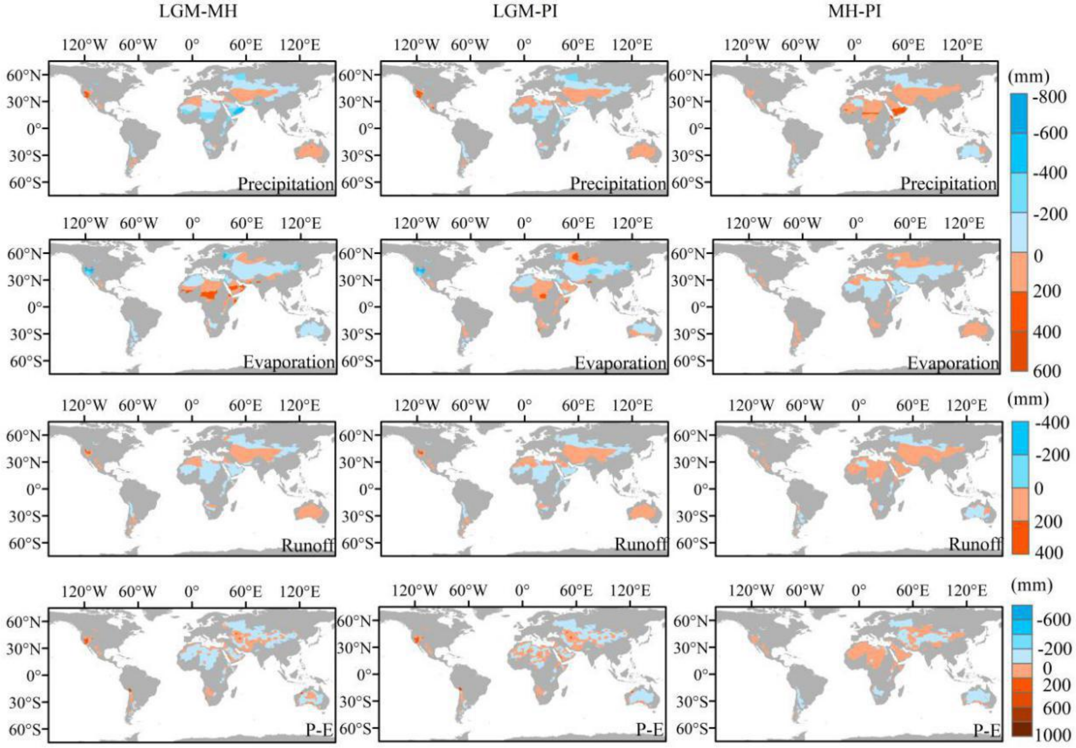

Figure 1. Annual mean precipitation, evaporation and runoff from TraCE 21 kyr simulations, and precipitation minus evaporation (P-E) from multi-model ensemble, all units mm year^{-1}; (first column) difference between LGM and MH simulations; (second column) difference between LGM and PI simulations; (third row) difference between MH and PI simulations.

In continuous simulations, we partitioned the trend map of water balance into positive and negative components to highlight the spatial patterns of water balance change (Fig. 2). In the global mid-latitude westerlies, simulations indicate widespread effective moisture declines since the LGM except the northern Caspian Sea, whereas, effective moisture increases since the LGM over the global Tropics. Meanwhile, the trend map exactly exhibits the spatial differentiation of the millennial scale water balance change between the global low-latitude monsoon dominated regions and the mid-latitude westerly winds dominated regions. This differentiation provides the basis to explore the continuous evolution of monsoons and westerly winds in the closed basins since the LGM.

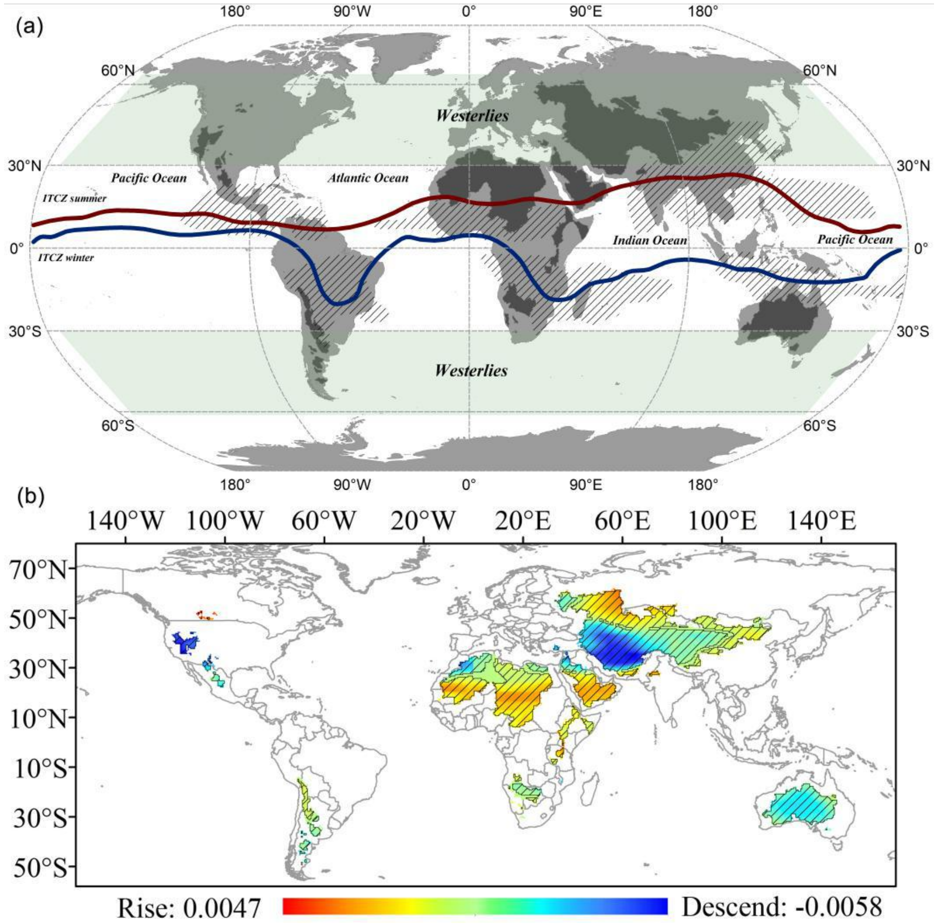

Figure 2. (a) Distribution of global closed basins and circulation system: The dark areas are global closed basins; summer and winter of the ITCZ are in accordance with the Northern Hemisphere; the shadows present the six monsoon areas according to Wang (2009), and (b) Trend analysis of continuous simulation in water balance change: The shadows indicate that the trends are statistically significant at 5% level.

3.2 Possible driving mechanisms of millennial scale water balance change

In this section, the possible driving mechanism that affects the millennial scale water balance change in the global closed basins is explored. Positive signs of the EOF1 represent most monsoon regions of mid-latitudes and low-latitudes, while negative signs of that are mainly located in the Northern and Southern Hemisphere westerlies. Spatial characteristics of the EOF2 have an opposite trend with the EOF1, except for the Caspian Sea. The contribution rate of PCA1 and PCA2 is 51% and 14% respectively, therefore the following discussion mainly focuses on PCA1 with the high contribution rate. The PCA1 extracted from water balance simulation tends to represent the effective moisture fluctuation of closed basins in low-latitude monsoon regions, indicating a relative humid climate during the early-to-mid Holocene. By comprehensively analyzing a variety of paleoclimate proxies, Wang et al. (2017) suggested that moisture change revealed by the Australian monsoon, the East African monsoon and the Indian monsoon regions reaches the wettest status in the early Holocene, while the wettest condition in the East Asian summer monsoon regions occurs between 8 and 6 kyr. Likewise, Qin (1997) presented that the wettest period in the African and South Asian monsoon regions is the early-to-mid Holocene, coinciding well with our results.

The climatic significance of the $\delta^{18}O$ in the Asian speleothem records is always a long-standing debate, and some influential hypotheses regard $\delta^{18}O$ of the monsoon regions as a proxy for “Asian monsoon intensity”, “Indian monsoon intensity”, “summer monsoon rainfall amount” and “circulation conditions” (Cheng et al., 2012; Chen et al., 2016). Although the climatic significance is controversial, it is well accepted that $\delta^{18}O$ changes should bear the imprint of variations in the oxygen isotopic composition of precipitation (Cheng et al., 2012; Chen et al., 2016). According to the close similarity of the PCA1 with the speleothem records from Dongge and Hulu caves, our simulations are more inclined to suggest that the $\delta^{18}O$ stalagmite records indicate the change in water vapor brought by the monsoons. In addition, we not only compared the PCA1 with the stalagmite records of Dongge Cave with controversial climatic significance, but also with the summer solar radiation at low-latitudes in the Northern Hemisphere. This comparison provides evidence for the view that the evolution of low-latitude monsoons is generally controlled by summer insolation in the Northern Hemisphere (Yuan et al., 2004; Chen et al., 2006; An et al., 2015). Thus, we further speculated that the water balance change in monsoon regions of global closed basins is mainly driven by mid-latitude and low-latitude summer solar radiation.

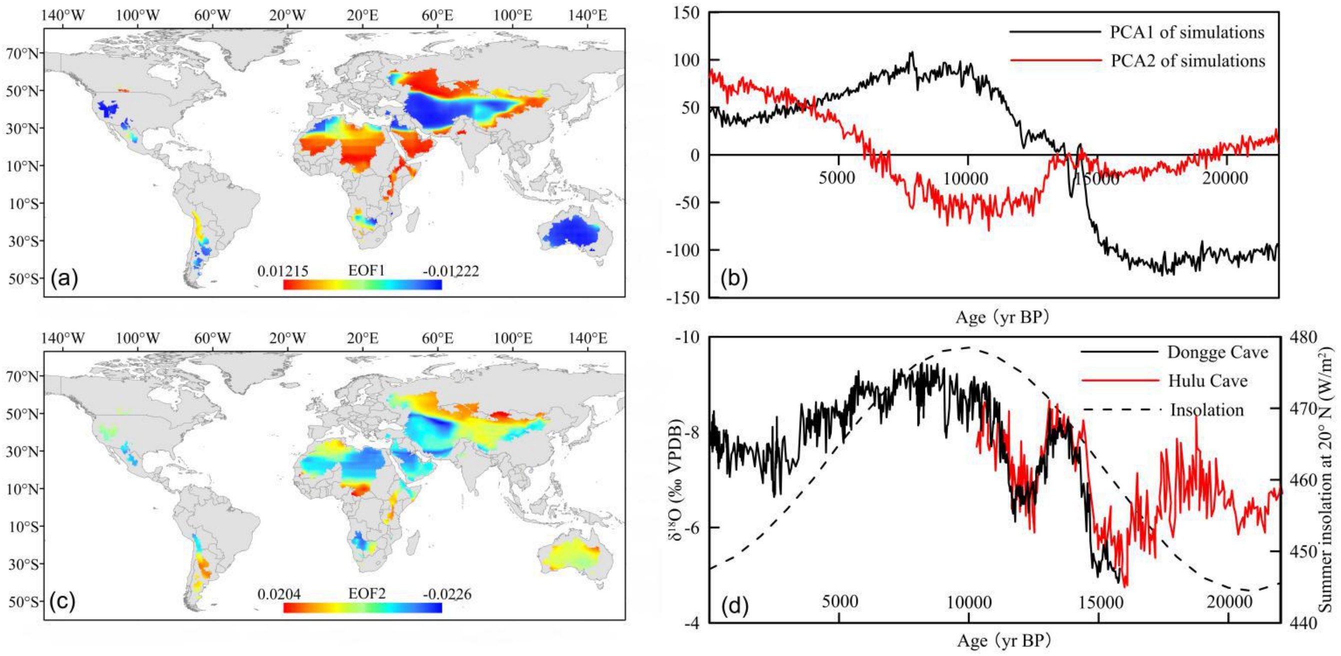

Figure 3. (a) Spatial distribution feature of EOF1, (b) PCA1 and PCA2 of simulated water balance change since the LGM, (c) Spatial distribution feature of EOF2, and (d) Comparison between stalagmite records and summer insolation: Stalagmite

records come from Dykoski et al. (2005) and Wang et al. (2008), and summer insolation comes from Berger (1978).

3.3 Evolutionary characteristics and causing factors of millennial scale hydroclimate change in the Northern Hemisphere mid-latitude closed basins

On the basis of the spatial characteristics of the EOF analysis, closed basins in the Northern Hemisphere, affected both by low-latitude monsoons and mid-latitude westerly winds, are ideal regions for revealing synergy of the westerly winds and monsoons. Between 30°N and 60°N, 27 paleoclimate records indicating dry or wet climate were collected from the Northern Hemisphere mid-latitude closed basins. As described in Sect. 2.2, we reconstructed moisture index from the early to late Holocene around that regions (Fig. 4). Simulated mean water balance curve corresponds well with mean moisture index in the Northern Hemisphere mid-latitude closed basins, indicating a transition from a humid climate in the early-to-mid Holocene to an arid climate in the late Holocene. Therefore, continuous simulations, well validated by the paleoclimate indicators, could be better used to track climate change during the LGM.

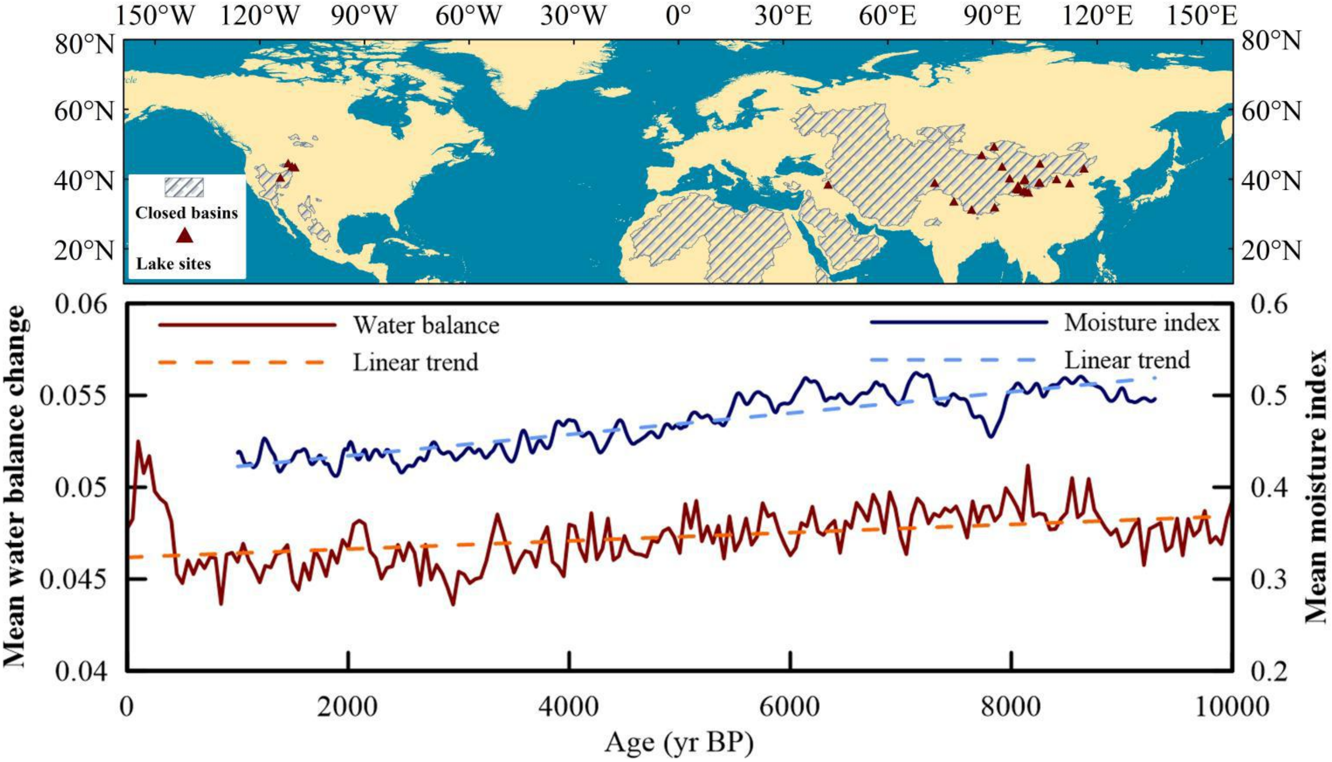

Figure 4. Comparison between simulated water balance change and reconstructed moisture index in the mid-latitude closed basins of the Northern Hemisphere during the Holocene. Triangles indicate locations of paleoclimate records (Table 3).

Water balance simulations since the LGM show that a humid climate not only appears in the early-to-mid Holocene but also occurs during the LGM, while the climate is relatively dry in the late Holocene. The maintained high moisture in the

LGM is possibly influenced by low evaporation and high precipitation (Fig. 5). Using paleoclimate modelling, Yu et al. (2000) mentioned that the low temperature during the glacial period causes a decrease of evaporation and a reduction of lake water loss, resulting in the appearance of high lake level. Afterward, solar radiation, atmosphere radiation, temperature, evaporation and precipitation simulations gradually increase (Fig. 5). When entering the warm Holocene, precipitation continues increasing and reaches a maximum in the MH, while solar radiation, atmosphere radiation and evaporation decrease during the early-to-mid Holocene and then increase around the late Holocene. Low (high) evaporation and high (low) precipitation are responsible for the MH (late-Holocene) relative humid (dry) climate (Fig. 5).

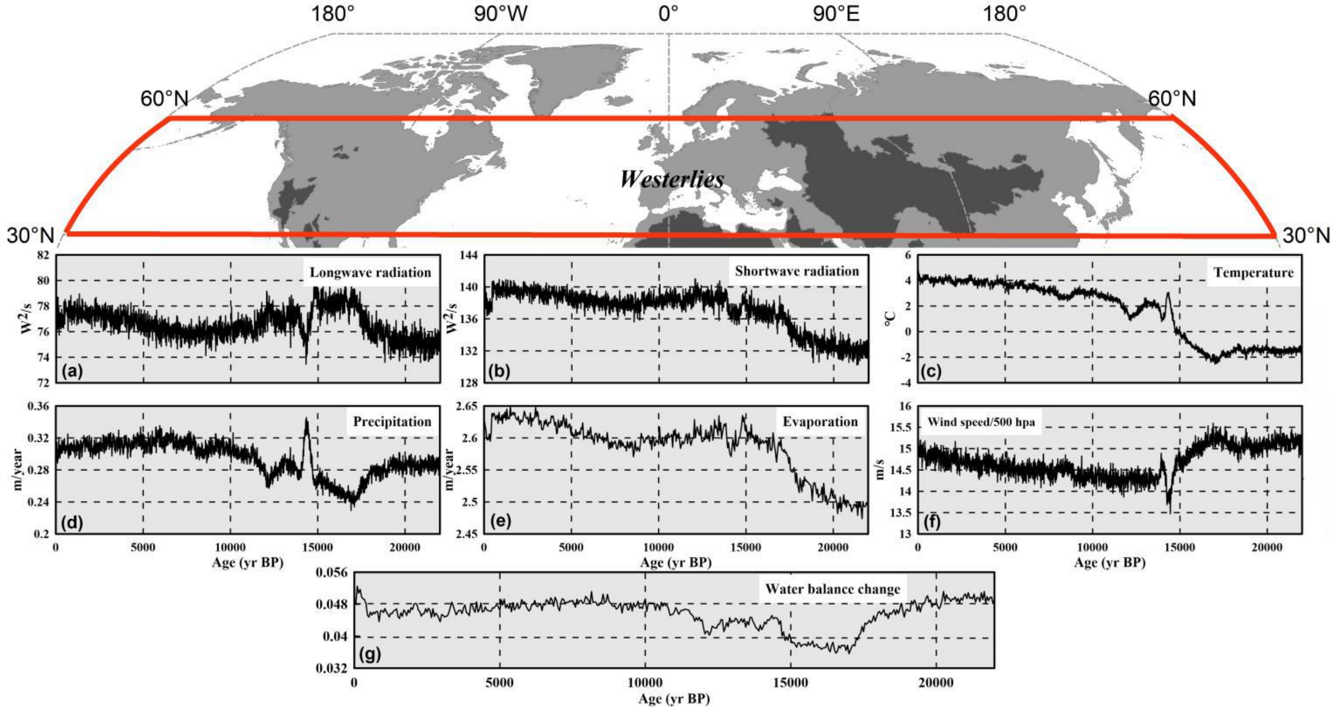

Figure 5. Time series of (a) longwave radiation, (b) shortwave radiation, (c) temperature, (d) precipitation, (e) evaporation, (f) 500 hpa wind speed and (g) water balance change between 30°N and 60°N closed basins since the LGM.

3.4 Evolutionary differentiation of millennial scale monsoons and westerly winds in Asian closed basins

Spatial distributions of the EOF1 and EOF2 clearly exhibit that a prominent boundary exists in the interactional zones between East Asian summer monsoon and westerly winds in Asia. Since the boundary of the monsoon will be adjusted accordingly with the change of East Asian summer monsoon strength, evolution of Asian lakes on the millennial scale probably not follows a single climate changing pattern (Wu et al., 2000; Editorial Committee of China's Physical Geography, 1984; An et al., 2012). The regions dominated by East Asian summer monsoon and westerly winds were then selected respectively based on the spatial characteristics of two modes extracted from the EOF, to explore millennial scale evolution features of two climate systems (Fig. 6). In the westerly winds dominated regions, the LGM and MH are characterized by humid climate, and relative dry climate prevails in the early and late Holocene. Whereas, the water balance in the monsoon dominated regions is generally affected by East Asian summer monsoon which brings much water vapor over the early-to-mid Holocene, and leads to relative dry climate in the LGM and late Holocene. Li (1990) first proposed the "monsoon" and "westerly" modes on the millennial scale since the late Pleistocene in northwest China, then different climate changing patterns between arid central Asia and monsoonal Asia were demonstrated by numerous paleoclimate records (Chen et al., 2006, 2008; An and Chen, 2009; Li et al., 2011; Chen et al., 2019). Thereinto, a viewpoint that millennial scale East Asian summer monsoon change is possibly driven by summer insolation change in low-latitudes is the most widely accepted (Yuan et al., 2004; Dykoski et al., 2005; Hu et al., 2008; Fleitmann et al., 2003). And the sea-surface temperatures (SSTs) of North Atlantic and air temperatures of high-latitudes are responsible for the Holocene effective moisture evolution of arid Central Asia which is dominated by the westerly winds (Chen et al., 2008). The moisture transport in the arid Central Asia mainly comes from the Northern Hemisphere westerlies of which the moisture source derives from the Black Sea, the Mediterranean Sea, the Arctic Ocean and the Atlantic Ocean. Winter precipitation accounts for a large proportion of annual precipitations in these regions (Li et al., 2008).

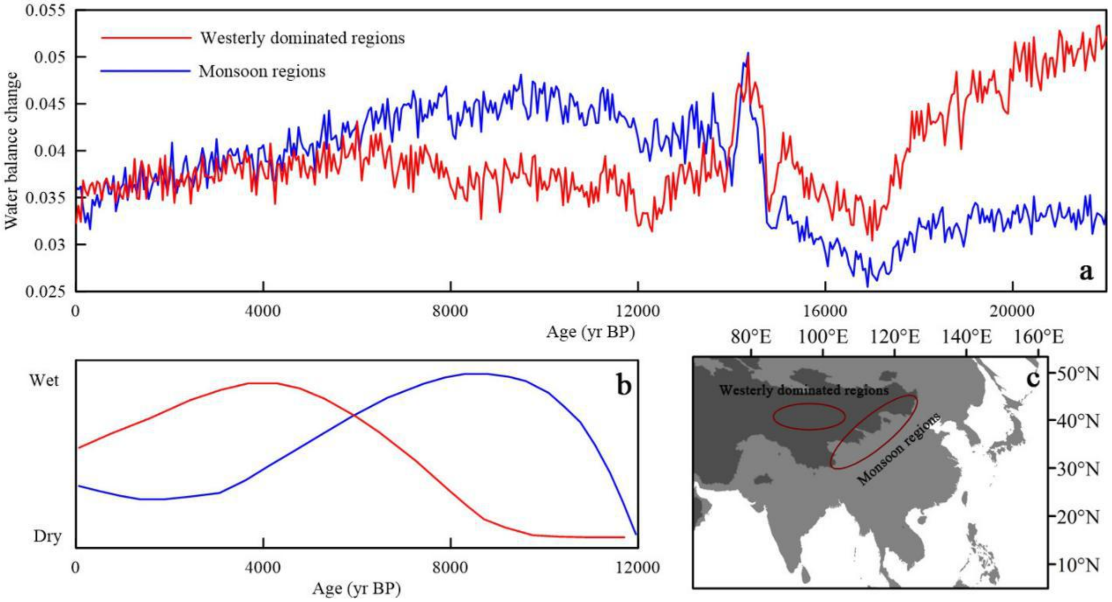

Figure 6. (a) Simulated water balance change between westerly dominated regions and monsoon regions in the Asian closed basins since the LGM, (b) General climate changing patterns during the Holocene in monsoon Asia and westerly Central Asia come from Chen et al. (2006), and (c) Extracted westerly dominated regions and monsoon regions in the Asian closed basins.

The water balance change in the Asian monsoon regions we extracted largely represents the hydroclimate variation in East Asian summer monsoon dominated regions since the LGM, while the water balance change in the westerly regions in

Central Asia can represent the hydroclimate variation in the entire Northern Hemisphere westerlies. Qin (1997) made a large-scale spatial analysis and presented that lake levels in south-central North America change from high to low since the LGM and reach the lowest in early-to-mid Holocene. The LGM proxies indicate the southwestern America experienced a climate that was wetter than present, and the Pacific Northwest through the Rockies experienced a climate that was drier than present, as well as a transition from wetter to drier conditions happened along a northwest-southeast trending band across the northern Great Basin (Oster et al., 2015). Our results generally reflect that the climate of westerlies is relatively wet at the LGM and relatively dry at the MH. For the Asian tropics in the Northern Hemisphere, the increased summer solar radiation from 12000 to 6000 yr induces the enhancement of thermal contrast between land and sea, and further causes the strengthening of summer monsoons, so that more water vapor is brought (COHMAP Members, 1988). Collected records in the Northern Hemisphere indicate evolution of westerly winds and monsoon systems (Fig. 7). Speleothem records from central and southern China confirm that the periods of weak East Asian summer monsoons are coincided with the cold periods of the North Atlantic (Yuan et al., 2004, Dykoski et al., 2005; Wang et al., 2008). The longest and highest-resolution drill core from Lake Qinghai (An et al., 2012) indicates that the summer monsoon record generally resembles the changing trends of Asian summer monsoon records derived from Dongge and Hulu speleothems over the last 20 kyr, and the mid-latitude westerlies climate dominates the Lake Qinghai area in glacial times. Low-latitude summer insolation is broadly recognized as a major control on low-latitudes monsoon systems, as a result, the tropical monsoons are weak during the LGM and late Holocene, and strong monsoons prevail in the early-to-mid Holocene (Fig. 7). Accordingly, the intensity of monsoon systems and westerly winds varies in different periods so that the main control system in the interactional regions depends largely on which system is much stronger during that period.

The Northern Hemisphere westerlies shifting northward or southward has a significant impact on global atmosphere circulation and inevitably affects the monsoon systems. Quaternary ice sheets of the Northern Hemisphere in the LGM develop to its maximum extension, and consequent existence of persisting strong glacial anticyclone leads to the southward displacement of the westerly winds (Yu et al., 2000). Many researches suggested the Northern Hemisphere westerlies in the LGM move to the southwest of the United States and the eastern Mediterranean region (Lachniet et al., 2014; Rambeau, 2010). Therefore, the narrowed temperature difference between sea and land causes the East Asian summer monsoon weaken, and may further induces the strong westerly winds throughout the year and then the precipitation increases (Yu et al., 2000). Furthermore, a growing body of evidence shows that the position and orientation of the westerly jet (WJ) probably control the Holocene East Asian summer rainfall patterns. A link between the northward seasonal progression of the WJ and the spatial pattern of East Asian summer monsoon precipitation shows that earlier northward progression of the WJ causes abundant precipitation at high-latitudes and less precipitation at low-latitudes (Nagashima et al., 2013). Especially the northward evolution of the WJ from south of the Tibetan Plateau and seasonal transition exert great influences on East Asian paleoclimate change (Chiang et al., 2015). Herzschuh et al. (2009) proposed that the position of summer monsoon rain band changes as the WJ axis shifts gradually southward, leading to the occurrence of spatiotemporal difference in Holocene China's maximum precipitation. In summary, the above views emphasize that the complex interaction between the monsoon and the westerly systems on the millennial scale should receive more attention.

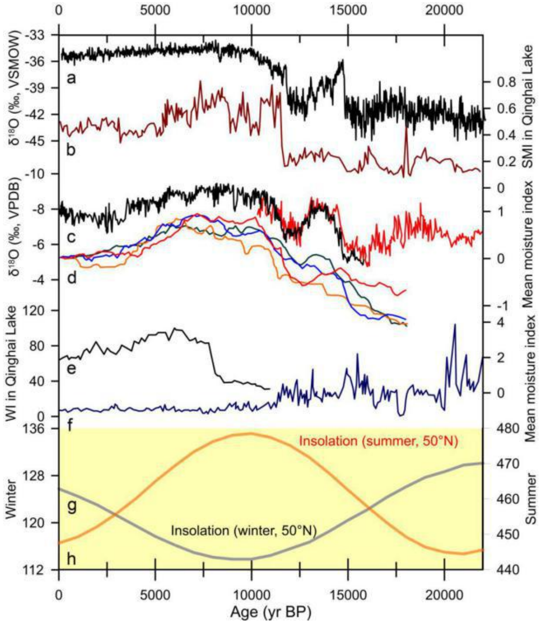

Figure 7. Comparison of records between the westerly and monsoon regions of the Northern Hemisphere. (a) NGRIP δ^{18}O (Rasmussen et al., 2006); (b) Lake Qinghai Westerlies climate index (An et al., 2012); (c) Dongge and Hulu cave speleothem δ^{18}O records (Dykoski et al., 2005; Wang et al., 2008); (d) moisture indexes in East Asian Monsoon (red line), East African Monsoon (green line), Indian Monsoon (blue line) and Australian Monsoon (orange line) regions (Wang et al., 2017); (e) The average moisture index for arid central Asian region as a whole during the Holocene (An and Chen, 2009); (f) Lake Qinghai Asian summer monsoon index (An et al., 2012); (g) and (h) are summer 50°N insolation and winter 50°N insolation, respectively (Berger, 1978).

4 Conclusion

On the basis of 37 lake status records near global closed basins and 27 paleoclimatic records near mid-latitude closed basins of the Northern Hemisphere, we applied a lake energy balance model, a lake water balance model and paleoclimate simulations to exploring the millennial scale differentiation between global monsoons and westerly winds. Water balance simulation shows that the effective moisture in most closed basins of the Northern Hemisphere mid-latitudes gradually decreases since the LGM, which matches well with reconstructed moisture index. Effective moisture change in most closed basins of the low-latitudes (monsoon regions) presents an opposite changing trend with that in the mid-latitudes. In the Asian mid-latitude closed basins, climate change in regions dominated by westerly winds exhibits a relative humid climate in the LGM and MH, and a relative dry climate in early and late Holocene. Whereas, East Asian summer monsoon generally influences the climate change in closed basins dominated by monsoons, which brings more water vapor over the early-to-mid Holocene but less water vapor in the LGM and late Holocene.

Data Availability. The TraCE-21kyr dataset comes from Climate Data Gateway at National Center for Atmospheric Research (NCAR) website https://www.earthsystemgrid.org/project/trace.html. PMIP3/CMIP5 simulations are available from the Earth System Grid Federation (ESGF) Peer-to-Peer (P2P) enterprise system website https://esgf-node.llnl.gov/projects/esgf-llnl/. Global closed basins boundaries are derived from the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) website https://www.hydrosheds.org/page/hydrobasins.

Author contributions. Yu Li and Yuxin Zhang designed this study and carried it out.

Competing interests. The authors declare that they have no conflict of interest.

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