Synergy of the westerly winds and monsoons in lake evolution of global closed basins since the Last Glacial Maximum

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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 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.

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 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, δ¹⁸O 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.
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 (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). CO₂, CH₄ and N₂O 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).

|                | 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° |
| CO₂ (ppm)      | 280            | 280          | 185                  |
| CH₄ (ppb)      | 760            | 650          | 350                  |
| N₂O (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 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:

\[ D = A_B R + A_L (P_L - E_L), \]

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):

\[ \frac{A_L}{A_B} = \frac{R}{(P_L - E_L)}, \]

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.

2.2 Records selection and moisture index inference

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.

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   |
| Ulungar 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 |
| Lake                  | Location       | Lat (°) | Lon (°) | Elevations (m) | Dating method     | Time period (cal yr BP) | Proxies used                  | References                  |
|----------------------|----------------|---------|---------|----------------|-------------------|-------------------------|-------------------------------|-----------------------------|
| Ebinur Lake          | China          | 44.9    | 82.7    | Sediments and OSL dating | High                     | High                    | High                          | Wu et al., 1995; Lin 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                     | Similar                 | Low                           | Ibarra et al., 2014           |
| Bonneville Lake      | America        | 40.5    | -113    | Terraces and 14°C | High                     | High                    | Low                           | Ovitt, 2015; Hart et al., 2004 |
| Yitang Lake          | China          | 40.3    | 94.97   | Sediments and OSL dating | High                     | Low                     | Low                           | Zhao et al., 2015             |
| Lop Nur Lake         | China          | 40.29   | 90.8    | Sediments and U-Th dating | High                     | High                    | High                          | Yan et al., 2000              |
| Yanhai 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                    | Low                           | Zhang et al., 2004            |
| Karakul Lake         | Tajikistan     | 39.02   | 73.53   | Sediments and AMS 14°C | Low                     | High                    | High                          | Heincke et al., 2017          |
| Van Lake              | Turkey         | 38.5    | 43      | Sediments and AMS 14°C | Low                     | High                    | Low                           | Çagatay et al., 2014          |
| Hala Lake             | China          | 38.20   | 97.40   | 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          | 36.57   | 99.60   | Terraces and AMS 14°C | Low                     | Low                     | Similar                       | Madsen et al., 2008          |
| Bangong Co            | China          | 33.70   | 79      | Sediments and AMS 14°C | Similar                 | High                    | High                          | Ross et al., 1996; Li et al., 1991 |
| Cochihe Lake         | America        | 32.1    | -109.8  | Sediments and 14°C | High                     | High                    | High                          | Waters, 1989                  |
| Clarevalde Lake       | America        | 31.3    | 109     | Terraces and 14°C | High                     | High                    | High                          | Keider, 1998                  |
| Zhabuye 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             |
| Babrona Lake          | Mexico         | 29      | -108    | Sediments and U-Th dating | High                     | High                    | High                          | Metcalfe et al., 2002         |
| Chen Co               | China          | 28.93   | 90.6    | Sediments and AMS 14°C | Low                     | Similar                 | Low                           | Zhu et al., 2009              |
| La Piscina de         | Mexico         | 20.22   | -100.13 | Sediments and 14°C | High                     | High                    | /                             | Davies, 2011                  |
| Yuritika Lake         | China          | 19.16   | -99.53  | Sediments and 14°C | High                     | High                    | /                             | Caballero et al., 2002        |
| Chuiguhuan Lake       | Mexico         | 19.15   | -101.5  | Sediments and AMS 14°C | High                     | High                    | Low                           | Bradbury, 2000                |
| Pátzcuaro Lake        | Mexico         | 19.46   | -100.14 | Sediments and AMS 14°C | High                     | High                    | Low                           | Keeney et al., 2011           |
| Malawi Lake           | Malawi         | -10.02  | 34.19   | Sediments and OSL dating | Low                     | Low                     | High                          | Rowe et al., 2002             |
| Ticuca Lake           | Peru/Bolivia   | -16.7   | -69.4   | Sediments and AMS 14°C | High                     | High                    | Low                           | Metcalfe et al., 2002         |
| Makadekadi Lake       | Botswana       | -20     | 24.76   | Terraces and 14°C | High                     | High                    | High                          | Riedel et al., 2014           |
| Uuyini Lake           | Bolivia        | -20.2   | -67.5   | Sediments and U-Th dating | High                     | High                    | /                             | Baker et al., 2001            |
| Mega-Frme Lake        | Australia      | -31     | 140     | Terraces and AMS 14°C | High                     | High                    | High                          | Cohen et al., 2011            |
| Cari Laufenke Lake    | Argentina      | -41.4   | -69.6   | Sediments and 14°C | High                     | High                    | /                             | Cartwright et al., 2011      |
| Huelmo Lake           | Chile          | -41.5   | -73     | Sediments and AMS 14°C | High                     | High                    | /                             | Moreno and León, 2003        |
| Potrok Alke Lake      | Argentina      | -52     | -70.4   | Sediments and OSL dating | High                     | High                    | /                             | Klein et al., 2013            |

Table 3. Paleoclimatic records indicating dry or wet status
3 Results

3.1 Comparison of TraCE simulation and multi-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](https://doi.org/10.5194/cp-2020-53)

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.

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.
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 4. Comparison between simulated water balance change and reconstructed moisture index during the Holocene. Triangles indicate locations of paleoclimate records (Table 3).
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 δ¹⁸O (Rasmussen et al., 2006); (b) Lake Qinghai Westerlies climate index (An et al., 2012); (c) Dongge and Hulu cave speleothem δ¹⁸O 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.

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.

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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