Northern Westerlies during the Last Glacial Maximum: Results from CMIP5 Simulations

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(Manuscript received 13 May 2017, in final form 15 October 2017)

ABSTRACT

Based upon simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5), the vertical and regional characteristics of the northern westerlies during the Last Glacial Maximum (LGM) are investigated in this study. At the Northern Hemispheric scale, all nine available models simulate a poleward shift of the 200-hPa jet, and eight models simulate an equatorward shift of the 850-hPa jet compared to the preindustrial period; these shifts are of approximately 2° – 3° latitude for the arithmetic multimodel mean. The upper-tropospheric cooling in the tropics, possibly due to reduced latent heat release, is expected to account for the poleward shift of the 200-hPa jet through the thermal wind relationship. Changes in the midlatitude baroclinic instability in response to the amplified polar cooling are associated with the jet stream in the lower troposphere through anomalous eddy activity. In particular, the types of predominant baroclinic eddies are regionally dependent. The behavior of the 850-hPa jet over the North Pacific is steered by transient eddies and characterized by a southward displacement during the LGM. By contrast, the remarkable enhancement of the North Atlantic jet stream throughout the troposphere is associated with the notably increased stationary eddy momentum convergence, presumably due to the presence of the Laurentide ice sheet over North America. In comparison with the proxy records, although there is no observational evidence explicitly indicating changes of the upper-level northern westerlies, the simulated LGM 850-hPa westerly wind field is indirectly concordant with the reconstructed moisture conditions over the Mediterranean region and southwestern North America.

1. Introduction

Midlatitude westerlies are the prevailing eastward winds extending from the earth's surface up to the stratosphere in both hemispheres. As one of the major

components of large-scale circulation, westerlies exert a considerable influence on the global climate by modulating the transport and distribution of momentum, heat, and moisture. The jet stream, a narrow band of maximum wind speeds in the westerlies, favors the development of synoptic-scale disturbances into extratropical storms (Holton and Hakim 2012). Changes in the position and intensity of the westerly jets associated with storm tracks play a key role in reshaping precipitation patterns in the middle latitudes (Yin 2005). Given the significance of the westerlies for global and regional

Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JCLI-D-17-0314.s1>.

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DOI: 10.1175/JCLI-D-17-0314.1

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climate, the response of the westerlies to increased greenhouse warming has been extensively investigated in recent years. The poleward shifts of westerly jets and storm activity in the past few decades have been detected in observational and reanalysis studies in both hemispheres (McCabe et al. 2001; Fyfe 2003; Archer and Caldeira 2008; Fu and Lin 2011). In particular, this phenomenon is more prominent and zonally symmetric in the Southern Hemisphere (Barnes and Polvani 2013). Numerical simulations agreed with observations and suggested that such changes would continue in future climate projections forced by increased greenhouse gas concentrations (Yin 2005; Lorenz and DeWeaver 2007; Rivière 2011). The meridional temperature gradient is considered as one of the primary factors that steers the westerlies through the thermal wind relationship. On this basis, the displacement of westerlies is connected with various thermal processes, including the enhanced stratospheric cooling due to ozone loss (Polvani et al. 2011), the increased latent heat release from water vapor (Frierson et al. 2006), and the uplifting of the tropopause height in a warmer climate (Williams and Bryan 2006; Lorenz and DeWeaver 2007). Dynamical diagnostics emphasized the role of wave–flow interactions in modulating the fluctuations of the mid-latitude jet streams, which were indicated by the eddy momentum flux convergence anomalies (Lorenz and Hartmann 2001; Chen 2007).

To comprehensively understand the mechanisms responsible for the fluctuations of the westerlies, it is essential to examine the behavior of westerlies forced by different boundary conditions from those of the present day. The Last Glacial Maximum (LGM; approximately 21 000 calendar years ago) was the period of maximum glacial advances within the latest ice age, featuring lowered greenhouse gas concentrations, expanded ice sheets, and altered coastlines due to the sea level drop. The LGM simulations provide an opportunity to investigate the response of large-scale atmospheric circulation to a glacial climate and to increase our understanding of past climatic change reconstructed by proxy data. Since the role of the glacial Southern Ocean in modulating the global carbon cycle was proposed in the 1980s (Knox and McElroy 1984; Sarmiento and Toggweiler 1984; Siegenthaler and Wenk 1984), more attention has been paid to the large-scale circulation in the Southern Hemisphere. Idealized model studies suggested that the equatorward shift of southern westerlies restrained upwelling and CO₂ ventilation near Antarctica, which provided a possible explanation for the lower greenhouse gas concentrations during the LGM (Toggweiler et al. 2006). However, simulations of southern westerlies during the LGM showed considerable

discrepancies between different models. An equatorward shift of the surface westerlies associated with a weakening and shrinking of the Hadley cell was implied by the idealized aquaplanet model (Williams and Bryan 2006), whereas in the atmosphere-only model simulations the southern westerlies were strengthened and moved poleward in the lower troposphere, despite a reduction in the Hadley cell strength (Sime et al. 2013). Even under the coordinated protocol of the Paleoclimate Modelling Intercomparison Project (PMIP), the southern westerlies showed paradoxical behaviors in different models, possibly due to the distinct implementations of altered boundary conditions related to the Antarctic ice sheet and Southern Ocean sea ice (Chavaillaz et al. 2013; Rojas 2013; Sime et al. 2016).

The simulation studies of the surface westerlies and jet streams in the Northern Hemisphere during the LGM are relatively insufficient compared with those in the Southern Hemisphere. Nevertheless, the effect of the northern westerlies on the glacial climate cannot be ignored. The adjustment of the land–sea thermal contrast in the Northern Hemisphere regulated the semi-permanent pressure cells and the monsoon circulation during the glacial periods. The interplay of the westerlies and these systems largely determined the regional climate over Eurasia and North America. In addition, the iron-rich dusts carried by the northern westerlies are transported from central Asia downwind to the North Pacific (Sun et al. 2001; Tanaka and Chiba 2006). The role of iron in enhancing oceanic primary productivity has been hypothesized to affect the glacial–interglacial cycle on geological time scales (Martin 1990; Maher et al. 2010). Previous studies of the Northern Hemisphere atmospheric circulation during the LGM indirectly reflected changes of the westerly jet, including the concordant southward shift of the North Pacific storm tracks and jet streams (Lainé et al. 2009), and the increased precipitation associated with a stronger upper-level jet over Europe (Ludwig et al. 2016). In general, the investigation of the LGM northern westerlies has been mainly focused on the regional scale, and there is a lack of analysis of the underlying mechanisms.

Based upon the state-of-the-art model simulations in the framework of phase 5 of the Coupled Model Intercomparison Project (CMIP5) or PMIP phase 3 (PMIP3), changes of the LGM northern westerlies at both the hemispheric and regional scales are investigated in this study, with a focus on the intensity and position of the jet streams. Three questions are expected to be answered: 1) What are the robust characteristics of the northern westerlies in response to the LGM boundary conditions? 2) What are the mechanisms responsible for the northern westerlies behavior in a cold

TABLE 1. Basic information about the nine CMIP5/PMIP3 models and variables used in this study. Here ua, ta, zg, ps, hus, and tos refer to monthly mean zonal wind, temperature, geopotential height, surface pressure, specific humidity, and sea surface temperature, respectively; ua^d and va^d refer to daily mean zonal and meridional winds, respectively. (Expansions of acronyms are available online at <http://www.ametsoc.org/PubsAcronymList>.)

Model identifier	Country	Atmospheric resolution	Years used in analysis	Variables used in analysis
CCSM4	United States	$1.25^\circ \times \sim 0.9^\circ$, L26	20	ua ta zg ps hus tos (ua ^d va ^d)
CNRM-CM5	France	$\sim 1.4^\circ \times 1.4^\circ$, L31	30	ua ta zg ps hus tos
COSMOS-ASO	Germany	$3.75^\circ \times 3.75^\circ$, L19	30	ua ta zg ps hus (ua ^d va ^d)
FGOALS-g2	China	$\sim 2.8^\circ \times 3^\circ$, L26	30	ua ta zg ps hus
GISS-E2-R	United States	$2.5^\circ \times 2^\circ$, L40	30	ua ta zg ps hus tos
IPSL-CM5A-LR	France	$3.75^\circ \times \sim 1.9^\circ$, L39	30	ua ta zg ps hus tos
MIROC-ESM	Japan	$\sim 2.8^\circ \times 2.8^\circ$, L80	30	ua ta zg ps hus tos
MPI-ESM-P	Germany	$1.875^\circ \times 1.875^\circ$, L47	30	ua ta zg ps hus tos
MRI-CGCM3	Japan	$1.125^\circ \times 1.125^\circ$, L48	30	ua ta zg ps hus tos

world? 3) Are the simulated results in agreement with the regional paleoclimate indicated by proxy records?

2. Data and methods

CMIP5/PMIP3 monthly mean zonal wind, temperature, geopotential height, surface pressure, specific humidity, and sea surface temperature, as well as daily mean zonal and meridional winds, are required to analyze changes in the LGM northern westerlies and associated physical processes. All available CMIP5/PMIP3 model outputs participating in both the preindustrial and LGM experiments are included in this study. These models are listed in order from the lowest to highest horizontal resolutions as follows: COSMOS-ASO, FGOALS-g2, MIROC-ESM, IPSL-CM5A-LR, GISS-E2-R, MPI-ESM-P, CNRM-CM5, MRI-CGCM3, and CCSM4 (more information in Table 1). The first eight models are correspondingly abbreviated as COSMOS, FGOALS, MIROC, IPSL, GISS, MPI, CNRM, and MRI in the following sections. All these coupled models have fully considered the interactions between different components of the climate system, including the atmosphere, ocean, sea ice, and land surface. The preindustrial experiments of the aforementioned models are regarded as the control experiments in this study (Taylor et al. 2012). For an assessment of the ability of models to reproduce the northern westerlies and jet streams, the preindustrial simulations are compared with the National Centers for Environmental

Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996) for the period of 1971–2000. The boundary conditions for the coordinated LGM experiment strictly follow the protocol provided by PMIP3 (Table 2). For this period, the orbital parameters are set to their values at 21 000 years ago (Berger 1978), and the atmospheric concentrations of CO₂, CH₄, and N₂O are adjusted from 280 to 185 ppm, from 760 to 350 ppb, and from 270 to 200 ppb, respectively. A blended ice sheet product is adopted in the LGM experiment that averages three sets of the latest ice sheet reconstructions. Accordingly, the topography and land–sea mask are altered due to the expansion of the ice sheets and the lowering of sea level.

The preindustrial and LGM experiments are equilibrium ones constrained by constant boundary conditions. The internal variabilities of the preindustrial and LGM simulations, indicated by the global mean surface temperature (not shown), are both much smaller (by approximately two orders of magnitude) than the mean state difference between these two periods. In this study, we computed and analyzed the climatological mean of all variables over the last 30 years of each simulation, with the exception of CCSM4, the preindustrial daily outputs of which are only available for the last 20 years. All model and reanalysis data are aggregated to a fine horizontal resolution of $0.5^\circ \times 0.5^\circ$ using bilinear interpolation to capture tiny displacements of the westerlies and make a comparison between the different results.

TABLE 2. Summary of the boundary conditions for the CMIP5/PMIP3 preindustrial and LGM experiments. For detailed information, please refer to the PMIP3 official website (<http://pmip3.lsce.ipsl.fr/>).

	Ice sheets	CO ₂ (ppmv)	CH ₄ (ppbv)	N ₂ O (ppbv)	Eccentricity	Obliquity (°)	Angular precession (°)
Preindustrial	Modern	280	760	270	0.016 772	23.446	102.04
LGM	ICE-6G et al.	185	350	200	0.018 994	22.949	114.42

FIG. 1. Climatological zonal wind (color shading) at (a) 200 and (b) 850 hPa, as derived from the NCEP–NCAR reanalysis for the period of 1971–2000. The closed curves are indicators of the westerlies axes from the CMIP5 preindustrial simulations (control experiments) and NCEP–NCAR reanalysis. MMM refers to the arithmetic multimodel mean.

3. Climatological zonal wind field

In the middle latitudes, the prevailing westerly wind is prominent throughout the whole troposphere. Here, we only focus on the zonal winds at the 200- and 850-hPa levels. The zonal wind at 200 hPa, featuring the maximum speed of westerly wind in the vertical direction, is examined for changes in the upper-level jet. Compared to the surface westerlies, the 850-hPa zonal wind reveals accordant behavior and excludes the influence of the boundary layer processes. In particular, the 850-hPa zonal wind characterizes the eddy-driven jet and its fluctuations, while the upper-level jet is modulated by the joint effect of the Hadley cell and baroclinic eddy activity (Chavaillaz et al. 2013).

The spatial distribution of westerly winds at 200 and 850 hPa is dominated by a beltlike structure, where the wind speed decreases gradually from the center to its northern and southern edges (Fig. 1). In the study of the southern westerlies, the locations of maximum wind speeds at each longitude were linked up to form the westerlies axis (Rojas et al. 2009). However, the westerly wind in the Northern Hemisphere is less zonally symmetric due to the land–sea distribution, especially at the lower levels (Fig. 1b). At 850 hPa, the Tibetan Plateau

and Rocky Mountains split the westerlies into northern and southern branches, increasing the spatial heterogeneities of the westerlies. The strong westerly wind over South Asia, fed by the cross-equatorial flow during the boreal summer, is an essential component of the Asian monsoon circulation. To obtain a positional indicator of the northern westerlies, we identify the latitudes of maximum wind speeds after the meridional running average at each longitude, and then smooth the annular axis using the zonal running average. The running average covers 21 grids (the equivalent of 10°) in both directions to filter out the regional signals caused by topographic effects and other climate systems, with the large-scale features of the westerlies being conserved.

The indicators of the westerly axes are illustrated by the closed curves in Fig. 1. The model–reanalysis discrepancies are relatively small over the strong wind regions, such as the western margin of the North Pacific and North Atlantic at both levels. By contrast, the models display unsatisfactory performances over the discontinuous zones of the wind field, including the eastern boundaries of the North Pacific and North Atlantic at 200 hPa and Europe at 850 hPa. The latitudinal distribution of wind speed over these regions features a bimodal structure. The westerlies axis, located by the latitude of

FIG. 2. Climatological zonal mean zonal wind at (a) 200 and (b) 850 hPa as obtained from the CMIP5 pre-industrial simulations (control experiments) and NCEP–NCAR reanalysis. MMM refers to the arithmetic multimodel mean.

the maximum wind speed, is sensitive to the relative intensity of these two peaks. Given that the meridional distance between these two peaks spans more than 10° , we consider that the shift of the westerlies axis from one peak to another accounts for the great model–reanalysis and intermodel discrepancies over the discontinuous zones. In addition to the evaluation of the model ability in reproducing the zonal features of the northern westerlies, we examine the latitudinal distribution of the simulated northern westerlies by computing the zonal mean zonal wind. As shown in Fig. 2, models are capable of depicting the distribution pattern of the zonal mean zonal wind, but some fail to simulate the exact locations and values of the wind speed maxima. MRI, GISS, and IPSL suggest a stronger and equatorward shift of the maximum wind speed at the 200-hPa level, while COSMOS presents a stronger and poleward bias at both levels. Most models simulate enhanced wind speed maxima at the 850-hPa level, especially in MIROC, FGOALS, and CCSM4. Since the preindustrial experiments are constrained by constant boundary conditions and weaker greenhouse gas forcing, the slight difference compared to the reanalysis is reasonable.

Reconstructions show that, during the LGM, the Laurentide ice sheet expanded southward to northern North America, while the Fennoscandian ice sheet covered most of northwestern Europe. The prominent changes of the zonal wind at 200 hPa between the LGM

and preindustrial periods are located to the southeast of these ice sheets (Fig. 3). All models simulate a striking enhancement of the North Atlantic jet stream, and most simulate stronger westerly winds over the eastern European plain. Except at the periphery of the Fennoscandian ice sheet, the simulated LGM westerly winds are reduced over most parts of Eurasia, especially over the Iranian Plateau and Tibetan Plateau with high model agreement (shown in Fig. 4a). These negative anomalies along the axis indicate a weakened upper-level jet over Eurasia. Although there is a similar robust reduction in the wind speed over the northern North Pacific, the anomaly areas are too far to influence the basin-scale jet stream. At 850 hPa, all models simulate an equatorward shift of the westerly jet over southern Europe (Fig. 5), presumably due to the blocking effect of the elevated ice sheet. However, this factor is insufficient to explain the remarkably enhanced North Atlantic jet stream at both levels. In the eastern North Pacific, changes in the westerly wind exhibit a consistent dipole pattern with positive anomalies south of the axis and negative anomalies in the north, which indicates an equatorward shift of the jet stream. As mentioned above, changes in the 850-hPa westerly wind reflect the fluctuations of the eddy-driven jet. The underlying mechanism responsible for the behavior of the 850-hPa westerly jet over the North Atlantic and North Pacific as related to anomalous eddy activity will be discussed in section 5.

FIG. 3. Statistically significant changes (color shading) of the 200-hPa zonal wind (LGM minus preindustrial) at the 95% confidence level as derived from (a)–(i) the individual models. The black and red dashed lines are indicators of the preindustrial and LGM westerlies axes, respectively. Solid lines show the 50% ice sheet concentration boundaries for the preindustrial in orange and the LGM in green, as derived from the constructions of ICE-6G (Argus et al. 2014; Peltier et al. 2015).

4. Behavior of jet streams

From the analysis of the climatological zonal wind, jet streams over Eurasia, the North Pacific, and the North Atlantic are highlighted for their prominent anomalies during the LGM. For a unified comparison between the jet streams at both levels, the longitudinal ranges of 0° – 110° E, 120° E– 120° W, and 90° – 20° W are selected to represent the aforementioned three key regions. These sectors cover the main body of the jet streams and the

prominent wind speed anomalies at both levels. To assess the capability of the models in simulating regional westerly jets, we compared the zonal mean zonal wind over each sector from the preindustrial experiments with those from the NCEP–NCAR reanalysis (similar to Fig. 2, but not shown). In general, the models agree with the reanalysis in the shapes of the jet streams. MRI, GISS, and IPSL simulate stronger and equatorward shifts of the 200-hPa jet streams over each sector, which coincide with the hemispheric-scale results mentioned in

FIG. 4. Comparison between the MMM and proxies. Robust changes of the (a) 200- and (b) 850-hPa zonal wind (LGM minus preindustrial, shading) that for 7 out of 9 models agree with the sign of change from the MMM are shown. Proxy estimates of LGM moisture changes (markers), the indirect evidence of westerlies changes, are divided into three categories: wetter (blue), drier (red), and no change (gray).

section 3. At the 850-hPa level, model–reanalysis discrepancies are relatively larger over Eurasia, especially for FGOALS, IPSL, and MIROC. As illustrated in Fig. 1b, these models exhibit an equatorward shift of the jet stream with remarkable bias over Europe. To weaken the effect of individual model bias on our results, only robust signals that seven out of nine models agree with the sign of change from the arithmetic multimodel mean (MMM) are analyzed in this study.

Based on the quadratic interpolation of the zonal mean zonal wind, we quantify the latitudinal displacements and intensity anomalies of the jet streams at the Northern Hemispheric scale and over three key regions. The latitude and velocity of the interpolated zonal mean zonal wind maximum are defined as the location and intensity indices of the jet stream (Chavaillaz et al. 2013).

The most significant feature of the intensity changes is the remarkable enhancement of the North Atlantic jet stream at both levels (Figs. 6a,b). The MMM of the

North Atlantic jet stream is intensified by approximately 20% and 26% at 200 and 850 hPa, respectively. In addition, there is a considerable correlation between the anomalies at the 200-hPa level and those at the 850-hPa level. The correlation coefficient calculated from individual models is 0.83, which is significant at the 99% confidence level. It is suggested that the upper- and lower-level jet streams over the North Atlantic were possibly controlled by the same physical process during the LGM. The consistently weakened upper-level jet over Eurasia mentioned above is further confirmed, and the maximum wind speed is reduced by $2\text{--}6\text{ m s}^{-1}$. In addition, all models simulate a slightly intensified 850-hPa jet stream at the Northern Hemispheric scale.

With regard to the position of the jet stream, the upper and lower levels show opposite changes at the hemispheric scale (Figs. 6c,d). All models suggest a poleward shift of the jet stream at 200 hPa of approximately 2.2° latitude, while most models (except for COSMOS) suggest an equatorward shift at 850 hPa of approximately

FIG. 5. As in Fig. 3, but for 850 hPa. The grid points with elevations >1500 m are ignored.

3.2° latitude for the MMM. The 850-hPa jet streams over Eurasia and the North Pacific are characterized by a consistent equatorward movement, even though there are differences in the magnitudes of these anomalies for the different models. The equatorward shift over Eurasia is the strongest in CCSM4 and MIROC, at approximately 5° latitude, and ranges from 0.5° to 2.7° latitude for the other models. By contrast, the equatorward shift of the North Pacific jet stream is relatively small, at less than 2° latitude for all models except for COSMOS.

Since both the intensity and location indices reflect changes in the center of jet streams, an additional width index is defined to indicate variations in the latitudinal range of strong winds. The detailed algorithms are shown as follows: 1) the maximum zonal wind speed ($U_{\max}$) is derived from the intensity of the jet stream, and 50%, 70%, and 90% of $U_{\max}$ are labeled $U0.5$, $U0.7$, and $U0.9$, respectively; 2) the southernmost and

northernmost latitudes where the wind speeds are greater than $U0.9$ on the northern and southern sides of $U_{\max}$ are found (referred to these latitudes as $\text{LatN}0.9$ and $\text{LatS}0.9$); 3) the same is done as in step 2, but for $U0.7$ and $U0.5$; and 4) the average of $\text{LatN}0.9$, $\text{LatN}0.7$, and $\text{LatN}0.5$ is defined as the northern boundary of the jet stream, while the average of $\text{LatS}0.9$, $\text{LatS}0.7$, and $\text{LatS}0.5$ is defined as the southern boundary. Considering the nonuniform variations of wind speed with latitude, three thresholds are used to obtain robust changes at the flanks of the jet stream. Toward unified criteria to confine the range of the strong winds for both periods, the $U_{\max}$ value of the LGM is set to that of the preindustrial experiment. If 50%, 70%, and 90% of the preindustrial $U_{\max}$ are nonexistent for the LGM, the corresponding latitudes are replaced by the latitude of the LGM $U_{\max}$.

At the 200-hPa level, the southern flanks of the westerly jet over each sector all shrink northward (Fig. 7a). The movement of the boundary position is

FIG. 6. (a),(b) Intensity and (c),(d) location anomalies of the westerly jet at (left) 200 and (right) 850 hPa in the Northern Hemisphere and over three key regions—Eurasia, the North Pacific, and the North Atlantic (0° – 110° E, 120° E– 120° W, and 90° – 20° W, respectively). The intensity and location of the westerly jet are defined as the velocity and latitude of the quadratic interpolated zonal mean zonal wind maximum. MMM refers to the differences between the LGM and preindustrial indices, which are obtained from the arithmetic mean of the westerly wind field of each simulation.

equivalent to the nearby wind speed changes; northward shrink indicates that the westerly wind is reduced south of the upper-level jet streams. For the hemispheric-scale jet stream, the southern boundary shifts by approximately 2° latitude while changes in the northern boundary are relatively small, suggesting the northward shift of the jet stream presented above is largely due to low-latitude processes. For Eurasia and the North Pacific, the upper-level jet streams become narrower in the LGM simulation, with both borders moving toward the center as a manifestation of the large-scale westerly wind weakening (Fig. 3). At the 850-hPa level, the jet

streams except over the North Atlantic are characterized by an equatorward shift in both the northern and southern boundaries, indicating that the westerly wind is enhanced to the south of the jet axis and weakened to the north (Fig. 7b). For Eurasia, the contribution of the northern boundary is much larger, which supports the hypothesis that the ice sheet at high latitudes is responsible for the displacement (COHMAP Members 1988). Even though there is no consistent change in the location of the 850-hPa jet axis over the North Atlantic (Fig. 6d), the southern and northern boundaries both move away from the jet center (Fig. 7b). The results

FIG. 7. Latitudinal boundaries of the (a) 200- and (b) 850-hPa westerly jets, with vertical bars representing the preindustrial and stars representing the LGM for the Northern Hemisphere and over three key regions—Eurasia, the North Pacific, and the North Atlantic (0° – 110° E, 120° E– 120° W, and 90° – 20° W, respectively). The boundaries are estimated as the average of the three latitudes where the zonal mean zonal wind speed is approximately 50%, 70%, and 90% of the preindustrial jet intensity at its both flanks.

suggest the enhancement of the westerly wind is not confined to the jet axis but rather occurs over a large span of latitudes.

5. Underlying mechanisms

To understand the mechanisms behind the consistent behaviors of the westerly jets in the LGM experiments, we analyze the changes in the zonal mean zonal wind, temperature, meridional temperature gradient, and baroclinicity of the MMM (shown in Fig. 8).

a. Changes in thermal processes

The LGM air temperature anomalies relative to those of preindustrial period are dominated by a large-scale tropospheric cooling and stratospheric warming (Figs. 8e–h). In the middle and high latitudes, the tropospheric cooling decreases upward from the surface. However, in the tropics, a prominent cooling above the middle troposphere is revealed over each sector, with the maximum negative anomalies between 250 and 300 hPa. We consider that the depressed latent heat release caused by the

FIG. 8. Latitude–height cross section of the arithmetic MMM, including the (a)–(d) mean eastward wind U , (e)–(h) air temperature T , (i)–(l) MTG, and (m)–(p) MEGR. The color contours represent the robust LGM minus the preindustrial anomalies that for 7 out of 9 models agree with the sign of change from the MMM, while the black contours represent the preindustrial era. From left to right, the columns refer to the Northern Hemisphere, Eurasia, the North Pacific, and the North Atlantic. For MTG, positive represents the temperature increases with latitude, and vice versa.

arid glacial climate is a possible explanation for this tropical upper-level cooling.

Observations and coupled atmosphere–ocean simulations have suggested a large-scale tropical cooling over both the ocean and land during the LGM (Bush and Philander 1998; Pinot et al. 1999; Ballantyne et al. 2005). The depressed evaporation in response to the cold ocean leads to tropical drying, which is another feature of the LGM tropical climate (Braconnot et al. 2007). By examining changes in the specific humidity (not shown), we detect a global-scale reduction in atmospheric water vapor, in particular over the tropical oceans and the areas covered with ice sheets. The latent heat is a key component of the heat source in the tropics, resulting from the transitions of water phases. Numerical simulations suggest that a decrease in the latent heat associated with convective activities mainly accounts for the decreased tropical atmospheric heat during the LGM (Zhao et al. 2004). It is likely that the drier air carried by the convective column diminishes the latent heat release aloft and, finally, reshapes the thermal structure of the upper-level troposphere in the tropics. The tropical upper-level cooling is most prominent over the North Atlantic, followed by those over Eurasia and the North Pacific (Figs. 8f–h), which is in accord with the uneven cooling of the LGM tropical sea surface temperatures (SSTs) estimated from proxies (Ballantyne et al. 2005). In addition, taking all available models and all three key regions into account, the correlation between the regionally averaged tropical upper-tropospheric cooling and tropical SST anomalies is 0.91 (significant at the 99% confidence level), which supports the aforementioned hypothesis.

Figures 8i–l show the changes in the meridional temperature gradients (MTGs). In the troposphere, the MTGs are negative as temperature decreases from the equator to the pole; as a result, the negative anomalies (blue) indicate the increased absolute values of MTGs, and vice versa. All the following changes in MTGs refer to the absolute values unless otherwise stated. In the subtropics, the MTGs in the middle-upper troposphere are reduced due to the tropical upper-level cooling over each sector. Through the thermal wind relationship, the decreased vertical wind shear in response to the weakened MTGs possibly accounts for the negative westerly wind anomalies south of the upper-level westerly jet in the Northern Hemisphere. These results are seen in the poleward shift of the 200-hPa westerly jet at the Northern Hemispheric scale presented in section 4. The reduced MTGs in the upper-level middle latitudes, as a result of the joint effect of the low-latitude cooling and high-latitude warming, are considered to be responsible for the weakened 200-hPa westerly jet over Eurasia.

b. Changes in dynamical processes

The midlatitude atmosphere over the North Pacific and North Atlantic features prominent baroclinic instabilities under the influence of various factors, including the latitudinal distribution of solar radiation, the sensible heat supply from the ocean surface, and the intersection of cold and warm currents at the western boundaries (Hotta and Nakamura 2011). The baroclinic mean flow facilitates the generation and progression of eddies, which shape and modulate the midlatitude climate via the transport of heat, moisture, and momentum. Changes in the low-level baroclinicity, represented by the maximum Eady growth rate (MEGR), have been emphasized in previous studies for their connections to the anomalous storm activity and eddy-driven jets (Hall et al. 1994; Yin 2005; Rivière 2011). Here, we estimate the MEGR following Vallis (2006):

$$\sigma_E = 0.3098 \frac{|f| |\partial u / \partial z|}{N}; \quad N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z},$$

where f is the Coriolis parameter, z is the vertical coordinate, and $|\partial u / \partial z|$ represents the vertical shear of the zonal wind component. Also, N is the Brunt–Väisälä frequency, where g is the gravitational acceleration and θ is the potential temperature. The baroclinicity is determined by two factors: the vertical wind shear and static stability. The former is equivalent to the MTG, and the latter is associated with the vertical temperature structure.

The midlatitude baroclinic zones over the North Pacific, in response to changes in the MTGs, tend to shift equatorward at the lower levels (Figs. 8k and 8o). In addition, the static stability, which is reduced in the tropics due to the anomalous upper-level cooling and increased at the high latitudes due to the surface cooling, also contributes to the displacement of the baroclinic zones. The lower atmosphere over the North Atlantic is strongly affected by the expanded ice sheets and is characterized by prominent negative temperature anomalies north of 40°N. As a result, the MTGs are reduced by approximately 50% in the midlatitudes, leading to a remarkable enhancement of the baroclinic instabilities at the lower-level troposphere (Figs. 8l and 8p).

For the North Pacific and North Atlantic, changes in the locations and intensities of the midlatitude maximum baroclinicity show considerable consistency with changes in those of the westerly jets. The baroclinic instability of the mean flow, augmented by the mean available potential energy (APE), is associated with the behavior of the midlatitude westerly jet. From the view of the Lorenz energy cycle, the mean APE is first converted to the eddy APE via the generation of baroclinic

disturbances and is then converted to the eddy kinetic energy under the process of warm air rising and cold air sinking, induced by the eddies. Through the convergence of the eddy momentum flux regulated by atmospheric waves, kinetic energy is finally extracted from eddies to the mean flow, which plays an important role in the maintenance of the midlatitude westerly jet.

To examine the role of eddy–mean flow interaction in modulating the LGM westerly jets, we analyze the meridional eddy momentum flux convergence (EMFC) over the North Pacific and North Atlantic using the model outputs of CCSM4 and COSMOS. They are the only two models with daily outputs required for transient eddy analysis. For the behavior of the North Pacific and North Atlantic jet streams involved in this study, the simulations of these two models are in agreement with the others (Fig. 6), and thus the analysis still makes sense. The relative contributions from the transient and stationary eddy are identified as follows:

$$\overline{uv} = \overline{[u][v]} + \overline{[u]v^*} + \overline{u^*[v]} + \overline{u^*v^*} + \overline{u'v'}.$$

By the time and zonal decomposition of the wind field—where $(\cdot)'$ is the deviation derived from the time mean $(\overline{\cdot})$, and $(\cdot)^*$ is the deviation from the zonal mean $([\cdot])$ —the time-mean meridional momentum flux is divided into three parts: the contribution from the mean meridional circulation, represented by $\overline{[u][v]}$; that from the stationary eddy, represented by $\overline{[u]v^*} + \overline{u^*[v]} + \overline{u^*v^*}$; and that from the transient eddy, represented by $\overline{u'v'}$. The total contributions of the transient and stationary eddy are equivalent to $\overline{uv}$ minus $\overline{[u][v]}$. The regional zonal mean EMFC values over the North Pacific and North Atlantic are calculated and then vertically integrated from 1000 to 100 hPa. As illustrated in Fig. 9, the total EMFC is positive in the midlatitude and subarctic regions, where the momentum transferred from eddies to the mean flow leads to the generation of an eddy-driven jet. However, the eddy-driven jet and subtropical jet are intertwined in the background westerly wind field; it is difficult to separate them from each other (Lee and Kim 2003; Walker and Schneider 2006). Since the subtropical jet, driven by the Hadley cell, mainly occupies the upper-level troposphere, while the eddy-driven jet has a strong surface component, variations in the 850-hPa westerly jet are empirically chosen as indicators of the anomalous eddy-driven jet behavior.

The distribution of the total EMFC over the North Pacific is dominated by the transient eddy in both the preindustrial and LGM simulations (Figs. 9a,b). The LGM positive transient EMFC moves equatorward, which agrees with the equatorward displacement of the 850-hPa westerly jet presented in section 4. It is inferred

that the anomalous transient eddy activity in response to changes in the baroclinic instability accelerates the mean flow south of the eddy-driven jet and exerts the opposite effect to the north, eventually leading to the equatorward displacement of the 850-hPa westerly jet during the LGM. On account of the possible feedback between the baroclinic instability and the jet stream (Robinson 2006; Kidston et al. 2010), additional idealized model experiments are expected for more dynamical explanations. For the EMFC over the North Atlantic, the contributions from the transient and stationary eddies are comparable during the preindustrial period. However, a significant enhancement of the stationary EMFC dominates the distribution of total EMFC during the LGM. By contrast, changes in the transient EMFC in the midlatitudes can be ignored. The LGM maximum stationary EMFC is approximately 6 times greater than that of the preindustrial period (Figs. 9c,d). We argue that the enhancement of the stationary EMFC over the North Atlantic is so strong that it accelerates the midlatitude westerly wind throughout the whole troposphere, as shown in Fig. 8d. Earlier simulations have shown that the modern North Atlantic jet stream appears to be more influenced by eddy processes (Franzke et al. 2004; Woollings et al. 2008). For the LGM, we further confirm the significance of the baroclinic eddies for modulating the North Atlantic jet stream and highlight the leading role of the stationary wave, which is probably forced by the Laurentide ice sheet.

At the Northern Hemispheric scale, the distributions of the MMM low-level baroclinicity and westerly wind are analogous to those of the North Pacific (Fig. 8), which suggests the similar mechanisms behind the coincident equatorward shift of the 850-hPa jet stream presented in section 4. Since COSMOS and CCSM4, the only two models with daily outputs, simulate the poleward shift and tiny equatorward shift of the 850-hPa jet stream, respectively (Fig. 6), the role of transient eddies in modulating the 850-hPa jet at the Northern Hemispheric scale is expected to be confirmed in further studies.

6. Data–model comparisons

Although reconstruction at a single site might be affected by local factors, regionally uniform implications of proxies indicate the large-scale climate change. In general, changes in the moisture conditions at a continental scale are in response to changes in the atmospheric circulation, which potentially indicate the fluctuations of the westerlies. A collection of the reconstructed LGM moisture conditions as indicators of

FIG. 9. Vertically integrated (from 1000 to 100 hPa) meridional eddy momentum flux convergence (solid lines) over the (a),(b) North Pacific and (c),(d) North Atlantic, calculated by the daily outputs of (left) CCSM4 and (right) COSMOS, for the preindustrial in orange and the LGM in green. The contributions from transient and stationary eddies are distinguished by line types, dashed and dot-dashed, respectively.

the northern westerlies is shown in Fig. 4, including records from lakes, vegetation (pollen and plant macrofossil), glaciers, and other lines of evidence (see Table S1 in the supplemental material). It should be noted that some proxies are sensitive to multiple potential changes in the background environment, which increases the uncertainty of reconstructed variables. For example, the stomatal conductance of plants tends to be greater at the lowered CO_2 concentrations during the LGM, causing greater transpiration per unit leaf area, and contributes to the underestimate of plant available moisture (Farrera et al. 1999). Also, lake levels estimated from sites located near mountains and ice sheets might be affected by glacier variations and restrained evaporation due to the low temperature (Qin and Yu 1998). Given the difficulty in dissociating changes in the moisture conditions

from other effects of the glacial climate, we qualitatively divide the results into three categories: wetter, drier, and no change.

The available moisture proxies indicating possible changes in the LGM northern westerlies are concentrated in three regions: western North America, southern Europe, and northwestern China. Other regions may also feature significant moisture changes, but no connections between them and the LGM northern westerlies have been found so far. For the changes along western North America, the proxies suggest a dipole pattern with drier conditions near the ice sheet and wetter conditions in the southwest (Oster et al. 2015). In particular, the regional homogeneity is prominent to the south of the Great Basin, where the present desert and steppe were replaced by the open conifer woodland during the LGM (Thompson and Anderson 2000), and

the nearby inland lakes were reported at a higher level synchronously (Lyle et al. 2012). Changes in these records were explained by the increased LGM precipitation, as a result of the southward shift of the westerlies and steering of the westerly storms due to the presence of ice sheet (COHMAP Members 1998; Oster et al. 2015). All models in this study simulate a southward displacement of the 850-hPa jet stream over the eastern North Pacific, with positive (negative) wind anomalies in the upper reaches of the wetter (drier) regions in western North America, which agrees well with the observations and previous model studies.

A similar displacement of the westerly jet may have occurred over the Mediterranean zone (Fig. 4b). The modern climate of this region is determined by the seasonal migration of the westerlies. The maximum precipitation in winter is associated with the southward displacement of the westerlies, while the summer precipitation is relatively small due to the steering of subtropical anticyclones. During the LGM, lake records indicate moisture conditions wetter than those today at the west and northwest of the Mediterranean region, reflecting the southward displacement and dominance of the westerly jet streams (Harrison et al. 1996; Qin and Yu 1998). A consistently strengthened 850-hPa westerly wind over the Mediterranean and its surrounding regions in our study is consistent with the records. For the downwind central Asia and western China, Yu et al. (2003) reported that lakes in these regions registered higher levels during the LGM, in response to the decreased evaporation caused by the low temperature and the increased precipitation associated with the strengthened jet stream. By contrast, Li and Morrill (2013) argued that nearly all lake levels were lower across Asia compared to the present, and suggested this conflict as being the result of dating uncertainties in the previous lake level records. The simulated westerlies over these regions characterized by the weakening of the 200-hPa jet stream do not support the moisture changes in either of the observations. In general, although the available moisture proxies are limited, the simulated 850-hPa westerlies are in good agreement with moisture changes over western North America and southern Europe. These regions are also representative for featuring the maximum southward shift of the 850-hPa jet stream (Fig. 4b).

In addition to the moisture-related reconstructions, aeolian sediments also have the potential to reflect past regimes of atmospheric circulations. Costas et al. (2016) explored the transgressive dunefields along the Portuguese coast, and found the sustained records of larger grain sizes and dune volumes for the last termination (including the LGM). Based on the present-day analogs, the reconstructed aeolian activity was suggested to be

compatible with a southward shift and intensification of the North Atlantic westerlies. This hypothesis is supported by our results, as the enhanced 850-hPa westerly winds over the Iberian Peninsula and its upstream areas are simulated by most models (Fig. 5). The spatial pattern of oxygen isotopic composition in continental European land-snail shells implies a shift of water vapor sources from the modern North Sea to the LGM mid-Atlantic (Kehrwald et al. 2010), which also suggests that the influence of westerly jet was intensified during the LGM.

Based upon the uranium–lead (U–Pb) detrital zircon age spectrum, Pullen et al. (2011) proposed that the loess of the Chinese Loess Plateau during Quaternary glacial periods was largely derived from the Qaidam basin and the northern Tibetan Plateau. These findings differ from modern observational studies, which suggest that the bulk of the loess come from deserts located to the northwest and indicate an equatorward shift of the polar jet streams over central Asia during the glacial periods. Ono and Irino (2004) suggested that aeolian dust aloft over Japan is transported by the subtropical westerly jet from central Asia, based on analysis of the spatial and temporal distributions of the atmospheric aluminum concentrations. In their study, the LGM higher dust flux over five sites from the Taklimakan Dessert to the North Pacific is attributed to the expansion of the dust source area, and also to the southward shift of the subtropical jet. However, the equatorward shift of the jet streams over the Loess Plateau and Japan suggested by aeolian dust is absent in the simulations at both levels. For the presented data–model disagreement, the limited ability of models to reproduce wind anomalies over these regions is a possible factor. In addition, the suitability of proxies for the particular period and spatial range should also be kept in mind. To be specific, the loess records used by Pullen et al. (2011) reflect the major changes in the zonal wind pattern during Quaternary glacial periods, which do not necessarily apply to the LGM. For the equatorward shift of the subtropical jet suggested by Ono and Irino (2004), the sparse data source of aeolian dust flux in their study also has uncertainty in reflecting changes in the large-scale circulation. Considering the good data–model agreement based on the continental-scale moisture conditions, we propose more synthesis work of dust flux reconstructions from the dust source area along the transport route to the deposition sites to estimate changes in the LGM westerlies.

7. Conclusions and discussion

The behavior of the northern westerlies during the LGM has been investigated using CMIP5/PMIP3

FIG. 10. Schematic diagram of the mechanisms responsible for the LGM behaviors of northern westerlies.

simulations, with a focus on the jet stream at 200 and 850 hPa. The comparison between the NCEP–NCAR reanalysis and preindustrial control experiments verifies the capability of the models to reproduce the modern large-scale features of the zonal wind field in the Northern Hemisphere. Based on the distribution of the modern westerly jet and the LGM minus preindustrial zonal wind anomalies, we identified three key regions along the parallel: Eurasia, the North Pacific, and the North Atlantic. Quantitative analyses of the annual mean zonal mean zonal wind at the Northern Hemispheric scale and over the aforementioned key regions lead to the following conclusions. 1) Compared with the preindustrial period, changes in the Northern Hemispheric-scale westerly jet during the LGM exhibit considerable vertical differences. The wind speed maxima shift southward at 850 hPa and northward at 200 hPa,

by approximately 2° – 3° latitude at both levels. 2) The upper-level westerlies over Eurasia feature a large-scale weakening, and the maximum wind speed of the 200-hPa jet decreases by 2 – 6 m s^{-1} for the MMM. In the lower troposphere, the Fennoscandian ice sheet blocks the westerly flow, causing the jet stream to move southward to the Mediterranean region. 3) With regard to the North Pacific, all models show that the 850-hPa jet shifts southward, especially over the eastern boundaries, most of which reveal a displacement magnitude of 0.5° – 2° latitude from the regional zonal mean. 4) The midlatitude westerlies throughout the troposphere are considerably strengthened over the North Atlantic. The intensity of the westerly jet at 200 and 850 hPa, in response to the glacial climate, increases by 20% and 26%, respectively.

The possible mechanisms behind the anomalous westerly behaviors are illustrated in Fig. 10. The LGM

climate features a large-scale tropospheric cooling constrained by changes in the greenhouse gas concentrations and expanded ice sheets. However, the temperature anomalies are characterized by considerable spatial heterogeneities (Figs. 8e–h). There are two distinct negative centers located at the tropical upper levels and the lower troposphere of the high latitudes. In the midlatitudes, these centers exert the opposite effects on the MTGs in the vertical direction. According to the thermal wind relationship, the reduced MTGs in the tropical upper troposphere possibly account for the decreased subtropical westerly wind over each sector, which contribute to a poleward shift of the 200-hPa jet at the hemispheric scale and the weakening of the 200-hPa jet over Eurasia. For the North Pacific and North Atlantic, this study highlights the connection between the abnormal baroclinic eddy activity and the behavior of the midlatitude westerly jet during the LGM and emphasizes the different contributions of transient eddies and stationary waves to each sector. An equatorward shift of the midlatitude baroclinic zones, in response to changes in the MTGs and static stability over the North Pacific, is associated with an equatorward displacement of the transient eddy activities and subsequent changes in 850-hPa westerly jet. For the North Atlantic, a remarkable enhancement of the eddy momentum flux convergence dominated by the anomalous stationary waves is coincident with the equivalent barotropic strengthening of the westerly wind throughout the troposphere. The predominant stationary waves over the North Atlantic are conjectured to be a result of the uplift and expansion of the Laurentide ice sheet during the LGM, which is beyond the scope of this study.

From the data–model comparison, the simulated 850-hPa westerly jets are in agreement with the observed LGM moisture conditions over southwestern North America and southern Europe, possibly through the anomalous precipitation caused by westerly storms. But for the 200-hPa westerly winds, there is no unambiguous connection between the observations and simulations. This implies that the traditional reconstructions of westerlies, based upon the continental-scale moisture changes, mainly reflect westerly anomalies at the lower troposphere. Given the significance of upper-level westerlies in the long-range transport of mineral dust, aeolian dust flux could be used as a potential proxy to indicate changes in the upper-level westerlies. It is worth noting that dust flux from individual sites may not be representative for the large-scale circulation, so syntheses of multipoint records from the dust source area along the transport route to the deposition sites are needed for future upper-level westerlies reconstructions.

In this study, we have shown the importance of tropical upper-level cooling to the changes of the upper-level westerlies. However, the cause of this anomalous heat distribution remains ambiguous. Given the substantial decrease in the water vapor content during the LGM, the reduced latent heat release is a possible contributor. Additional research on the heat transfer and energy balance is required to identify the underlying mechanisms of this tropical upper-level cooling. For the lower-level westerlies, we found good correlations between changes in the eddy momentum flux convergence and those in the 850-hPa westerly jet, based on the daily outputs from CCSM4 and COSMOS. It is far from sufficient to study the glacial eddy–mean flow interaction using only two models; thus, more daily-resolution outputs should be provided by models participating in future coordinated experiments for the LGM. To summarize, the behavior of the LGM northern westerlies is closely connected to the tropical and polar processes suggested in our study. Hence, we need to deepen our understanding of the impact of interactions between different latitudes on the glacial large-scale atmospheric circulation in the future.

Acknowledgments. We sincerely thank the three anonymous reviewers for their insightful comments and suggestions to improve this manuscript. We also acknowledge the climate modeling groups participating in the CMIP5/PMIP3 for producing and sharing their model outputs. This work was supported by the National Natural Science Foundation of China (41625018, 41421004, and 41430962).

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