Dear Editor,

We have made the revision, according to the reviewers' comments. Especially, we have added a few more paragraphs, in responding to Reviewer #2's comments 1 and 2, which are about model and data resolutions (see pages 5-6 and Table S1), ICE-G5 vs. ICE-G6 (see page 5 and Figure S1), rotated EOF analysis (see the second paragraph in page 9).

Point-by-point replies are as follows.

Thank you very much for handling the review process of our paper.

Yours sincerely

Yongyun Hu

**Reply to Reviewer #1**

Based on climate model simulations and sensitivity experiments, this study shows that the PNA was largely distorted or broken at the LGM, which was attributed to a split of the westerly jet stream over North America induced by the thick Laurentide ice sheet. It further indicates that ENSO had little influence on North American climate at the LGM. The results are intriguing and the mechanism proposed is convincing. I would recommend a minor revision to address the comments below.

We thank the reviewer for the reviews. Replies to the comments are as follows. All our replies are in blue.

1. If the PNA is defined as the leading EOF of the 500hPa geopotential height, the results would change or not?

We have done analysis, using different methods. The results are almost the same as our correlation analysis.

Figure R1 shows the geographic distributions of the Rotated Empirical Orthogonal Function (REOF) analysis of 500 hPa height in NCEP/NCAR reanalysis. The second REOF mode well represents the loading pattern of the PNA. The second REOF in the PIC simulation of PMIP2 CCSM3 also shows the PNA pattern (Figure R2).

However, the second REOF in the LGM simulation of the PMIP2 CCSM3 does not show the PNA pattern (Figure R3). The third and fourth modes indicate connections between the North Pacific and Arctic.

A few sentences of the REOF analysis will be added to the text. Figures will not be shown since there are already too many figures.

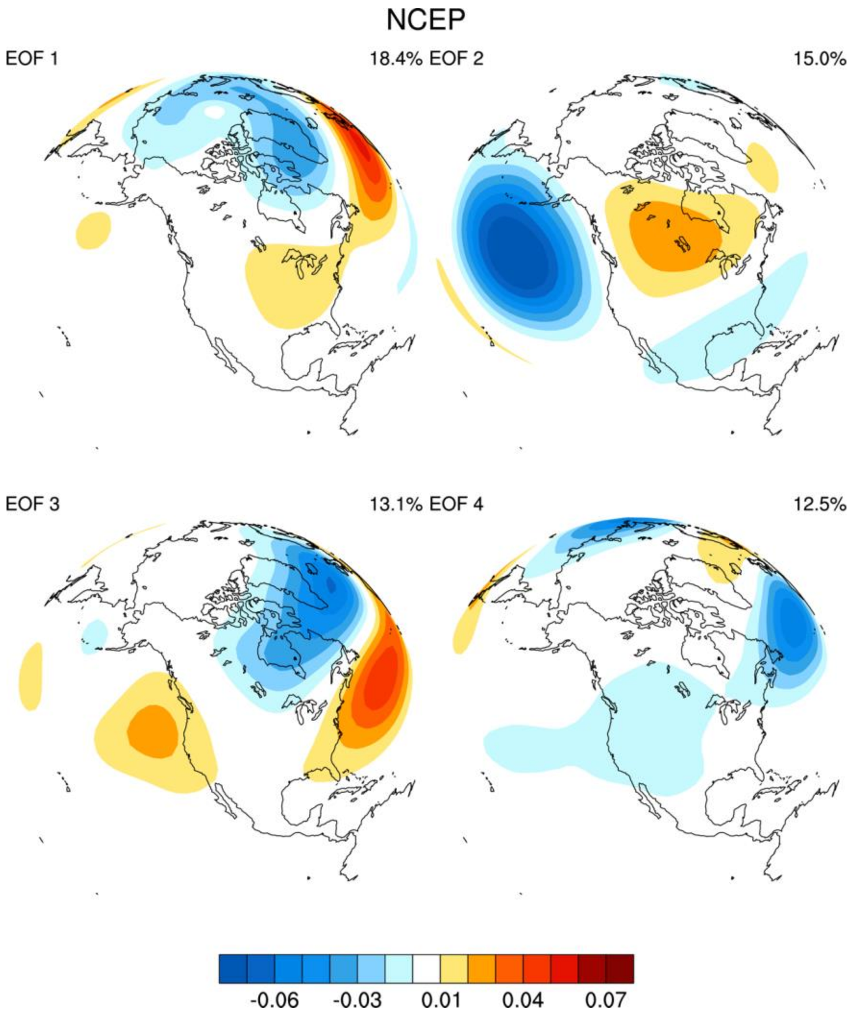



Figure R1. Spatial patterns of the Rotated Empirical Orthogonal Function (REOF) analysis of 500 hPa height in NCEP/NCAR reanalysis.

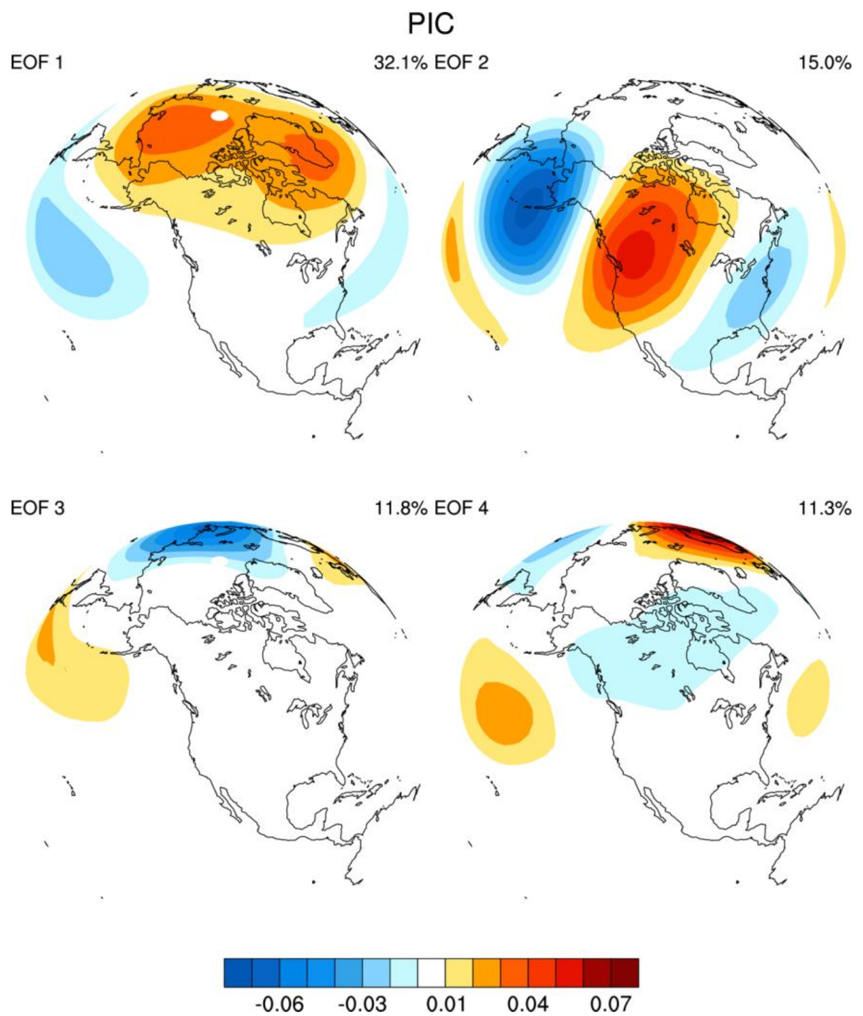



Figure R2. Spatial patterns of REOFs of 500 hPa height in the PIC simulation of PMIP2 CCSM3.

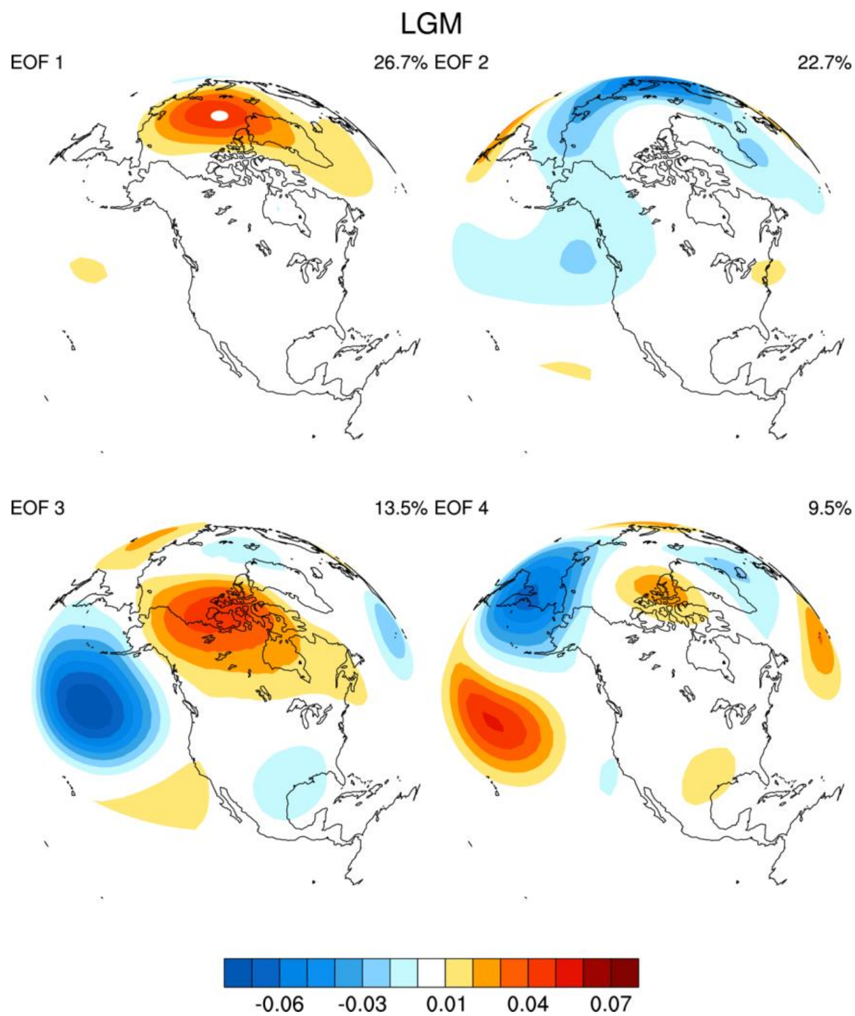



Figure R3. Spatial patterns of REOFs of 500 hPa height in the LGM simulation of PMIP2 CCSM3.

2. It is better to replace Figs. 6d-f with the meridional temperature gradient, and present a figure showing the sensitivity simulation result that meridional temperature gradient become sharper with increasing ice sheet thickness. This would clearly illustrate how a split of the westerly jet stream over North America is connected to the thick ice sheet through the thermal wind relation.

Thanks for the suggestion. We have replaced Figs. 6d-f with the meridional temperature gradients. As shown in the updated figure, one can clearly see that the subtropical temperature gradients in the LGM simulation are stronger than those in NCEP/NCAR reanalysis and the PIC simulation.

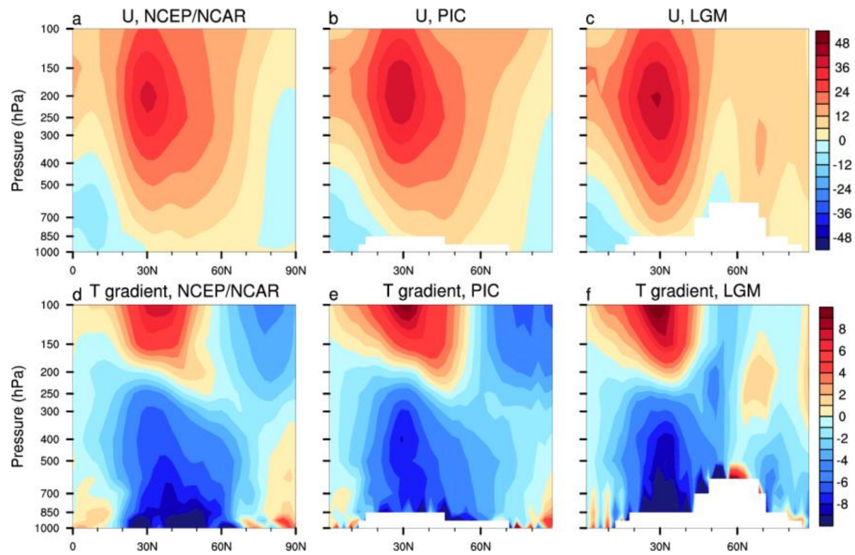



**Fig. 6.** Vertical cross sections of DJF zonal winds and meridional temperature gradients along the longitude of 100 °W in the NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. Top panels: zonal winds, and bottom panels: meridional temperature gradients. Left panels: NCEP/NCAR, middle panels: PIC, and right panels: LGM. Zonal-wind unit is $ms^{-1}$, and temperature gradient unit is K/(1000 km).

A new figure will be added to the papers to how meridional temperature gradients change with increasing ice-sheet thickness (Figure S4). The figure shows that subtropical temperature gradients becomes stronger with increasing ice sheet thickness, which leads to the strengthening of the subtropical jet.

Figure S4 also shows that positive temperature gradients occur above the ice sheet as ice sheet thickness reaches 80%. It is consistent with the occurrence of easterly winds.

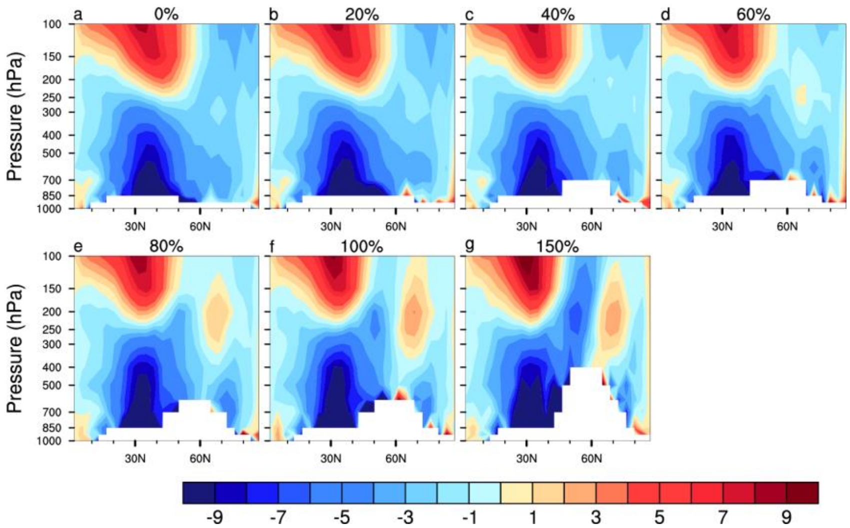
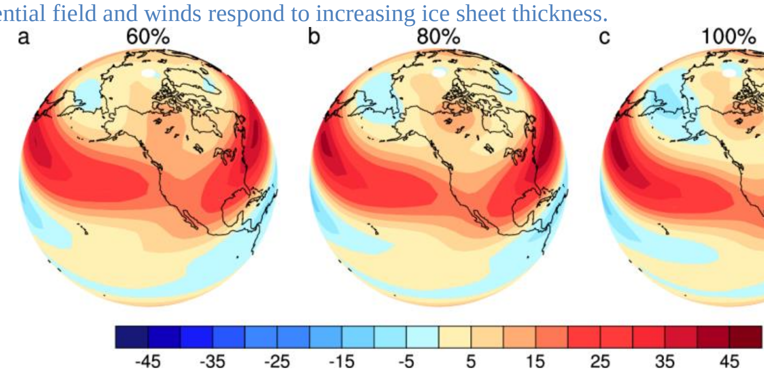



Figure S4. Vertical cross sections of DJF meridional temperature gradients along the longitude of 100 °W in sensitivity simulations with different ice sheet thicknesses. (a) 0%, (b) 20%, (c) 40%, (d) 60%, (e) 80%, (f) 100%, and (g) 150%. The color interval is 1 K/(1000 km) .

3. Fig. 8 is kind of needless. Instead, the zonal wind in the 60%, 80%, 100% thickness simulations can be added to Fig. 7 to show the occurrence of easterly winds over the Laurentide ice sheet.

Yes, zonal winds in the 60%, 80%, and 100% thickness simulations will be added to Fig. 7. It is shown below.

It is better to keep Figure 8, we feel. Readers shall have some intuition of how the geopotential field and winds respond to increasing ice sheet thickness.




4. How are the wave activity flux and stationary wavenumbers calculated?

The three-dimensional wave activity fluxes are calculated using equation 7.1 in Plumb (1985), which is cited in the paper.

The stationary wavenumbers are calculated using equation 6.29 in Held (1983), which is also cited in the paper.

5. The temporal span used for the individual simulations of PMIP2 and PMIP3 should be clarified. What is the degree of freedom used for the correlation coefficient of 0.35?

Thanks for your suggestion! We used the last 30-year simulations for each model of PMIP2, PMIP3, and our sensitivity simulations. The degree of freedom used for the correlation coefficient of 0.35 is 30. It is explicitly pointed out in the Model and Data section.

6. L189: Alberta->North Pacific

Revised.

References:

Held IM (1983) Stationary and Quasi-stationary Eddies in the Extratropical Troposphere: Theory. in B. J. Hoskins, Pearce RP (eds.) Large-scale Dynamical Processes in the Atmosphere. Academic Press, pp. 127–168.
Plumb RA (1985) On the Three-Dimensional Propagation of Stationary Waves. Journal of the Atmospheric Sciences 42:217-229.

**Reply to Reviewer #2**

**General Comments**

The goal of this paper is to investigate whether teleconnections from the Tropical Pacific to North America and the Gulf of Mexico (via the Pacific/North American pattern) are maintained during the Last Glacial Maximum when large ice sheets covered much of North America. The analysis is performed using PMIP2 and PMIP3 simulations, the NCEP/NCAR reanalysis and some low-resolution simulations performed using CCSM3. I think this is interesting and novel, and the authors' results are supported in the datasets they analyse. However, the authors make a few methodological choices that make me wonder about the general applicability of their results, especially to historical climate conditions.

We thank the reviewer for the careful reviews, which are important for us to improve the paper. Replies to the comments are as follows. All our replies are in blue.

1. Most of the datasets that the authors use are old. Firstly, the sensitivity experiments are performed with a PMIP2-era climate model, CCSM3. While the dynamical phenomena that the authors are investigating are not likely to be strongly compromised by this choice, their

> choice to use a lower resolution with this model than was even used for PMIP2 is puzzling, unless it's a dataset of opportunity. This resolution choice can have important implications for the results they present, since the representations of stationary wave patterns under glacial boundary conditions are known to degrade at lower resolutions (cf Lofverstrom and Lora, 2018). Additionally, the use of the ICE-5G ice sheet reconstruction for their LGM boundary conditions is problematic, as the dome in this ice sheet reconstruction is so much larger than current estimates would predict. If the authors want to suggest that their results have applicability to the actual conditions at LGM, then it would be helpful if they present information on which sensitivity experiment best corresponds with current estimates of true LGM conditions.

We started this work a few years ago when there was only PMIP2 data, and PMIP3 data was not available yet. We found that the PNA is distorted in PMIP2 simulations. Then, we performed the low-resolution sensitivity simulations, with ICE-5G. The low-resolution simulation results were also used in a different work (Lu et al., 2016).

As PMIP3 data became available, we found the similar results in PMIP3 simulations. Especially, the LGM simulation of CCSM4 shows consistent result with that of CCSM3. Therefore, we feel that the result of distorted PNA path at LGM is not dependent on model versions.

**ICE-6G vs. ICE-5G:** To answer the question about the thickness difference of the Laurentide ice sheet between ICE-6G and ICE-5G, we plot vertical cross sections of the ice sheet thickness along 45 °N and 60 °N in Figure R1 below. It can be seen that the thickness of ICE-6G is close to 80% of ICE-5G in general. ICE-6G is even higher than 80% ICE-5G in some regions. The shape of 80% ICE-5G over North America does not well match the twin-peaks of ICE-6G at 45 °N. However, the shape of 80% ICE-5G matches that of ICE-6G reasonably well at 60 °N, except for the region between 200° and 230° in longitude where 80% ICE-5G is even lower than ICE-6G. Figure 2e shows that as 80% ICE-5G is applied, the PNA path is distorted toward Arctic, and that the present-day PNA no longer exists.

The PNA is a large-scale atmospheric circulation system. It may not be very sensitive to the small-scale structures of the ice sheet, we feel.

In the revised manuscript, we will explicitly point out the differences between ICE-5G and ICE-6G. Figure R1 will be added to the Supporting Information. In the conclusion section, we will add a few sentences to point out how the PNA path changes with increasing ice-sheet thickness. For example, the present-day PNA path remains for ice sheet thicknesses no more than

60% ICE-5G (Figs. 2a-d). However, the PNA is distorted as ice sheet thickness reaches 80% ICE-5G (Figs. 2e-g).

In the revised manuscript, we add a table of model resolutions in Table S1. Model resolutions are also described in the Model and Data section (page 5-6). Differences between ICE-5G and ICE-6G are also discussed on page 5.

Figure R1 below is added to Supplementary Materials, as Figure S1.

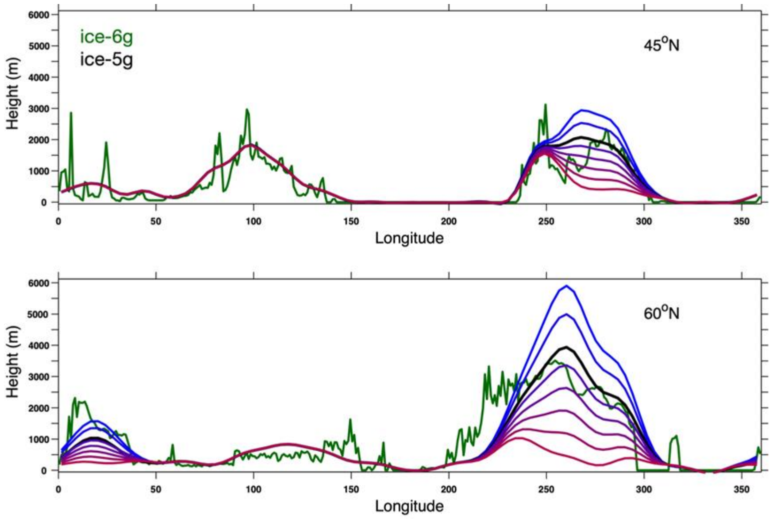



Figure R1. Vertical cross sections of ice sheet thicknesses of ICE-5G and ICE-6G at 45 °N and 60 °N. Different ice sheet thicknesses in our sensitivity experiments (from 0% to 150%) for ICE-5G are all plotted.

2. The authors use a point-based definition for the PNA rather than a principle component-based definition. Given the locations of modes of variability can change under different boundary conditions, restricting themselves to fixed locations in space seems limiting. The authors attempt to compensate for this choice by including a buffer zone around each centre of action, but it feels like the analysis is more convoluted as a result, requiring multiple sets of correlation figures with different centres of actions to explain their results. I would like to see the analyses repeated using PCA for at least one set of model data to see whether that alters the interpretation of their results at all. It should also help with separating the signal they are investigating from the subtropical wave train.

We have done analysis, using different methods, such as EOF and rotated EOF (REOF). The results are almost the same as the correlation analysis. Figures R2-4 shows the REOF results of 500 hPa height in NCEP/NCAR reanalysis, CCSM3-PMIP2 PIC and LGM simulations. The 2nd REOFs in the NCEP/NCAR reanalysis and the CCSM3 PIC simulation well represents the loading pattern of the present-day PNA (Figures R2 and 3).

In contrast, the 2nd REOF in the CCMS3 LGM simulation does not show the PNA pattern (Figure R4). The 3rd and 4th REOFs demonstrate connections between North Pacific and Arctic, and between North Pacific and the southern part of North America. Discussion of the REOF results is added to page 9.

The reason why we stay with the point-based method is because the four base-points demonstrate the traditional view of the PNA path. Moreover, it is easier for us to quantify how far the PNA path is distorted away from the present-day PNA path, as shown in Figure 3.

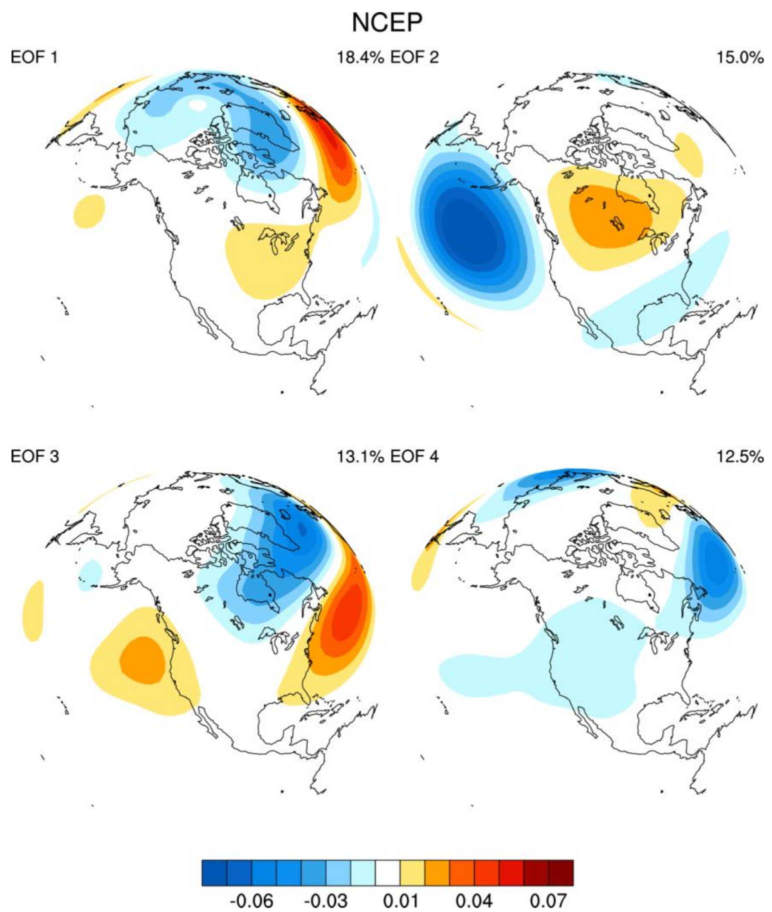



Figure R2. Spatial patterns of the Rotated Empirical Orthogonal Function (REOF) analysis of 500 hPa height in NCEP/NCAR reanalysis.

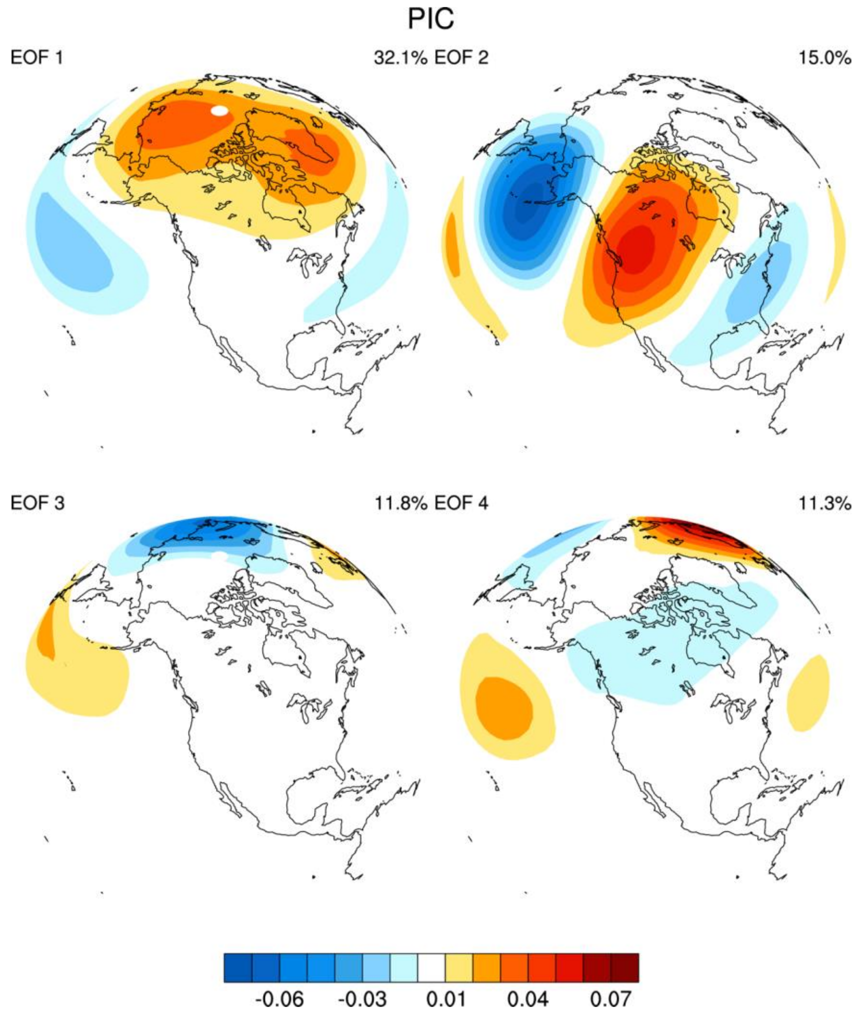


Figure R3. Spatial patterns of REOFs of 500 hPa height in the PIC simulation of CCSM3.

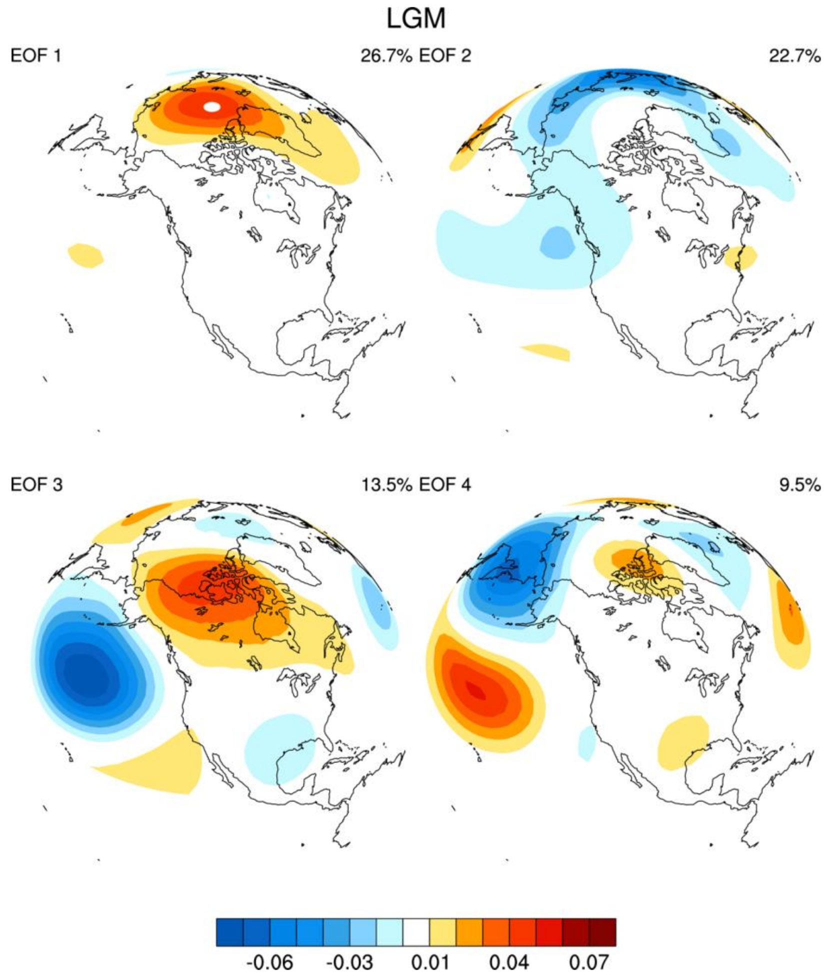



Figure R4. Spatial patterns of REOFs of 500 hPa height in the LGM simulation of PMIP2 CCSM3.

Finally, I find these results interesting from the perspective of altered atmospheric dynamical regimes and altered atmospheric variability in the presence of large ice sheets. I don't understand the authors' interpretation that a rerouting of the teleconnection pattern and reduced strength of the present-day pattern of the PNA makes it "broken". What's so special about Alberta and the Gulf of Mexico? Isn't it also interesting that a re-routed teleconnection means that regions of the Arctic are now being affected more directly by tropical Pacific variability? Also, a discussion of how the tropical variability itself might be different at LGM (weaker, as I understand it) would help contextualize the work better. As it is, it makes me curious whether there is an implication for this result they are working toward that isn't communicated in the manuscript.

Thanks for the suggestion!

When we use the word “broken”, it means breaking of the present-day PNA teleconnection. We agree with the reviewer that “distorted PNA” is good enough. Therefore, “broken” will be removed. We shall also focus on the distorted PNA path in the revised version, emphasizing the connections toward Arctic and southern part of North America.

Yes, previous works showed weaker ENSO at LGM (Zhu et al., 2017). We will add brief discussion in the revised version.

**Scientific Comments**

I feel like insufficient information is provided about the datasets provided, particularly for the reanalysis. What years were used? What is its resolution and the resolution of the model results presented?

We use the recent 30-year NCEP/NCAR reanalysis from 1988 to 2017. Information of horizontal resolutions of reanalysis and models will be added.

The reanalysis seemed to be used as a proxy for observational conditions. How well does this reanalysis reproduce observed PNA variability? There is observational data for both the pattern and time series of the PNA from 1950 to compare against.

Yes, reanalysis cannot be considered “real” observational data. At present, most modeling works are compared with reanalysis by taking the advantage of its easier access.

The 2nd REOF in the NCEP/NCAR reanalysis in Figure R2 is almost the same as that given by the Climate Prediction Center of NCEP (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna_loading.html ).

At present, there are three different time periods being presented in the plots in Figures 1, 3 and in the supplement: transient years 195? to 200? in the reanalysis, and fixed boundary conditions under preindustrial and LGM conditions. While it’s unlikely that a simulation that doesn’t generate a realistic PNA pattern under preindustrial conditions will produce a realistic PNA under late 20th century conditions, it is not accurate to treat the reanalysis and PIC simulations as representing the same climate state. Since the historical experiment is a Tier 1 experiment, results that do match the reanalysis time period should be available for all of the PMIP models presented here.

We agree that the PIC simulations of PMIP2 models are different from the NCEP/NCAR reanalysis that includes climate changes. However, the datasets from PMIP2 simulations are only available for the PIC and LGM experiments, not including historical simulations.

In the present paper, our key point is to address the difference of the PNA path between two very different climate states: LGM vs. present. Therefore, NCEP/NCAR reanalysis is not much different from the PIC simulation in this context.

I would like to see a discussion of how the significance of correlations was determined.

We used 30-year data for the reanalysis (1988-2017), all models of PMIP2 and PMIP3, and our sensitivity simulations. The degree of freedom is 30. For a two-tailed test, the critical value of the correlation coefficient is 0.35 for the 95% confidence level. We will explicitly point out this in the revised version.

Be more precise about criteria for considering a PIC simulation to have represented the PNA successfully. Do there have to be significant correlations between Hawaii and within 10deg of every other centre of action or also between each of the other centres of action? I understood the criteria to suggest that the all regions had to be significantly correlated with Hawaii, but a visual inspection of Figure S2 suggests that some of the "well-performing" runs do not capture the Gulf of Mexico centre of action within 10degrees and the defined significance thresholds.

First, we pointed out that our definition is a "loose definition". Such a loose definition is to figure out how much the PNA at LGM is distorted away from its present-day path. The quantitative results is shown in Figure 3. It can be seen from Figure 3e that the correlation coefficient just reaches the criteria at the Gulf Coast for the PIC simulation of HadCM3M2 and CNRM-CM33 models. Figures S3b and c show two small shallow blue areas that are just at the margin of the 10 degree circle.

Ln 196 The authors claim that FGOALS-1.0g, IPSL-CN4-V1-MR and MIROC3.2 are unable to reproduce the North Pacific centre of action correlations with Hawaii, but only FGOALS-1.0G appears to have insignificant correlations at this site in Fig 3c. Why the claim that they are not reproducing it, then?

Agree. Changes are made. IPSL-CN4-V1-MR and MIROC3.2 have insignificant correlations at the Gulf Coast instead of the North Pacific.

Ln 242-243 The authors state there are two jets at LGM: a subtropical jet at 30N and a subpolar jet at 63N. Do they actually intend to say that the southward branch is actually a subtropical jet or a subtropically-located eddy-driven jet?

Yes, the southward branch is the subtropical jet.

ln 247-248 It is true that the latitudinal temperature gradients are sharper at 35-50N, but not much at 70N, where the subpolar jet the authors are discussing arises, unless you include the temperature gradient associated with the ice sheet surface. Due to the lack of evident meridional gradients in temperature here, I question their interpretation. What about the role of katabatic winds or non-linear interactions of the winds with the ice sheet at their westernmost interaction point?

Agree.

Following the suggestion, we have replotted Figure 6. The bottom panels of temperatures are replaced with meridional temperature gradients (Figs. 6d-f), which are shown below. Meridional temperature gradients show a local maximum at about 70N, right over the northern side of the ice sheet.

Katabatic winds are mainly near the surface. Here, the subpolar jet is located between 400 and 300 hPa.

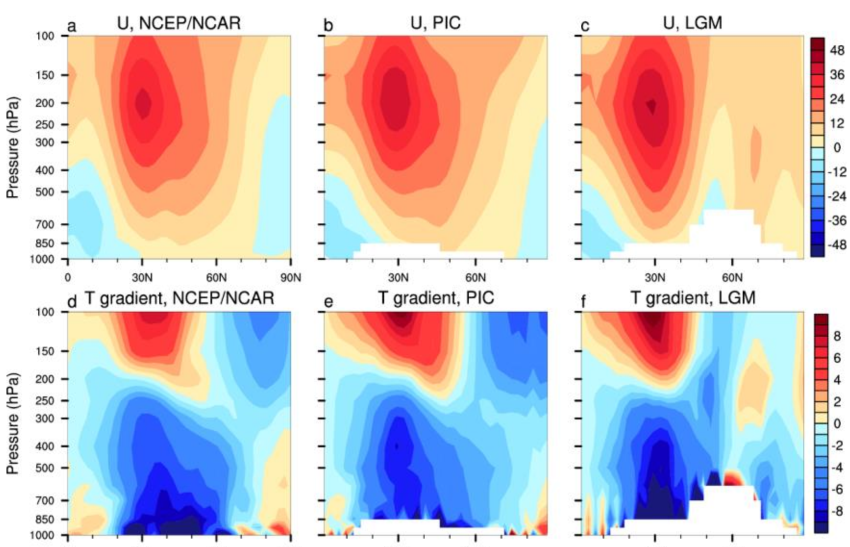



**Fig. 6.** Vertical cross sections of DJF zonal winds and meridional temperature gradients along the longitude of 100 °W in the NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. Top panels: zonal winds, and bottom panels: temperature gradients. Left panels: NCEP/NCAR,

middle panels: PIC, and right panels: LGM. Zonal-wind unit is $ms^{-1}$, and temperature gradient unit is K/(1000 km).

Ln 260-261 How much does the core of the jet shift southward as the ice sheet height increases in supplemental figure 4e? It doesn't appear to be more than a couple of degrees and is barely discernible from these plots. The more apparent feature is that the core of the jet becomes much narrower as it strengthens, while the 12 m/s isoline initially expands northward and eventually breaks away from the rest of the jet.

Agree. The subtropical jet shifts southward by about 3 degrees. In the revised version, we will point out that the jet core becomes narrower with increasing ice sheet thickness.

**Technical Details**

Given the authors are analysing CCSM3 simulations at different resolutions, it would be helpful to specify which resolution version they are referring to in plots and discussions.

We will add more specific information of data resolutions in the revised version.

In Figures 3c and d, it would be helpful for interpreting the results if PMIP2 and PMIP3 models from the same model tree were given the same symbols (where possible).

We have updated Fig. 3.

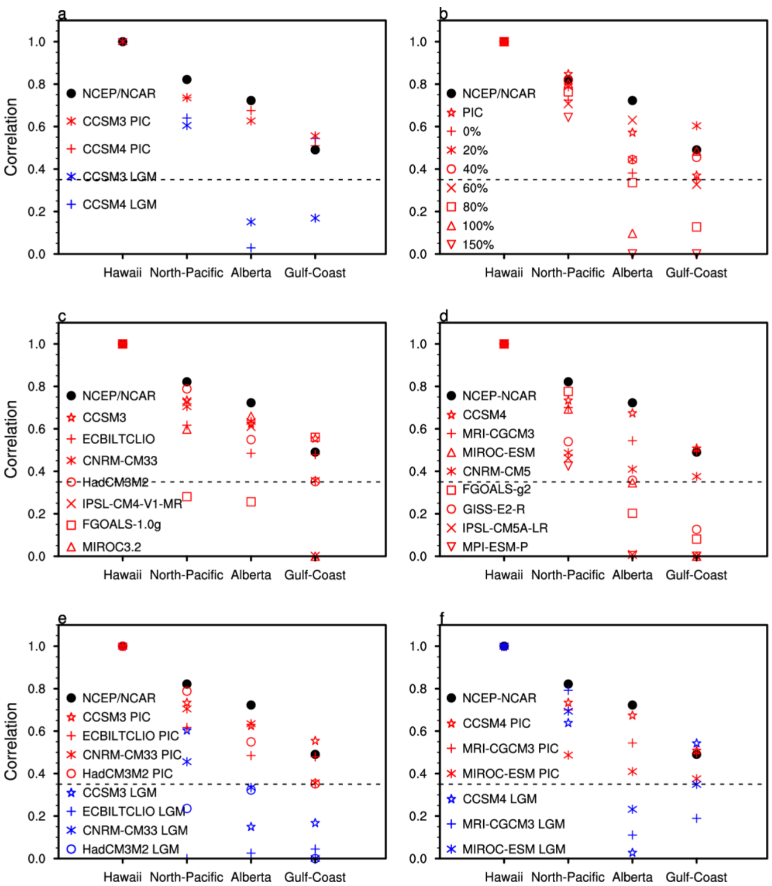



**Fig. 3.** Correlation coefficients at the four PNA action centers in PIC and LGM simulations for PMIP2 and PMIP3 models, with the base point near Hawaii. The negative values over Alberta and the Gulf Coast are reversed to positive. The dashed lines correspond to 0.35, which represent the 95% confidence level. (a) CCSM3 and CCSM4, (b) sensitivity simulations, (c) PIC simulations of PMIP2 models, (d) PIC simulations of PMIP3 models, (e) LGM and PIC simulations for well-performing PMIP2 models, and (f) LGM and PIC simulations for well-performing PMIP3 models.

Figures 3e and f caption was difficult to understand without reading a few times and figuring out from the plots themselves. A modification as simple as "LGM and PIC simulations for well-performing PMIP2 models" would get rid of this problem.

Thanks, changed.

Ln 198 typo “FGOAL-1.0g” to “FGOALS-1.0g” ln 202 typo “Albert” to “Alberta”

Thanks, changed.

ln 203-205 missing key point in the text that it is at LGM that these simulations are unable to reproduce correlations of PIC.

Added.

Ln 240 “North American” to “North America”

Revised.

ln 261 “Significant jet split” to “Significant jet splitting”

Revised.

ln 271 “westerly jet act as wave guides” to “westerly jet acts as a wave guide ”

Revised.

ln 339 “We have showed” to “We have shown”

Revised.

ln 340 “forced jet split” to “forced jet splitting”

Revised.

ln 341-342 double negative makes this sentence say the opposite of what you’re trying to say “ENSO would have little direct influence”

Thanks, revised.

Figure 7 Overall, I find this plot very effective at illustrating the critical latitudes. However, the presentation of the results in units of m□1 rather than the number of wavelengths per latitude circle (e.g. a wave 1 field would have one complete wavelength around the hemisphere) makes it difficult to get meaning from the colour contours.

Thanks for the suggestion. We prefer to keep the unit because it is the standard unit. The stationary wavenumbers are calculated following equation 6.29 in Held (1983).

Figure 8 and S5 Showing the zonal anomalies of geopotential heights would make the author's argument clearer without being limited to the height scale capturing the background zonal gradient.

We feel that Figure 8 and S6 can give readers better intuition on how atmospheric circulation is forced by the large ice sheet. We prefer to keep the two Figures.

None of the data used in this study was acknowledged. Acknowledging data sources is good practice, and it is also stipulated as a condition of usage in some cases. CMIP data archives also require users to include a table listing information about each simulation used in their publications. The supplement is fine for this, I think.

Thanks for the reminder! All the data sources used in the paper will be acknowledged.

References:

Held IM (1983) Stationary and Quasi-stationary Eddies in the Extratropical Troposphere: Theory. in B. J. Hoskins, Pearce RP (eds.) Large-scale Dynamical Processes in the Atmosphere. Academic Press, pp. 127–168.

Lu Z, Liu Z, Zhu J (2016) Abrupt intensification of ENSO forced by deglacial ice-sheet retreat in CCSM3. Climate Dynamics 46:1877-1891.

Zhu J, Liu Z, Brady E, Otto-Bliesner B, Zhang J, Noone D, Tomas R, Nusbaumer J, Wong T, Jahn A, Tabor C (2017) Reduced ENSO variability at the LGM revealed by an isotope-enabled Earth system model. Geophysical Research Letters 44:6984-6992.

# Distorted Pacific-North American Teleconnection at the Last Glacial Maximum

**Yongyun Hu[1*], Yan Xia[1], Zhengyu Liu[1,2], Yuchen Wang[1], Zhengyao Lu[1], and Tao Wang[3]**

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**Abstract**

The Pacific-North American (PNA) teleconnection is one of the most important climate modes in the present climate condition, and it enables climate variations in the tropical Pacific to exert significant impacts on North America. Here, we show climate simulations that the PNA teleconnection was largely distorted or broken at the Last Glacial Maximum (LGM). The distorted PNA is caused by a split of the westerly jet stream, which is ultimately forced by the thick and large Laurentide ice sheet at the LGM. Changes in the jet stream greatly alter the extratropical wave guide, distorting wave propagation from the North Pacific to North America. The distorted PNA suggests that climate variability in the tropical Pacific, notably, El Niño and Southern Oscillation (ENSO), would have little direct impact on North American climate at the LGM.

## 1 Introduction

The Pacific-Northern-American (PNA) teleconnection is the major atmospheric teleconnection mode that links climate variations from the tropical Pacific to North America for the present-day climate state (Horel and Wallace, 1981; Wallace and Gutzler, 1981). Especially, climate variability associated with El Niño and Southern Oscillation (ENSO) exerts great impacts on the North American climate through the PNA teleconnection (Henderson and Robinson, 1994; Lau, 1997; Leathers et al., 1991; Straus and Shukla, 2002). It is well known that the PNA is largely constrained by extratropical atmospheric flows, notably, the extratropical wave guide (Held, 1983; Held et al., 2002; Hoskins and Karoly, 1981; Jin and Hoskins, 1995). Thus, changes in extratropical atmospheric flows should alter the PNA under different climate conditions.

It has been shown that greenhouse warming leads to a strengthening and a shift of the PNA due to altered extratropical atmospheric flows (Allan et al., 2014; Chen et al., 2017). There has also been a large body of works that demonstrated significant differences in extratropical atmospheric circulations in cold climates, notably, the Last Glacial Maximum (LGM). It was shown that during the LGM the Aleutian low pressure system was enhanced in winter, the Pacific high pressure system was weakened in summer (Yanase and Abe-Ouchi, 2007; Yanase and Abe-Ouchi, 2010), the westerly jet shifted southward (Braconnot et al., 2007; Otto-Bliesner et al., 2006), and transient waves were weakened over the North Pacific and strengthened over the North Atlantic (Justino and Peltier, 2005; Justino et al., 2005). These works suggest that the PNA could be changed for different climate regimes. Therefore, a natural question is whether the PNA is also significantly altered due to atmospheric circulation changes at the LGM.

The LGM occurred between 23,000 and 19,000 years ago (Clark et al., 2009; Clark and Mix, 2002). One of the most significant climatic characteristics at LGM is the maximum expansion of mid-latitude ice sheets. Extensive ice sheets grew over North America and northwestern Europe, with the Laurentide ice sheet over North America, in particular, of an ice thickness of 3 to 4 kilometers (Marshall et al., 2002). Early simulations have shown that the thick and large Laurentide ice sheet forced a split of the extratropical westerly jet stream into the northern and southern branches (Cohmap, 1988; Kutzbach and Wright, 1985; Rind, 1987), and that the jet split leads to regional climate changes over the globe, especially over North America. Proxy records showed that there were more storms and precipitation associated with the southern branch, causing high lake levels and increased woodlands in the southwestern United States (Cohmap, 1988; Kutzbach and Wright, 1985).

Recent modeling studies showed that the Arctic Oscillation and storm tracks at LGM differ significantly from the present (Justino and Peltier, 2005; Laîné et al., 2009; Li and Battisti, 2008; Lü et al., 2010; Rivière et al., 2010), and that the Laurentide ice sheet can also influence the Southern-Hemisphere atmospheric teleconnection and climate variability over West Antarctic (Jones et al., 2018). Therefore, it is possible that changed atmospheric circulations at LGM might also significantly alter the PNA and thus climate linkage between the tropical Pacific and North America.

In the present paper, using climate simulation results, we show that the PNA is largely distorted or even broken by the Laurentide ice sheet at LGM, and that ENSO had little direct impact on North American climates. We will also address how the PNA is altered by the Laurentide ice sheet.

## 2 Models and data

The simulation results from the Paleoclimate Modeling Intercomparison Project 2 (PMIP2) (Braconnot et al., 2012; Braconnot et al., 2007) and 3 (PMIP3) (Abe-Ouchi et al., 2015) are utilized in this study. By comparing the PNA patterns in the Preindustrial condition (PIC) with LGM simulations as well as our own sensitivity simulations, the changes in the PNA pattern at LGM are identified. The horizonal resolution of the models we use are listed in table S1. For comparison, we also use the NCEP/NCAR reanalysis data from 1988 to 2017 (Kistler et al., 2001), with horizontal resolution of 2.5°×2.5°. We shall mainly focus on the simulation results from the Community Climate System Model version 3 (CCSM3) (Collins et al., 2006; Jones et al., 2018; Otto-Bliesner et al., 2006; Yeager et al., 2006), since our sensitivity simulations are performed with the same model.

To understand the impact of the topography of the Northern-Hemisphere glacial ice sheets on the PNA, we performed a series of sensitivity simulations with different ice sheet thicknesses, which are 0%, 20%, 40%, 60%, 80%, 100%, and 150% of the ice sheet thickness that was used in PMIP2. Note that different ice sheet reconstructions were used in PMIP2 and PMIP3 simulations. PMIP2 simulations used the ICE-5G (VM2) reconstruction ~~The ICE-5G (VM2) reconstruction is used here~~ (Peltier, 2004), while PMIP3 simulations used the ICE-6G reconstruction. In general, t~~We find that t~~he ice sheet thickness in ~~the latest~~ ICE-6G reconstruction~~, ICE-6G,~~ is ~~similar~~approximately equal to 80% of ~~the ice sheet thickness in~~ ICE-5G ~~in~~for most parts of the North American region (Figure S1). ~~Here~~In our sensitivity simulations, the case of 0% ice sheet thickness means that the thickness of the ice sheet is set to zero, but the surface albedo remains ice albedo. All other conditions ~~remain~~ are the same as that in the LGM simulations of PMIP2. The model for ~~the~~ our sensitivity simulations is a lower-resolution version of CCSM3 (T31), with horizontal a resolution of 3.8°×3.8°~~)~~. ~~, which~~ It differs from ~~that~~ the PMIP2 models (T42), with~~used in PMIP2 (T42,~~ a horizontal resolution of 2.8°×2.8°). ~~Previous work found that the lowest resolution where a poleward-propagating climatological wave train exists is T31, which corresponds to a zonal grid spacing of about 300 km in midlatitudes (Löfverström et al., 2016; Magnusdottir and Haynes, 1999). Using~~ Although the horizontal resolution in CCSM3 T31 is lower~~our simulations~~, it can~~we find that the CCSM3 at T31 resolution~~ well reproduce~~d~~ the present-day PNA pattern in the PIC simulation ~~(Fig. 2h)~~, ~~which is~~ consistent with the results in Magnusdottir and Haynes (1999) and Löfverström et al. (2016). Therefore, the results here are not sensitive to model resolutions.

~~All analyses are conducted with monthly-mean model outputs of the last 30-year simulations.~~

In the present paper, all correlation analyses are conducted with monthly-mean model outputs of the last 30-year simulations. Correlation coefficient 0.35 corresponds to the 95% confidence level for 30-year correlations.

## 3 Results

Fig. 1 shows one-point correlation maps of 500 hPa geopotential heights in DJF, with the base point near Hawaii. The correlation maps in Figs. 1a and 1b exhibit similar wave-train patterns, with centers of positive and negative correlations extending from Hawaii to North Pacific, Alberta, and finally to the Gulf Coast, respectively. Hence, the present-day PNA is reproduced reasonably well in CCSM3. In contrast, this PNA pattern is altered dramatically in the LGM simulation of CCSM3 (Fig. 1c). The negative correlation over North Pacific is reduced, and the center of positive correlation is rather weak and shifted to the Arctic. The most striking feature in Fig. 1c is that the center of negative correlation near the Gulf Coast completely disappears. The results in Fig. 1 indicate that the PNA teleconnection is largely distorted at LGM. This is the most important point of the present paper.

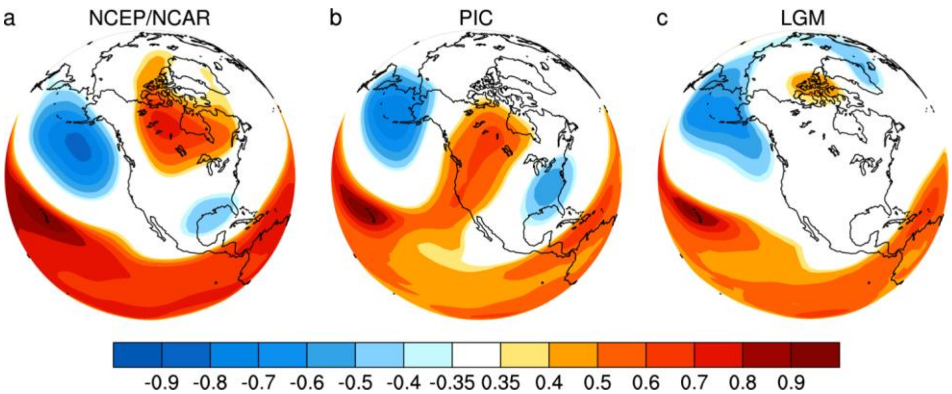



**Fig. 1.** One-point correlation maps of 500 hPa geopotential heights in DJF in NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. (a) NCEP/NCAR, (b) PIC, and (c) LGM. The base point is near Hawaii. The correlation coefficient of 0.35 corresponds to the 95% confidence level for 30-year correlations.

This distorted PNA at LGM can also be seen from correlation maps for the other three base points. When the base point is located over North Pacific (Fig. S2~~1~~c), the center of positive correlation over North America is shifted to northern Canada. For the base point over North America (Fig. S2~~1~~f), the negative correlations over North Pacific and the Gulf Coast are all largely reduced, and the center of positive correlation near Hawaii disappears. This result indicates a disconnection between North America and the tropical Pacific. For the base point near the Gulf Coast (Fig. S2~~1~~i), a wave train is established from North Pacific to the Gulf Coast, while the center of positive correlation over North America is largely reduced, and the center of positive correlation near Hawaii is absent.

The PNA teleconnection at LGM is even completely broken in other PMIP2 models. There are seven PMIP2 models that have simulations available online. According to our definition, CCSM3, ECBILTCLIO, HadCM3M2, and CNRM-CM33 can reasonably reproduce the PNA in their PIC simulations (Fig. 1b and Figs. S3~~2~~a-c), whereas IPSL-CM4-V1-MR, FGOALS-1.0g, and MIROC3.2 have poor performance. In LGM simulations, the center of negative correlation over North Pacific still exists in ECBILTCLIO, HadCM3M2, and CNRM-CM33 (Figs. S3~~2~~d-f), although they all shift away from the North Pacific base point and are largely reduced. However, the center of positive correlation over North America completely disappears in these plots. Moreover, the center of negative correlation near the Gulf Coast also disappears in the three models.

PMIP3 simulations are also used to demonstrate the changes in the PNA teleconnection at LGM. There are eight PMIP3 models that have LGM simulations available online. Again, according to our definition, CCSM4, MRI-CGCM3, and MIROC-ESM can reasonably reproduce the PNA in their PIC simulations (Figs. S4~~3~~a-c). The LGM simulations of CCSM4 and MRI-CGCM3 show the absence of the center of positive correlation over North America (Figs. S4~~3~~d and e). The center of positive correlation in MIROC-ESM is weak and biased toward the Arctic (Fig. S4~~3~~f). The center of negative correlation near the Gulf Coast is absent in MRI-CGCM3 and MIROC-ESM. Although there is a negative center in CCSM4 (Fig. S4~~3~~d), it is more like a result of the subtropical wave train, rather than a part of PNA. Thus, the LGM simulations in PMIP3 models demonstrate that the PNA is either distorted or completely broken.

We have also done Empirical Orthogonal Function (EOF) and rotated EOF (REOF) analysis to examine the PNA pattern for both LGM and PIC simulations (figures not shown here). It is found that the second REOF modes in both the NCEP reanalysis and the CCSM3 PIC simulation all well represent the loading pattern of the present-day PNA. However, the second REOF in the CCSM3 LGM simulation does not show the PNA pattern. The third and fourth REOFs in the

LGM simulation show teleconnections between North Pacific and Arctic as well as between North Pacific and the southern part of North America.

Fig. 2 illustrates PNA responses to different ice sheet thicknesses in sensitivity simulations. The PNA pattern remains for ice sheet thicknesses no more than 60% of that in PMIP2 (Figs. 2a-d). In contrast, the PNA is distorted as ice sheet thickness is increased to 80%. The center of positive correlation is shifted to the Arctic, and the center of negative correlation near the Gulf Coast disappears (Fig. 2e). As ice sheet thickness is further increased to 100 % and 150% (Figs. 2f-g), the center of positive correlation over North America disappears. Again, the center of negative correlation is more like a part of the subtropical wave train. These results of sensitivity simulations suggest that the PNA is distorted or even broken as the Laurentide ice sheet is sufficiently thick.

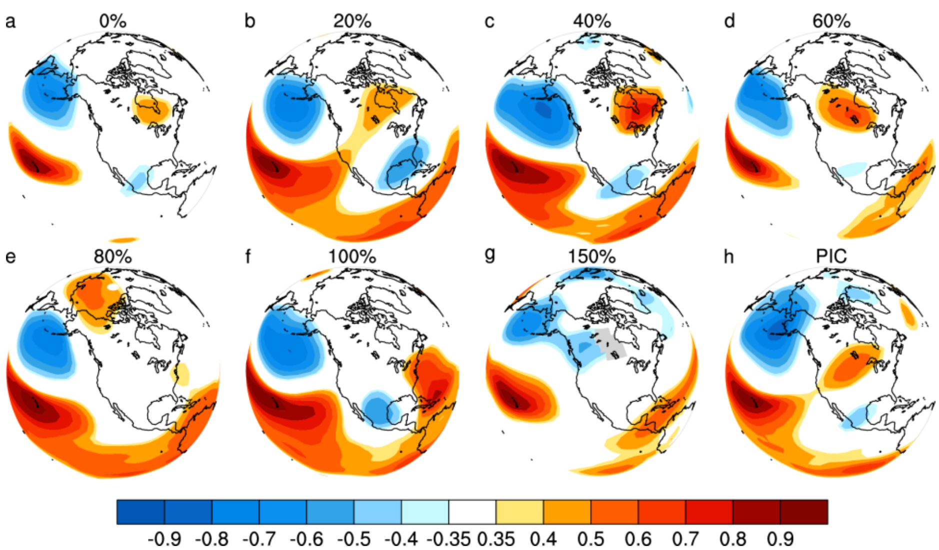
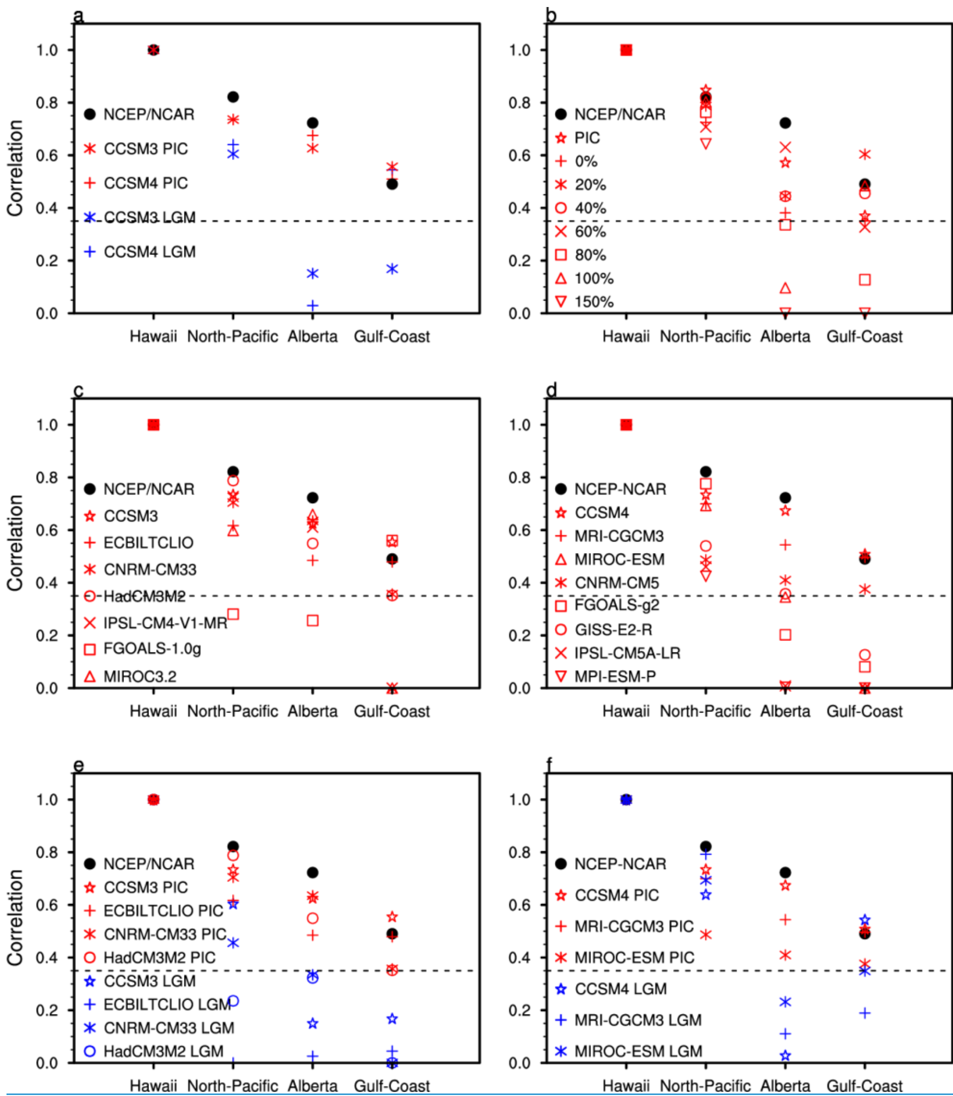



**Fig. 2.** One-point correlation maps of 500 hPa geopotential heights in DJF in sensitivity simulations, with different ice sheet thicknesses. The base point is near Hawaii. (a) 0%, (b) 20%. (c) 40%, (d) 60%, (e) 80%, (f) 100%, (g) 150%, and (h) PIC. The correlation coefficient of 0.35 corresponds to the 95% confidence level for 30-year correlations.

Fig. 3 summarizes correlation coefficients around the four base points for PMIP2, PMIP3, and our sensitivity simulations, according to our definition above. In Fig. 3a, both CCSM3 and CCSM4 show statistically significant correlations at all the four points in the PIC simulations. In contrast, they all demonstrate insignificant correlations near Alberta in LGM simulations. The significant correlation of CCSM4 LGM simulation near the Gulf coast is a result of subtropical wave train (Fig. S4~~3~~d), as mentioned above. In Fig. 3b, the correlation coefficient near Alberta becomes less significant as ice sheet thickness reaches 80%. Correlation coefficients at the Gulf coast are insignificant for 80% and 150% ice sheet thickness. The significant correlation for 100% ice sheet thickness is a result of subtropical wave train, as shown in Fig. 2f.



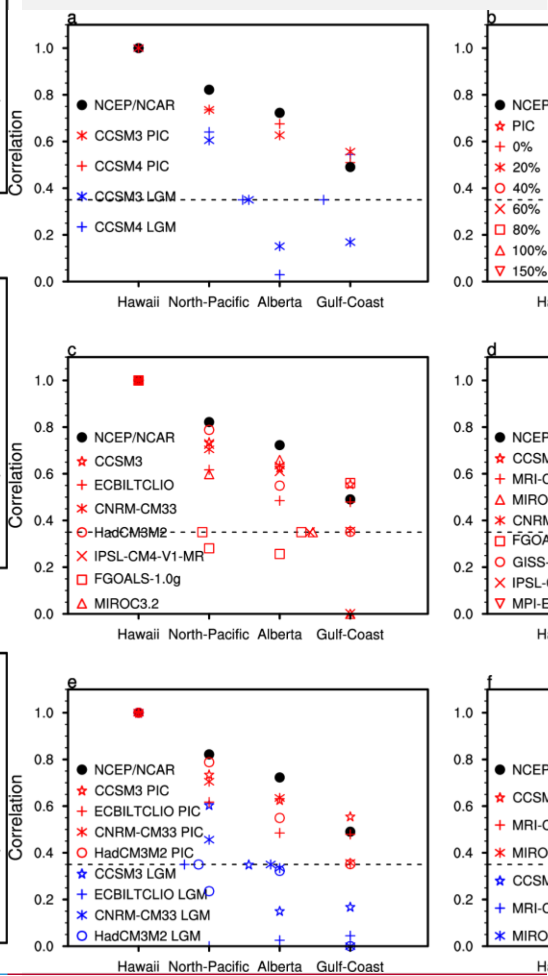



**Fig. 3.** Correlation coefficients at the four PNA action centers in PIC and LGM simulations for PMIP2 and PMIP3 models, with the base point near Hawaii. The negative values over ~~Alberta~~ North Pacific and the Gulf Coast are reversed to positive. The dashed lines correspond to 0.35, which represent the 95% confidence level. (a) CCSM3 and CCSM4, (b) sensitivity simulations, (c) PIC simulations of PMIP2 models, (d) PIC simulations of PMIP3 models, (e) LGM and PIC simulations for well-performing PMIP2 models~~comparison of LGM with PIC simulations for~~

~~PMIP2 good performance models~~, and (f) LGM and PIC simulations for well-performing PMIP3 models~~comparison of LGM with PIC simulations for PMIP3 good performance models~~.

Figs. 3c and d shows that most PMIP2 and PMIP3 models are able to reproduce the center of negative correlations over the North Pacific in their PIC simulations, except for FGOALS-1.0g~~.,~~ ~~IPSL-CN4-V1-MR, and MIROC3.2.~~ FGOALS-1.0g that generates insignificant correlations at either North Pacific or Alberta. CNRM-CM33 and MIROC3.2 cannot generate significant correlations near the Gulf coast. Fig. 3d shows that CCSM4, MRI-CGCM3, and MIROC-ESM are able to reproduce significant correlations at all four points in their PIC simulations, whereas the other 5 models have insignificant correlations at either Alberta or the Gulf Coast. Figs. 3e and f show that PMIP2 and PMIP3 models, which have good performance in simulating the PNA teleconnection in PIC simulations, all cannot reproduce significant positive correlations at Alberta or even negative correlations near the Gulf coast in the LGM simulations. These results all suggest that the PNA was distorted or broken at LGM.

Because the PNA pattern is characterized by a quasi-stationary wave train from the tropical Pacific to North America, the above simulation results suggest that the PNA wave-train propagation is largely altered at LGM. This can be confirmed by activity fluxes of stationary waves at 500 hPa calculated, using equation 7.1 in Plumb (1985) (Fig. 4), which represents the propagation direction of stationary waves (Plumb, 1985). At present, the wave activity fluxes have two branches for wave propagation from the North Pacific toward North America (Fig. 4a). The major branch propagates northeastward, forming the PNA teleconnection, while the minor branch propagates southeastward. At LGM, however, wave propagation is altered drastically. Wave propagation is deflected toward the subtropics (Figs. 4b and c). This is consistent with the correlation map in Fig. S2~~1~~i that shows a wave train from North Pacific to the Gulf Coast.

Therefore, the distorted or broken PNA at LGM is mainly due to the deflection of wave propagation toward the southeast.

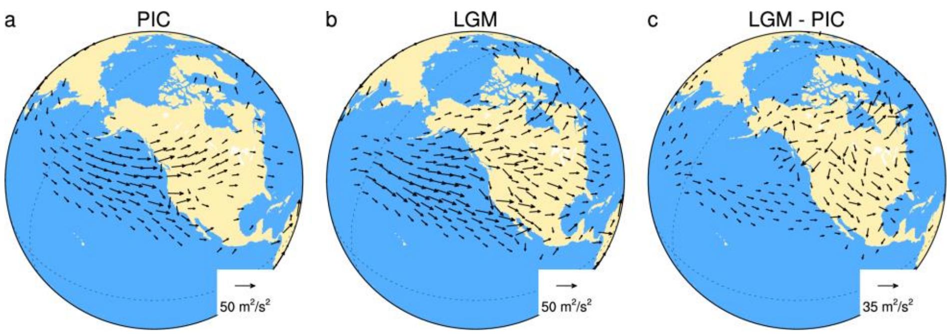



**Fig. 4.** Stationary wave activity fluxes in PMIP2 CCSM3 simulations at 500 hPa. (a) PIC, (b) LGM, and (c) LGM – PIC. Length scales of wave activity vectors are marked in plots. Wave activity vectors are plotted as their length scales are greater than 12 $m^2 s^{-2}$ in plots (a) and (b) and 6.5 $m^2 s^{-2}$ in plot (c). Here, stationary wave activity fluxes are calculated with monthly-mean data.

Wave propagation is oriented by the extratropical wave guide, which in turn is determined by extratropical zonal flows (Hoskins and Karoly, 1981; Jin and Hoskins, 1995). Therefore, the deflection of stationary wave propagation at LGM is caused due to changes in extratropical zonal flows. A comparison of zonal winds between PIC and LGM simulations shows several major differences (Figs. 5a vs. 5b). First, the zonal jet stream is much stronger at LGM than at present. Second, the jet is shifted equatorward at LGM, and the jet is turned southeastward as it approaches the North American continent, in contrast to the northeast orientation at present. Third, similar to that in early studies (Cohmap, 1988; Kutzbach and Wright, 1985; Rind, 1987), the jet splits over North America with the much stronger branch located in the subtropics, leaving the much weaker branch over northern Canada. These features can be seen more clearly in differences of zonal winds between LGM and PIC simulations (Fig. 5c).

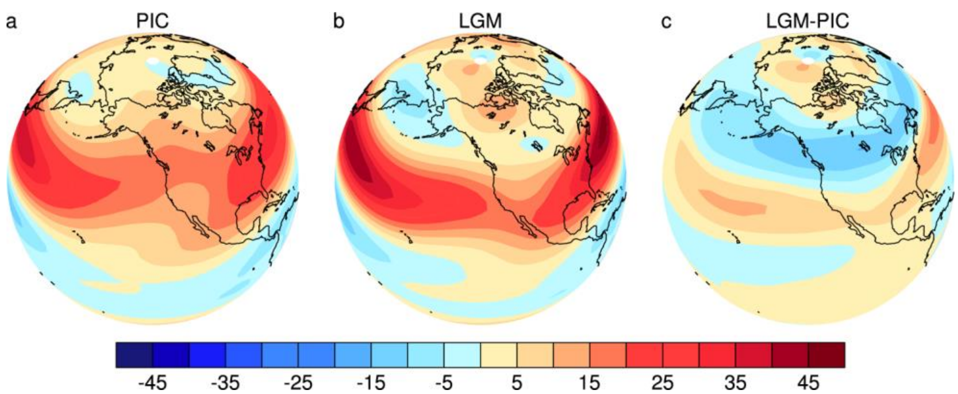
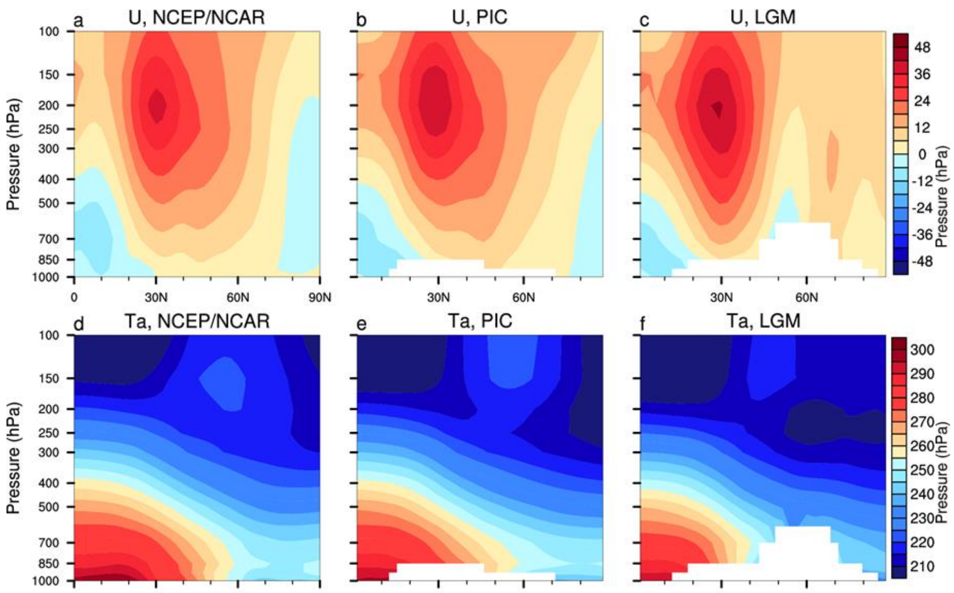



**Fig. 5.** Maps of 500 hPa zonal winds in DJF in PMIP2 CCSM3 simulations. (a) PIC, (b) LGM, and (c) LGM – PIC. Color interval: 5 m $s^{-1}$.

Differences of zonal winds over North America~~n~~ can also be illustrated with the vertical cross-sections along 100 °W (Fig. 6). The single subtropical westerly jet in the PIC simulation (Fig. 6b) is split into two jets at LGM (Fig. 6c): a subtropical jet at 30 °N and 200 hPa, and a subpolar jet at 63 °N and between 400 and 300 hPa. The subtropical jet is intensified to a maximum wind speed of 40 m $s^{-1}$ and is located at a lower latitude, and it is much stronger than that in the PIC simulation (~ 30 m $s^{-1}$). The subpolar jet is much weaker, with a maximum speed of about 12 m $s^{-1}$. The differences in zonal winds are associated with different thermal structures between LGM and PIC simulations. Comparison of Figs. 6f with 6e shows that latitudinal temperature gradients in the subtropics are sharper at LGM than at present. Thus, the stronger subtropical jet is associated with the sharper temperature gradient.



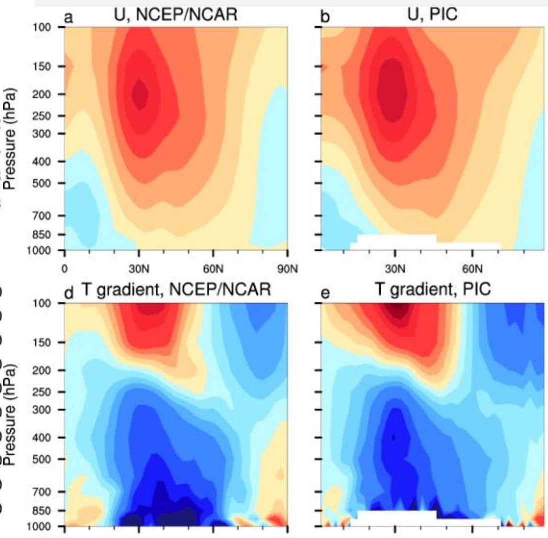



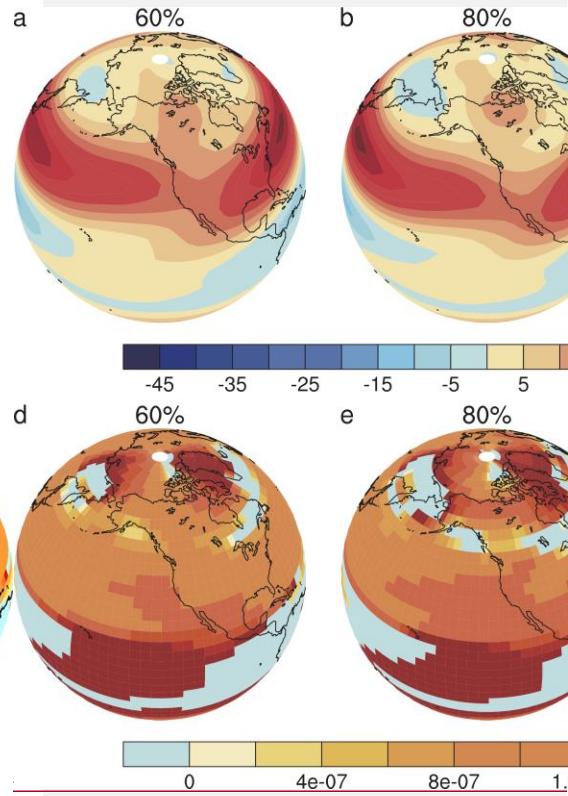

**Fig. 6.** Vertical cross sections of DJF zonal winds and meridional temperature gradients along the longitude of 100 °W in the NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. Top panels: zonal winds, and bottom panels: temperature gradients. Left panels: NCEP/NCAR, middle panels: PIC, and right panels: LGM. Zonal-wind unit is ms-1, and temperature gradient unit is K/(1000 km).~~Fig. 6. Vertical cross sections of DJF zonal winds and meridional temperature gradientsair temperatures along the longitude of 100 °W in the NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. Top panels: zonal winds, and bottom panels: meridional temperature gradientsair temperatures. Left panels: NCEP/NCAR, middle panels: PIC, and right panels: LGM. Zonal-wind unit is ms-1, and temperature unit is K/(1000 km).~~

The jet split and the equatorward shift of the major jet branch are caused by the orographic forcing of the large and thick Laurentide ice sheet. Fig. S5~~4~~ shows how the westerly jet responds to the ice sheet thickness in the sensitivity simulations. In the case with 0% ice sheet thickness, there is only a single jet in the subtropics (Fig. S5~~4~~a), almost the same as that in the PIC simulation. As ice sheet thickness is increased, the jet is strengthened associated with the sharper meridional temperature gradient (Fig. S6~~5~~), and ~~shows equatorward shift~~the core of the jet becomes narrower. Significant jet splitting occurs as ice sheet thickness reaches 80% (Fig. S5~~4~~e). It is the reason why the distortion of the PNA occurs as ice sheet thickness reaches 80%. As the ice sheet thickness is increased to 100% and 150%, the jet split becomes more significant, and easterly winds begin to develop over the ice sheet.

Note that the orographic forcing is further reinforced by the thermal forcing of the large ice sheet (Liakka, 2012). The high albedo of the ice sheet causes cold air aloft, resulting in sharper latitudinal temperature gradients in the subtropics at LGM. Thus, this enhanced temperature gradient causes a stronger subtropical jet through the thermal wind relation. Our sensitivity simulations also show that subtropical temperature gradients become sharper with increasing ice sheet thicknesses.

The split of the westerly jet acts as wave guides to orient wave propagation, as shown in Fig. 4. The major path of wave propagation is associated with the major jet branch. Both Figs. S2~~1~~c and S2~~1~~i all show that a southern wave train is established along the southern jet branch from North Pacific sweeping across the southern US. This wave train would lead to more storms and precipitation in the American Southwest, consistent with proxy records and previous modeling studies (Cohmap, 1988). The minor path of wave propagation toward the Arctic is along with the northern branch (Fig. 1c), but of a much reduced strength. As such, a southern wave guide is established along the subtropical jet, while the northern wave guide is either distorted toward the Arctic or completely broken.

Our sensitivity simulations demonstrate dramatic changes in the PNA wave train between 80% and 100% ice sheet thicknesses (Fig. 2e vs. Fig. 2f). The dramatic changes are associated with the occurrence of easterly winds over the Laurentide ice sheet (Figs. 7a-c). For the case of 80% ice sheet thickness, westerly winds remain between the two jet streams (Fig. 7b). In contrast, easterly winds appear over the ice sheet as the ice sheet thickness is increased to 100% (Fig. 7c). The zero-wind line between easterly and westerly winds acts as the critical layer to reflect stationary waves (Held, 1983). This can be addressed with calculations of critical stationary wavenumbers (Fig. 7 d-f) (eq. 6.29 in Held (1983)). The orange-red shading indicates the areas where stationary waves can propagate, while the shallow-blue shading indicates the areas with imaginary wavenumbers, in which propagation of stationary waves is prohibited. These shallow-blue areas are associated with the easterly winds. When the ice sheet thickness is 60% (Fig. ~~7a~~7d), North Pacific and North America are dominated with positive wavenumbers, and the PNA remains. For 80% ice sheet thickness, imaginary wavenumbers occur in Northeast Pacific and North America (Fig. ~~7b~~7e), and it forces the PNA wave train distorted toward the Arctic. For 100% ice sheet thickness, the subpolar region is dominated with imaginary wavenumbers (Fig. ~~7c~~7f). It causes stationary waves reflected southeastward, leading to the establishment of the southern wave train and the breaking up of the northern wave train.



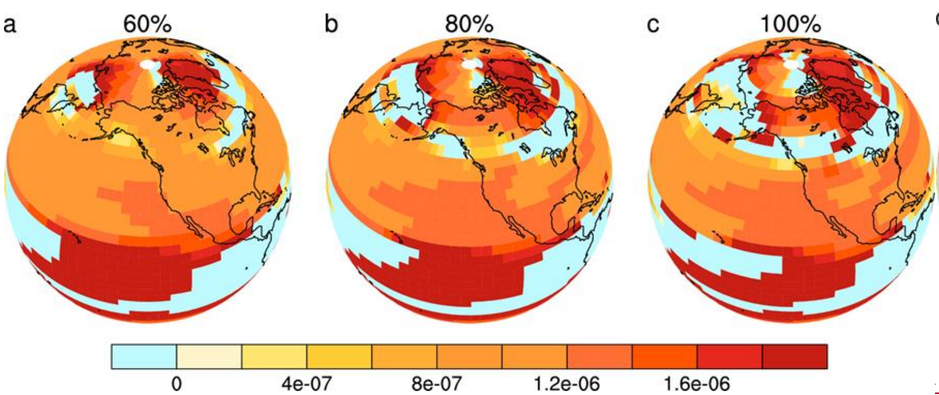




**Fig. 7.** Distributions of zonal winds and ~~critical~~ stationary wavenumbers for different ice sheet thicknesses in sensitivity simulations in DJF. Top panels: zonal winds, and bottom panels: ~~critical~~ stationary wavenumbers. (a, d) 60%, (b, e) 80%, and (c, f) 100%. Zonal-wind unit is m s$^{-1}$, and ~~critical~~ stationary wavenumber unit is m$^{-1}$ ~~Color interval is 0.2x10$^{7}$ m$^{-1}$~~. The shallow-blue areas in the bottom panels have imaginary wavenumbers.

The occurrence of easterly winds can be further illustrated with the geopotential heights at 500 hPa (Fig. 8). In both NCEP/NCAR reanalysis and the PIC simulation, there is only a weak ridge along the west coast of North America (Figs. 8a and b). In contrast, the ridge at LGM is largely enhanced and shows northwestern tilting (Fig. 8c). It is this strong ridge that leads to altered zonal flows. The major branch moves equatorward, and the minor branch flows around the ridge northward, resulting in the formation of easterly winds over the ice sheet and North Pacific. It also can be seen in the sensitivity simulations that the west-coast ridge increases with increasing ice sheet thickness (Fig. S7~~65~~).

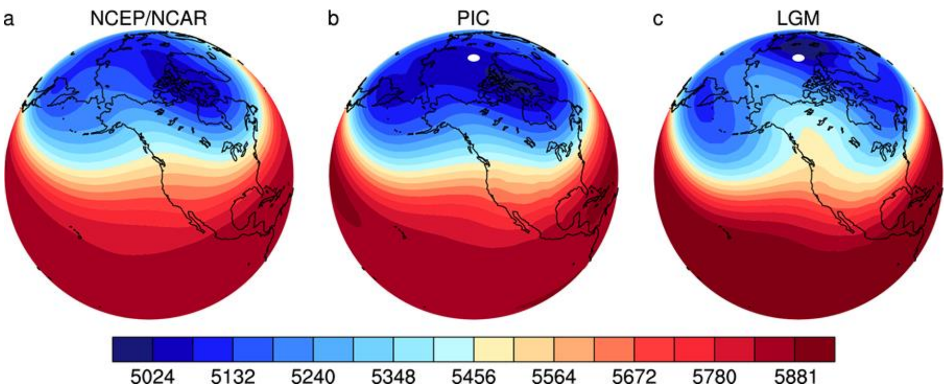



**Fig. 8.** Climatological mean 500 hPa geopotential heights in DJF in NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. (a) NCEP/NCAR, (b) PIC, and (c) LGM. The unit is meter.

The distorted or broken PNA teleconnection at LGM suggests a disconnection of climate variability from the tropical Pacific to the North American continent, such that ENSO would have little direct influence on North American climates. Fig. 9 shows regression maps of surface air temperatures (SATs) on the Nino3.4 index in DJF. At present, the remote ENSO impacts on North American SATs through the PNA teleconnection can be identified clearly (Figs. 9a and 9b), which is characterized by an anomalously warm climate over the northwestern North America and an anomalously cold climate over the southeastern United State. However, there are no significant regressions of SATs over North America at LGM (Fig. 9c), except for the positive values near the east coast.

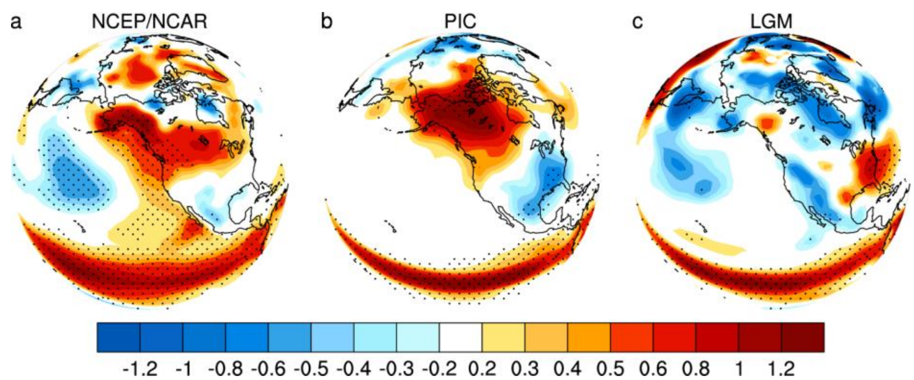



**Fig. 9.** DJF SAT regressions on the Nino3.4 index in NCEP/NCAR reanalysis and PMIP2 CCSM3 simulations. (a) NCEP/NCAR reanalysis, (b) PIC, and (c) LGM. The regression value of 0.21 corresponds to the 95% confidence level for 30-year regressions.

At present, ENSO also has important influences on North American precipitation. Similar features can also be seen from regression maps of precipitation (Fig. 10). Fig. 10a shows precipitation regression on the Nino3.4 index in the PIC simulation. The wave train pattern of precipitation is clearly shown in the plot. However, the wave train of precipitation is absent in the LGM simulations (Fig. 10b).

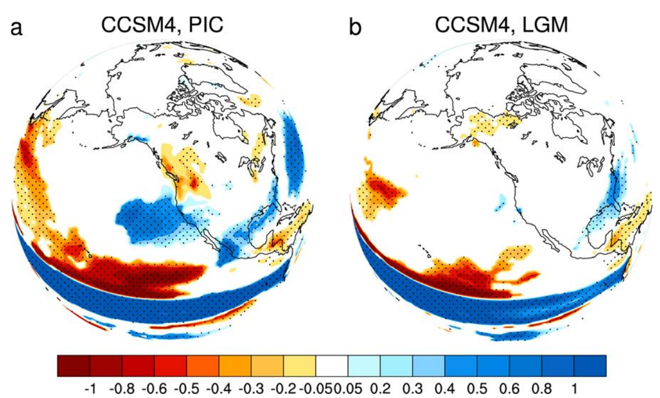



**Fig. 10.** Precipitation regressions on the Nino3.4 index in the CCSM4 PMIP3 simulations. (a) PIC, and (b) LGM. Dotted areas indicate significant regressions for the 95% confidence level for 30-year regressions.

## 4 Conclusions and Discussions

We have shown~~ed~~ in climate simulations that the large and thick Laurentide ice sheet at LGM forced jet splitting and the formation of easterly winds over North America. It consequently causes altered wave guides and distorted or broken PNA. It appears that the PNA was separated into two teleconnections at LGM. One is from North Pacific to Arctic, and the other one is from North Pacific to the southern part of North America.

This result suggests that ENSO would ~~not~~ have little direct influence on North American climates at LGM. Our study provides a dynamic framework to understand the PNA teleconnection not only at LGM but also in other glacial periods. This understanding may help us interpreting proxy records in the past. For example, a previous study on varve record in New England linked the change of the intensity of interannual variability in the northeastern US during the early glacial period to the change of ENSO intensity (Rittenour et al., 2000). Our study suggests that this interannual variability is unlikely to be caused by the climate variability from the tropical Pacific, because of the distorted or broken PNA teleconnection; instead, it reflects mainly the change of local climate variability (Liu et al., 2014). Much further work is needed in developing proxy records of high temporal resolutions to identify the PNA change in paleoclimate records.

Previous works have shown weaker ENSO variability at LGM (Zhu et al., 2017). How the weaker tropical variability would impact climates over extratropics and high-latitudes, through the altered atmospheric teleconnections, deserves future studies.

## Acknowledgements

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