Thermal forcing expected to modulate convection in a mechanically forced stationary wave

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This is a reply to the comment by Lofverstrom and Thirumalai [1] on our publication in *Nature* [2]. That comment and this reply underwent peer review at *Nature*, and *Nature* declined to publish the exchange.

Lofverstrom and Thirumalai [1] make three arguments that they claim refute the main conclusion of our prior work [2], which was that the core North American monsoon (NAM) consists of convectively enhanced orographic rainfall in a mechanically forced stationary wave. Here we explain why their arguments do not refute that conclusion, and why further research is needed to explore not only why but whether core NAM precipitation was different in the mid-Holocene (∼6 ka). We note that we agree with their titular assertion—that thermal forcing modulates the intensity of the North American monsoon—because such modulation was how we accounted for the NAM seasonal cycle.

In their first argument, Lofverstrom and Thirumalai (hereafter LT22) imply that mechanically forced stationary waves cannot exist in the NAM region due to some combination of the easterly flow that we showed would exist there in the absence of orography (Fig. 1c of our prior work [2], hereafter BP21) and what they claim is a dominance of ageostrophic flow in that region. However, the existence of stationary waves over Mexico was well-established when the Great Plains Low-Level Jet was shown to be caused by the mechanical influence of orography [3]. Our nonlinear numerical solution further demonstrated that near-surface eastward flow up the western slopes of the Sierra Madre Occidental (SMO) is part of an adiabatic stationary wave; this wave did, indeed, penetrate into a region of basic easterlies (Fig. 2c,d and Extended Data Fig. 5 of BP21). Although assumptions commonly used in simple stationary wave theory, such as linearity, horizontal non-divergence, and the absence of basic-state meridional flow, are not valid here, the adiabatic response to orography nevertheless looks like a classic extratropical stationary wave arcing along a great circle over North America (Fig. 1 shows this in a larger domain than was presented in BP21).

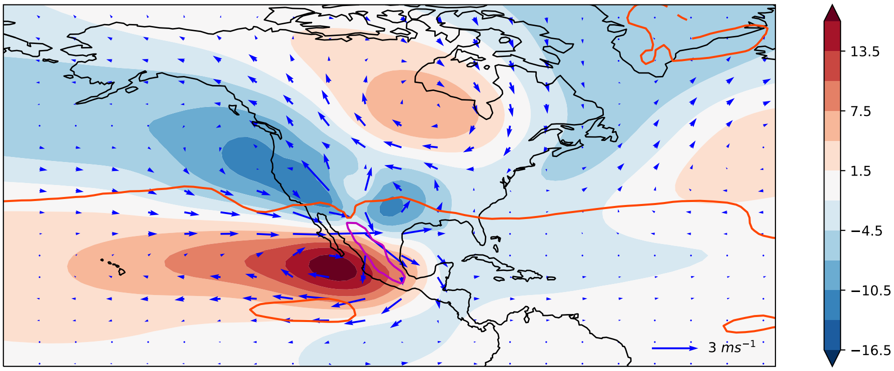

Fig. 1 Large-scale structure of the stationary wave mechanically forced by the Sierra Madre Occidental. The anomalous 700-hPa horizontal wind (vectors) and its streamfunction (shading, in metres; air flows clockwise around maxima) for the stationary wave model forced by the Sierra Madre Occidental (SMO; outlined in magenta). The thick orange line is the zero contour of the basic-state zonal wind, which near 35°N divides westward trade winds from eastward extratropical flow. The streamfunction has been normalized by the gravitational acceleration and Coriolis parameter at 45° N, giving it the units of geopotential height. This illustrates the structure of the wave in a larger domain than was shown in prior work [2], with the wave arcing northward from its source across North America into the Atlantic, but evanescing as it penetrates southward from the source deeper into the basic-state tropical easterlies. Mapping software: Cartopy with Natural Earth shapefiles.

The jet stream over the East Pacific lies far poleward of the NAM during boreal summer, which LT22 suggest makes a dynamical link between it and the NAM implausible. However, the Rocky Mountains deflect this jet toward the equator, creating southeastward flow along the west coast of North America in what LT22 mark as the "LLJ" in their Fig. 1. Ting and Wang [3] summarized this effect more than 15 years ago: "strong midlatitude westerlies over the North Pacific encounters the North American Cordillera and turn both northward and southward ... A strong cyclonic region develops over the Rockies" (see their Figs. 2c and 5d). Our finer-resolution stationary wave solutions demonstrated that the southern tip of the North American Cordillera (i.e. the SMO) extends this jet deflection into Mexico, with relevance for the NAM. The dynamical link between the East Pacific jet stream at 50°N and flow near the SMO was thus demonstrated by prior work, which BP21 referenced.

In their second main argument, LT22 claim that global climate model (GCM) simulations of the mid-Holocene disprove the main conclusion of BP21 because they feature both enhanced NAM precipitation and a poleward-shifted extratropical jet stream. We agree that, if BP21 is correct, a weakening of the extratropical jet should reduce core NAM precipitation, *all else being equal* (a poleward jet *shift* may have a similar effect, but this is not a forgone conclusion). However, BP21 discussed how the thermodynamic background state in which mechanically forced uplift occurs can also modulate NAM precipitation, with that thermodynamic state characterized by the moist static energy of surface air (h_s; BP21 Fig. 3c). This was stated in BP21: "core NAM precipitation ... requires mechanical forcing by the SMO, producing eastward, upslope flow that organizes convection to occur in a small part of a horizontally extensive pool of high-h_s air. The seasonal cycle of insolation generates that pool of high-h_s air in summer, with the diurnal cycle of insolation further enhancing h_s over coastal Mexico in afternoons." We thus expect the orbital forcing that enhanced Northern Hemisphere insolation during mid-Holocene boreal summer to alter h_s over and around Mexico, influencing moist convection in the mechanically forced stationary wave. Mid-Holocene jet shifts and local thermodynamic changes may thus exert competing effects on NAM precipitation. We suggest that these effects should be examined in a thorough study of GCM simulations performed at resolutions fine enough to well-resolve the SMO and the NAM, as compared to the coarse resolutions used in the PMIP4 models analyzed in LT22. Indeed, contrary to the assertion of LT22, a prior analysis of the PMIP4 models did not find a robust response of the NAM [4]: "Ensemble mean changes in the North American Monsoon System, and the Southern Hemisphere monsoons are also small ... and less consistent across the ensemble". We also suggest that future research should examine proxy data at locations in the core NAM precipitation maximum, as opposed to far southern Mexico (Fig. 2b of LT22) where BP21 suggested that a classic, thermally forced monsoon regime may exist.

The third argument made by LT22 is that the existence of a strong diurnal cycle over the western SMO implies that the core NAM is thermally forced. Specifically, they claim that diurnally reversing horizontal winds average to zero in the time mean, while the positive-definite nature of precipitation results in strong seasonal-mean rainfall. However, prior studies found that seasonal-mean core NAM precipitation was produced by seasonal-mean winds [5], a result discussed and confirmed by BP21 (Extended Data Fig. 4 of BP21). One can thus explain seasonal-mean core-NAM precipitation by explaining seasonal-mean upslope flow over the western SMO, which was the task undertaken by BP21. Furthermore, given a narrow region of strong mechanical uplift within a broader area of large convective available potential energy (CAPE), one would expect diurnal forcing of CAPE (or h_s) to result in a diurnal cycle of precipitation (e.g. Fig. 3a, b of BP21 and related discussion); one would also expect that forcing to produce an oscillation in wind about a non-zero seasonal-mean eastward flow, as observed (Extended Data Fig. 1 of LT22 and Fig. 1a of BP21). This is not to say that diurnal and subseasonal transients are irrelevant for the NAM. Synoptic transients contribute to moisture flux convergence north of the core NAM [5], e.g. in the southwestern United States; accounting for disturbances such as Gulf of California moisture surges is thus likely important for understanding precipitation in that more arid region. Despite the criticism of LT22, analyzing the influence of thermal forcing on these moisture surges is thus of little relevance to the core NAM.

In summary, we agree that more work is needed to understand the mechanisms governing NAM precipitation in past climates such as the mid-Holocene, and that additional simulations (e.g. with many more combinations of SMO heights and land surface albedos) may help in such efforts. Paleoclimate investigation, however, fell outside the scope of BP21, and the mid-Holocene jet-stream shifts and NAM precipitation changes simulated by a collection of coarse-resolution GCMs are not obviously inconsistent with the main conclusion of BP21. Other issues raised by LT22 were addressed in prior work cited by BP21, such as the nonlinear stationary wave dynamics that allow the Rocky Mountains to deflect the North Pacific jet stream from 50°N toward the SMO [3], and why the existence of a diurnal cycle of precipitation does not imply the core NAM is primarily thermally forced [2, 5, 6].

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Data availability. The data plotted in this document were generated by reference [2] and archived at https://doi.org/10.5281/zenodo.5076509.

References

[1] Lofverstrom, M., Thirumalai, K.: Thermal forcing modulates north american monsoon intensity. EarthArXiv (2022). https://doi.org/10.31223/X5Q634

[2] Boos, W.R., Pascale, S.: Mechanical forcing of the north american monsoon by orography. Nature 2021 599:7886 **599**, 611–615 (2021). https://doi.org/10.1038/s41586-021-03978-2

[3] Ting, M., Wang, H.: The role of the north american topography on the maintenance of the great plains summer low-level jet. Journal of the Atmospheric Sciences **63** (2006). https://doi.org/10.1175/JAS3664.1

[4] Brierley, C.M., Zhao, A., Harrison, S.P., Braconnot, P., Williams, C.J.R., Thornalley, D.J.R., Shi, X., Peterschmitt, J.Y., Ohgaito, R., Kaufman, D.S., Kageyama, M., Hargreaves, J.C., Erb, M.P., Emile-Geay, J., D'Agostino, R., Chandan, D., Carré, M., Bartlein, P.J., Zheng, W., Zhang, Z., Zhang, Q., Yang, H., Volodin, E.M., Tomas, R.A., Routson, C., Peltier, W.R., Otto-Bliesner, B., Morozova, P.A., McKay, N.P., Lohmann, G., Legrande, A.N., Guo, C., Cao, J., Brady, E., Annan, J.D., Abe-Ouchi, A.: Large-scale features and evaluation of the pmip4-cmip6 midholocene simulations. Climate of the Past **16** (2020). https://doi.org/10.5194/cp-16-1847-2020

[5] Berbery, E.H.: Mesoscale moisture analysis of the north american monsoon. Journal of Climate **14**, 121–137 (2001). https://doi.org/10.1175/1520-0442(2001)013⟨0121:MMAOTN⟩2.0.CO;2

[6] Barlow, M., Nigam, S., Berbery, E.H.: Evolution of the north american monsoon system. Journal of Climate **11**, 2238–2257 (1998). https://doi.org/10.1175/1520-0442(1998)011⟨2238:EOTNAM⟩2.0.CO;2