Replies to Anonymous Referee #2

Original comments received and published: 6 January 2020

This is an interesting paper assessing how cyclone activity differed in parts of the northern hemisphere during the last glacial maximum. The paper is well written and the results are interesting, particularly the cyclone composites from the regional model simulations showing the different cyclone impacts between the two periods.

Answer: We want to thank the Reviewer and the Editor for the thorough examination and positive assessment of our manuscript. We reply point-by-point to the Reviewer's comments or give detailed arguments about our reasoning for those cases in which we did not follow a Reviewer suggestion. Our responses are shown in red color. Text from the manuscript is identified by quotation marks and italic font style, added or modified text can be identified by red color.

My major comment is that the ice sheets and sea level change resulted in quite substantial differences in topography, MSLP etc between the two periods, which influences how the tracking scheme functions. I think there would be a great deal of value in using a higher level in the atmosphere (e.g. 500hPa) for identifying cyclones to assess how robust the observed changes are. I recognise that this is difficult (due to the time involved) or possibly impossible, depending on what data exists for the global model, but it could provide some useful insights, even just from the WRF simulations.

A: we thank the reviewer for this suggestion. As the reviewer correctly assumes, it would be very time consuming and in our opinion little informative to perform the tracking of cyclones at 500 hPa within the scope of this manuscript. Cyclones are typically tracked based on surface or near-surface fields, e.g. MSLP or relative vorticity at 850 hPa geopotential height (see Neu et al., 2013 for a description and comparison of many methodologies). In fact, the 500 hPa geopotential height field does not typically feature closed pressure systems, but rather troughs and ridges. In line with the reviewers suggestions, we thought about prepaing an additional figure showing the 500 hPa storm track field for the reanalysis, PI and LGM conditions. The storm track shows the variance of the 500 hPa geopotential height within the synoptic scale and is this a measure of synoptic activity (Hoskins and Valdes, 1990). Unfortunately, no 6-hourly nor even daily pressure level data is available in the PMIP3 database. This is why we have estimated the storm track in Ludwig et al. (2016) based on the MSLP fields (here also used for the cyclone tracking, see new Fig. S1). While a conversion between the MPI-ESM-P data from model levels to pressure levels is possible in principle, we have refrained from taking this path as we expect little added information compared to the MSLP storm track (Ludwig et al., 2016) and cyclone track information (here)

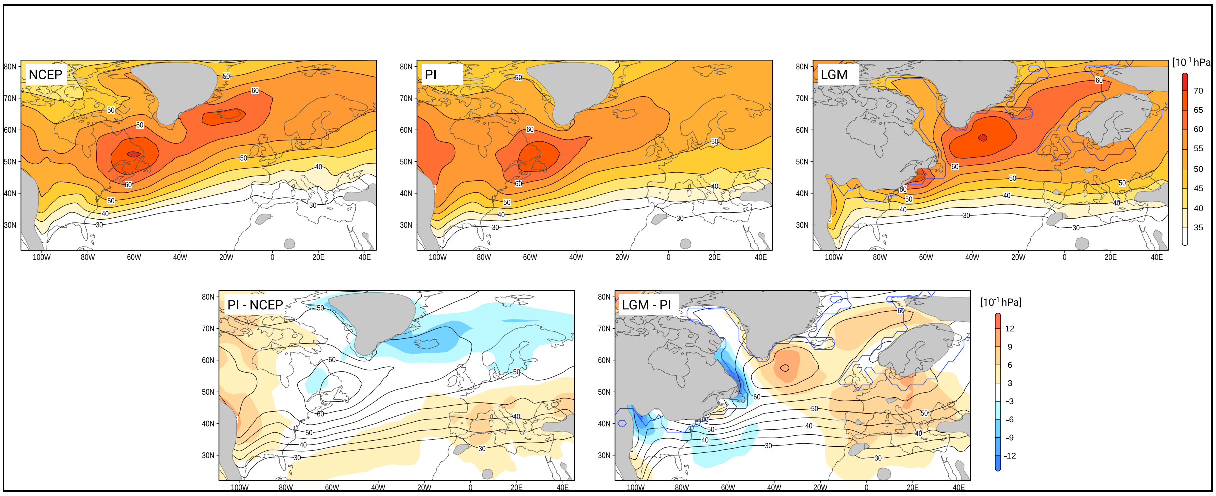


Fig. S1: Top: storm tracks (2–6 days band passed filter of daily MSLP data [1/10 hPa]) for the NCEP Reanalysis data and the MPI-ESM-P simulations for PI and LGM. Bottom: differences (shaded) between PI (lines) and NCEP and between LGM (lines) and PI. Areas with topography higher 1000 m shaded grey, LGM ice sheet extent marked by the blue line.

We agree with the reviewer that looking at the vertical structure of the cyclones (see Dacre et al., 2012; their Fig. 4 https://doi.org/10.1175/BAMS-D-11-00164.1) in WRF for LGM and PI conditions would be very interesting. While we think this does not fit well with the scope of the present study, we will surely look into this in the future.

Minor comments:

L89 - I would appreciate more information on why this specific global model was chosen, especially as you say its large-scale circulation is different from other models. Please also note its spatial resolution.

A: We are based in Germany and we had access via the DKRZ to the 6-hourly 3D MPI-ESM-P fields. These served as boundary conditions for the WRF simulations. Please note that the surface and atmospheric fields stored on the PMIP3 database are not sufficient to serve as boundary conditions for a regional climate model. Theoretically, we could ask each modelling group for the high resolution 3D-data and re-do the current analysis in case the needed data is available. This is one of the reasons we state in the conclusions that the analysis should be expanded based on other GCMs (and also RCMs) to confirm (or not) the current results.

We now indicate in the text that the choice of GCM was largely motivated by the data availability.

"This choice was motivated by the availability of six hourly 3-D model level data needed for running the RCM." (line 97)

L119 - does identifying cyclones manually make much difference compared to the tracking scheme used for the GCM cyclones?

A: The tracking scheme applied to the GCM data is fully automatic (Murray and Simmonds, 1991; Pinto et al., 2005) and widely used in the community (see e.g. review paper Neu et al 2013). These tracking schemes are optimised to process enormous amounts of data but with a rather low spatial and time resolution (e.g. 6-hourly, T63-data). For the RCM data, there was no need to use such a tracking method, particularly if only a very small amount of cyclones is analysed (TOP 30 for LGM and PI) and the spatial and time resolutions was very high (12.5 km, hourly). Given that the performance of the tracking methods typically increases with higher spatial and particularly time resolution, we assume that the results using a comparative tracking method would be similar to our manual analysis. Following one of the suggestions by the first reviewer, we now clearly indicate that the manual tracking was only performed for 2x 30 cyclones.

"The TOP 30 cyclone tracks simulated by WRF were identified manually based on relative vorticity field at 850 hPa." (line 126)

L130 - I would appreciate some more evaluation of how the model compares to reanalyses included within this paper.

A: We thank the reviewer for this suggestion. Also following a comment by the first reviewer, we have added a notes to the first and second paragraph of chapter 3 and two additional supplementary figures (Fig. S1, S2) comparing the storm track and the upper level jet stream in the MPI-ESM-P model for PI and LGM conditions and the NCEP/NCAR reanalysis.

"In this section, we analyse the general characteristics of cyclones over the North Atlantic and Europe under LGM conditions and compare them to PI climate conditions. Figure 2 shows the cyclone track density for the extended winter for PI and LGM climate conditions. In spite of the lower spatial resolution of MPI-ESM-P, the cyclone track density for the PI is

close to cyclone statistics obtained with Reanalysis datasets, with slight southerly shift of cyclonic activity (see Figure S1 for comparison with NCEP reanalysis data (Kalnay et al, 1996)), and CMIP GCMs for recent climate conditions (cp. Pinto et al., 2007; their Figure 1). Still, some regional shortcomings are identified, notably the limited cyclone activity over the Mediterranean basin. The North Atlantic storm track shows a clear tilt towards Northern Europe and the Arctic Ocean for PI, and its location and orientation are closely related with the eddy-driven jet stream (black contours in Fig. 2a) and the associated upper-air baroclinicity (Hoskins and Valdes, 1990; Pinto et al., 2009). A comparison of the jet stream between MPI-ESM-P PI and NCEP Reanalysis data shows a slight tilt towards Europe by the MPI model (Fig. S2), in line with the enhanced (reduced) southward (northward) cyclone activity (Fig. S1)"

Figure S1 (see above) reply to major concern

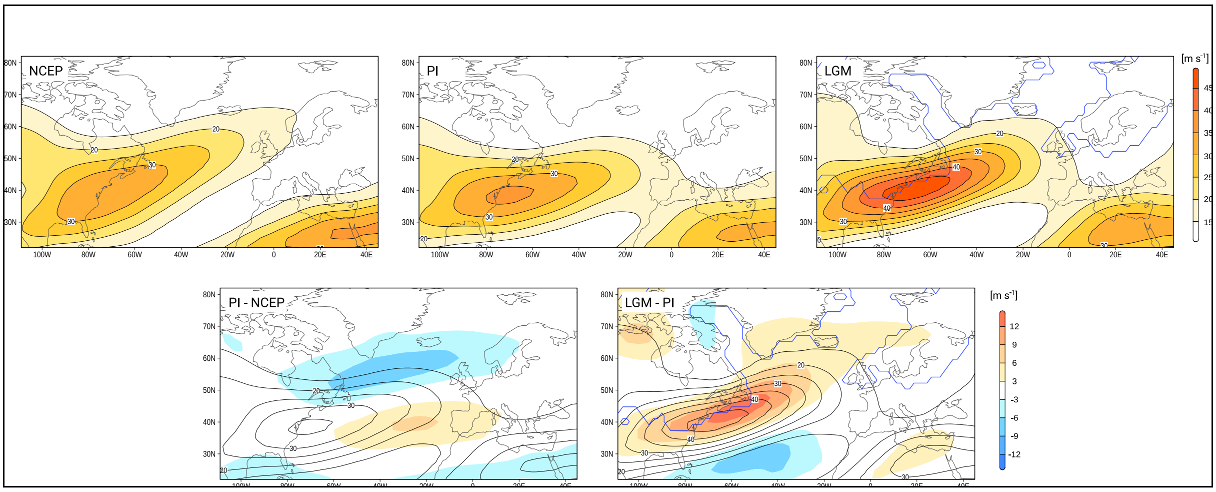


Fig. S2: Top: Upper level jet stream (wind speed at 300 hPa [m/s]) for the NCEP Reanalysis data and the MPI-ESM-P simulations for PI and LGM. Bottom: differences (shaded) between PI (lines) and NCEP and between LGM (lines) and PI. LGM ice sheet extent marked by the blue line.

L173 - please elaborate on how "care was taken" that the tracks align. It would be nice to see some statistics comparing e.g. mean biases in location/intensity, rather than just for a selected cyclone.

A: We have carefully analysed all 60 selected cases to make sure that the GCM and RCM tracks are consistent in terms of the initial location, track and timing, i.e. that we are analysing the same cyclone. The intensity in terms of Laplacian of MSLP is not comparable between RCM and GCM data because of the different spatial resolution.

Table 3 - In addition (or instead of) these stats for all cyclones, some summary statistics of the top 30 cyclones for each simulation would be helpful. E.g. mean intensity and cyclogenesis latitude from the GCM, or mean wind speed, rain rate, etc from the WRF simulations.

A: We thank the reviewer for this suggestion. Some mean statistics have been included for the GCM in Table 3 (see additional lines at the bottom). Since we only consider cyclones with peak intensity inside the box, the cyclone longitude/latitude is almost similar for PI and LGM. However, the mean/median of the intensity shows enhanced values for LGM cyclones. For the WRF-Simulations, we added an additional table (S1) in the supplementary showing mean (maximum) wind speed / rain rate, 12 hours before/ after and at peak intensity for PI and LGM (to be consistent with Fig.8, Fig. S4, Fig. S6) for comparison.

Table 3, only additional lines

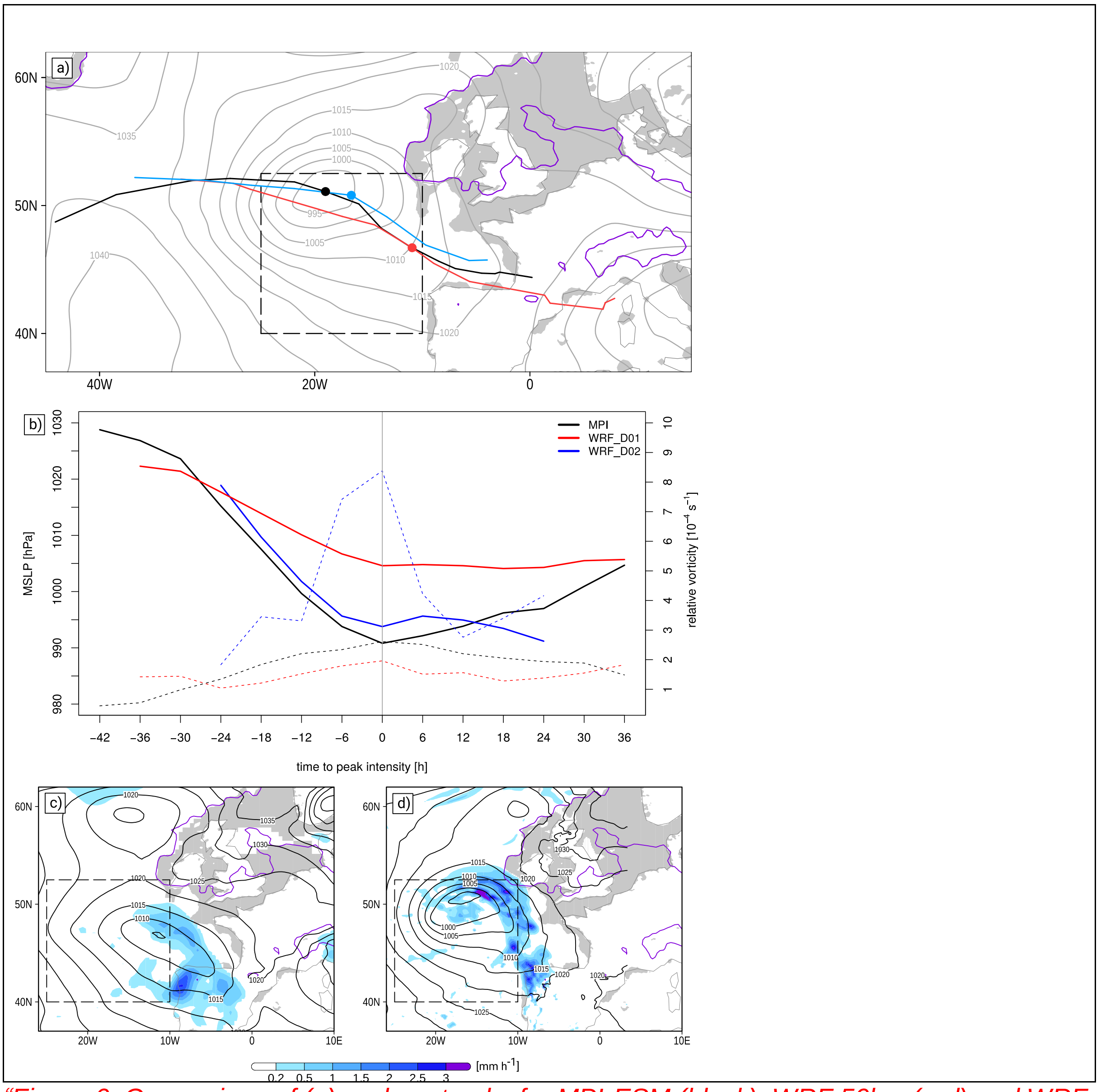
	PI					LGM				
	Date	Time	Lapl P	°Lat	°Lon	Date	Time	Lapl P	°Lat	°Lon
	Mean		2.52	47.51	342.72			2.80	48.53	342.53
	Media		2.49	47.59	343.56			2.73	49.76	343.54

Table S1: Summary of wind speed at 925 hPa, maximum near surface wind gust and total precipitation of the TOP 30 PI and LGM ensemble with 12.5 km resolution for 12 hours before / after and at peak intensity. Field mean and maximum corresponds to area depicted in Fig. S4, Fig. S6 and Fig. 8.

	wind925 (mean) [m/s]		wind925 (max) [m/s]		VMAX (mean) [m/s]		VMAX (max) [m/s]		PREC (mean) [mm/h]		PREC (max) [mm/h]	
	PI	LGM	PI	LGM	PI	LGM	PI	LGM	PI	LGM	PI	LGM
-12	9.56	11.37	24.71	27.23	12.46	14.10	23.04	25.24	0.29	0.20	3.45	2.05
0	10.67	12.25	25.96	27.95	13.47	15.49	26.84	26.98	0.28	0.24	3.56	2.70
12	11.69	12.91	26.68	28.82	14.50	16.09	28.66	30.31	0.24	0.24	1.66	1.27

Figure 6 c/d - it would be nice to have an additional panel showing the MSLP field in the GCM

A: The MSLP field from the GCM was included in Fig. 6a for comparison. Thus, now the MSLP fields are shown for the GCM, WRF-50km and WRF12.5km. Following a comment by the first reviewer, a bug in Fig. 6b was also corrected.



"Figure 6. Comparison of (a) cyclone tracks for MPI-ESM (black), WRF 50km (red) and WRF 12.5 km (blue) (coloured dots mark the location of peak intensity, black dotted box shows target area) and MSLP [hPa] for MPI-ESM at peak intensity, (b) timeseries of cyclone core pressure and relative vorticity for MPI-ESM, WRF 50km and WRF 12.5 km for LGM cyclone #24. Simulated precipitation rate [mm h-1] (shaded) and MSLP [hPa] (lines) at peak intensity for (c) WRF 50km and (d) WRF 12.5km."

Figure 7 - are the differences in panels c and f between the absolute values or between the anomalies? Given that there is the large mean MSLP difference between the simulations, I think the difference in local anomalies might be more informative for understanding how e.g. pressure gradients differ between simulations.

A: Based on the comment, we agree that the caption was not clear enough. Panels c and f indeed show differences of the anomalies (in line with the reviewers' suggestions), which is now clearly stated in the Figure caption.

"Figure 7. Composites of (a - c) mean sea level pressure, (d - f) ThetaE, and (g - i) vertical integrated water vapour (IWV) for PI, LGM and difference LGM – PI at peak intensity as defined by the maximum of the Laplacian of MSLP. (a, b) absolute MSLP values (lines, [hPa]), anomalies [hPa] from mean over displayed area (coloured); (c) absolute MSLP values (lines, [hPa]) from LGM, differences of the anomalies between LGM – PI in colours; (d, e) absolute ThetaE values (lines, [K]) and anomalies [K] from mean over displayed area (coloured); (f) absolute ThetaE values (lines, [K]) from LGM, differences of the anomalies between LGM – PI in colours; (g, h) absolute IWV values [mm], (i) difference [mm] LGM – PI."