Global River Discharge and Floods in the Warmer Climate of the Last Interglacial

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Abstract

We investigate hydrology during a past climate slightly warmer than the present: the Last Interglacial (LIG). With daily output of pre-industrial and LIG simulations from eight new climate models we force hydrological model PCR-GLOBWB, and in turn hydrodynamic model CaMa-Flood. Compared to pre-industrial, annual mean LIG runoff, discharge, and 100-year flood volume are considerably larger in the Northern Hemisphere, by 14%, 25% and 82%, respectively. Anomalies are negative in the Southern Hemisphere. In some boreal regions, LIG runoff and discharge are lower despite higher precipitation, due the higher temperatures and evaporation. LIG discharge is much higher for the Niger, Congo, Nile, Ganges, Irrawaddy, Pearl, and lower for the Mississippi, Saint Lawrence, Amazon, Paraná, Orange, Zambesi, Danube, Ob. Discharge is seasonally postponed in tropical rivers affected by monsoon changes. Results agree with published proxies on the sign of discharge anomaly in 15 of 23 sites where comparison is possible.

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- 28
- **Key Points:** 29
- 30 First modeling of hydrology and floods for the Last Interglacial •
- Boreal precipitation and runoff are higher than pre-industrial, and boreal river discharge 31 • and flood volume are (in %) even higher 32
- Most of the discharge occurs later in the year in large river basins of the Northern 33 Hemisphere 34

35 Abstract

- 36 We investigate hydrology during a past climate slightly warmer than the present: the Last
- 37 Interglacial (LIG). With daily output of pre-industrial and LIG simulations from eight new
- climate models we force hydrological model PCR-GLOBWB, and in turn hydrodynamic model
- 39 CaMa-Flood. Compared to pre-industrial, annual mean LIG runoff, discharge, and 100-year
- 40 flood volume are considerably larger in the Northern Hemisphere, by 14%, 25% and 82%,
- 41 respectively. Anomalies are negative in the Southern Hemisphere. In some boreal regions, LIG
- 42 runoff and discharge are lower despite higher precipitation, due the higher temperatures and
- evaporation. LIG discharge is much higher for the Niger, Congo, Nile, Ganges, Irrawaddy, Pearl,
 and lower for the Mississippi, Saint Lawrence, Amazon, Paraná, Orange, Zambesi, Danube, Ob.
- 45 Discharge is seasonally postponed in tropical rivers affected by monsoon changes. Results agree
- 46 with published proxies on the sign of discharge anomaly in 15 of 23 sites where comparison is
- 47 possible.
- 48

49 Plain Language Summary

50 It is still uncertain how the water cycle will respond to a warmer climate in the coming decades.

51 To increase our understanding of the relationships between climate and hydrology, we study the

52 past climates of the Last Interglacial, which was slightly warmer than the present. We present the

- results of a modeling approach, showing that while Northern Hemisphere precipitation was
- ⁵⁴ higher during the Last Interglacial, discharge of rivers was even higher, and floods were even
- ⁵⁵ larger. On the contrary, in the Southern Hemisphere precipitation, discharge and floods were
- 56 lower. We show that, for some regions, precipitation, discharge and floods do not have the same 57 direction of change. The seasonal timing of discharge also changes for some large basins of the
- direction of change. The seasonal timing of discharge also changes for some large basins of the
 Northern Hemisphere. Finally, for 23 sites, we compare our results to geological evidence. These
- results form a useful term of comparison to both projections of the future and geological studies
- 60 of past hydrology.
- 61

62 **1 Introduction**

63 With ongoing climate change, the need is pressing to anticipate the response of the hydrological

- 64 cycle to increasing global temperatures. This can be achieved through modeling frameworks that
- 65 include emission scenarios and simulation of climate, hydrology and river hydrodynamics
- 66 (Arnell and Gosling, 2016; Hirabayashi et al., 2013; van Vliet et al., 2013; Ward et al., 2017).
- One opportunity to increase our grasp of the earth's hydroclimate is offered by studying past
- responses of hydrological systems to different climate states that occurred during the earth's
- history, on which geology grants evidence (Harrison et al., 2015; Lunt et al., 2013b). As climate
- ⁷⁰ swung between glacials and interglacials of the Quaternary, global, or at least hemispheric,
- temperatures sometimes exceeded those of the present day (PAGES, 2016). The most recent of those intervals is the Last Interglacial (LIC: 120 to 116 thousand years ago). The LIC holds
- those intervals is the Last Interglacial (LIG; 129 to 116 thousand years ago). The LIG holds
 special relevance to the future, because of the unique combination of two factors: its proximity in
- 75 special relevance to the future, because of the unique combination of two factors. Its proximity 74 geological time, which means that the conditions of most climate system components are
- comparable to the present; and its partial temperature analogy with possible futures. Atmospheric
- surface temperatures were higher than the pre-industrial (PI) period and probably slightly higher
- than the present, with largest anomalies in the Northern Hemisphere and particularly at its high

⁷⁸ latitudes (CAPE_Members, 2006; Turney and Jones, 2010); however, global quantifications are

- still inadequate (Capron et al., 2017). Global estimates of LIG sea surface temperature anomalies
- compared to the present range between 0 and $+0.9^{\circ}$ C (Hoffman et al., 2017; Turney et al., 2020) and mean ocean temperature anomaly is estimated to ca. $+1^{\circ}$ C (Shackleton et al., 2020). The
- warmth of the LIG was due to the different latitudinal distribution of seasonal insolation and the
- resulting internal climate feedbacks, principally related to Arctic amplification of warming. The
- LIG has been abundantly studied in terms of temperature, using climate models (e.g., Lunt et al.,
- 2013a; Otto-Bliesner et al., 2020; Otto-Bliesner et al., 2013) and with proxies covering some
- Northern Hemisphere continents and many ocean sub-basins (Capron et al., 2017; Hoffman et
- al., 2017; Turney et al., 2020), and recently also in terms of precipitation (Nikolova et al., 2013;
- 88 Pedersen et al., 2017). In particular, the higher boreal LIG precipitation likely resulted from
- high-latitude warming and associated reduction in boreal latitudinal temperature gradients,
- ultimately linked to differences in insolation (Scussolini et al., 2019). While reconstructions of
 LIG runoff and river discharge are available for some locations (Table S1), for example for the
- Nile (Wu et al., 2018) and Congo rivers (Gingele et al., 1998), the hydrological implications of
- the different atmospheric and land climate of the LIG remain unexplored to this day. The
- application of hydrological modeling to study large-scale changes before the 20th century is rare.
- Exceptions are the modeling of Holocene discharge for a set of large river basins (Aerts et al.,
- 96 2006; Ward et al., 2007).
- 97 In this study we: 1) model global anomalies between LIG and PI surface runoff, river discharge
- and floods; 2) validate those anomalies by comparison with the available proxies; and 3) quantify
- modeled anomalies of hydrological extremes, in discharge and floods. To these ends, we use
- 100 results from the latest generation of climate models to force state-of-the-art global hydrological
- and hydrodynamic models. Our discharge and flood results form the first global picture of
- 102 hydrological conditions for the LIG.
- 103

104 2 Materials and Methods

105 To simulate the hydrology and hydrodynamics of the LIG and the PI, we use data from eight

- 106 global climate models of the Paleoclimate Modelling Intercomparison Project phase 4:
- 107 CESM1.2, CESM2, EC-EARTH3.2, HadGEM3-GC3.1, IPSL-CM6-LR, MPI-ESM1.2.01p1-LR,
- 108 NorESM1-F, NUIST-CSM. Depending on the model, the atmosphere's resolution ranges from
- 1° to 2°, and simulations last between 100 and 300 years. Simulations are conducted at
 equilibrium conditions, with forcing reflecting 127 ka for the LIG and AD 1850 for the PI.. From
- equilibrium conditions, with forcing reflecting 127 ka for the LIG and AD 1850 for the PI.. From the climate models, daily total precipitation and near-surface air temperature are inputted in the
- global hydrological model PCR-GLOBWB version 2 (Sutanudjaja et al., 2018). We test the
- climate model data against climate reanalysis (Text S2 and Fig. S1-S2) and determine that bias
- 114 correction of climate variables prior to input in the hydrological model is not warranted. Input
- 115 data is bilinearly interpolated to the 0.5° resolution of the hydrological simulations. The time
- step is daily. Potential reference evapotranspiration is calculated from air temperature using the
- Hamon method (Hamon, 1963). Simulations reflect natural conditions as much as possible, and
- human factors are excluded. Both LIG and PI simulations use present-day maps for land cover,
 river networks and sea levels. In hydrological simulations, we let the groundwater storage adjust
- river networks and sea levels. In hydrological simulations, we let the groundwater storage adjust to the different climatology, and then spin up the model for 50 years. From PCR-GLOBWB we
- analyze surface runoff. We then interpolate the daily surface runoff from PCR-GLOBWB for
- input into the global hydrodynamic model CaMa-Flood (Yamazaki et al., 2011), which runs at

- 123 0.25° resolution. This model has explicit representation of floodplains and solves the local
- inertial equation. From CaMa-Flood's output we analyze routed river discharge, flood
- (inundated) area and flood volume (i.e., flood area * flood depth) per grid cell. All variables are
- 126 averaged across the whole model time series, unless specified. Further, we investigate changes at
- 127 the river basin scale, for 27 major rivers selected to approximately cover all climatic regions
- 128 (Fig. S10). We report changes in seasonal discharge at the river mouth in the form of average
- annual hydrographs, along the boreal water year (October-to-September). To correctly compare
- the two simulations, we account for the seasonal implications of a different earth's orbit during the LIG by applying the angular definition of calendar (Bartlein and Shafer, 2019). See Text S1
- for additional details on each model and simulation, and Text S2 and Fig. S3-S5 for a test of the
- sensitivity of our results with respect to bias correction of the climate datasets.
- 134

135 **3 Results**

136 **3.1 Large-scale patterns of runoff and discharge**

Compared to the PI simulation, the global area-weighted average precipitation rate for the LIG
displays slightly positive anomaly (i.e., rate is higher in the LIG than in the PI), namely an
ensemble mean of +2.3% (with -0.6 to +5.0% inter-model spread) (Fig. 1). This results in
negligible runoff anomaly of +0.1% (-11.7 to +4.7%), and negligible anomaly of the routed river

- discharge of -0.2% (-2.7 to +3.8%). In the Northern Hemisphere anomalies are consistently
- 142 positive: +16% (+5 to +24%) for precipitation, +14% (+1 to +27%) for runoff, and +25% (+14 to
- +34%) for discharge. Conversely, in the Southern Hemisphere negative LIG precipitation
- anomaly of -7.3% (-4.9 to -11.1%) result in negative runoff anomaly of -10% (-21 to -5%) and in
 more negative discharge anomaly of -17% (-22 to -12%). Inter-model spreads are wider in the
- 145 more negative discharge anomaly of -17% (-22 to -12%). Inter-model spreads are wider 146 Northern Hemisphere.
- 147 For the vast majority of regions, anomalies of LIG runoff and precipitation coincide in sign (Fig.
- 148 2). In departure from this rule, some areas present negative runoff anomaly where LIG
- 149 precipitation is positive, mostly over eastern and northern Asia, norther continental Canada,
- northern South America and Iberian Peninsula. In most of these cases, the LIG runoff coefficient
- is lower (Fig. S7), indicating that a smaller portion of precipitation converts into runoff. This is
- mainly a result of higher evaporation (Fig. S9) due to higher air temperature (Fig. S6).
- 153 Comparing anomalies in discharge (Fig. 3, S11) and precipitation, areas where negative LIG
- discharge corresponds to positive precipitation are found mostly over northeast Asia (Amur and Lena river basins), northern Canada and the east coast of North America; positive discharge
- Lena river basins), northern Canada and the east coast of North America; positive discharge corresponds to negative precipitation over smaller areas: mainly northeast Brazil, northwestern
- 157 North America and Madagascar. Last, comparing runoff and discharge, areas of positive
- discharge anomaly and negative runoff emerge mostly over northeast Asia, northern South
- America, Iberian Peninsula and Central Asia; whereas small areas of negative discharge and
- 160 positive runoff are found over East and Central Asia, northern North America and southern
- 161 Australia.
- 162

163 **3.2 Annual and seasonal discharge of main rivers**

Annual hydrographs show much higher discharge at the river mouth in the LIG than PI for basins in Africa: Nile, Niger, Jubba-Shebelle (Fig. 4). LIG Discharge is clearly higher almost

year-round for the Congo, Irrawaddy, Lerma-Santiago and Douro. It is clearly lower for rivers

- 167 Flinders, Murray-Darling, Zambesi, Orange, Paraná, Amazon, Mississippi, Saint Lawrence,
- Danube, Ob, and slightly lower for the Yenisei, Rhine and Mackenzie. A common pattern is that
- several rivers with higher LIG yearly discharge display somewhat negative anomalies in
- spring/summer: the Ganges-Brahmaputra-Meghna, Pearl, Lena and Anadyr. The opposite
- happens for the Rhine and Mackenzie, where positive summer anomalies emerge amidst
 annually negative anomalies. Inter-model spread in the percent anomaly of seasonal and annual
- discharge varies across rivers, and tends to be larger in regions with higher LIG precipitation,
- runoff and discharge: in the North African monsoon and adjacent region (Nile, Niger, Jubba-
- 175 Shebelle), in the Indian monsoon (Ganges-Brahmaputra-Meghna, Irrawaddy), in the South
- American monsoon (Orinoco), and in northeast Asia (Lena, Anadyr). An exception is the large
- inter-model spread for the Murray-Darling, where precipitation and runoff anomalies also
- 178 diverge across models (Fig. 2).
- For most basins, the seasonal pattern of discharge is similar across LIG and PI simulations,
- 180 except from some rivers in the tropics, where strong changes in the timing of monsoonal
- precipitation and in the domains of monsoons (Scussolini et al., 2019) result in a different shape
- 182 of the hydrograph. Seasonality changes notably for the Congo, where a bimodal LIG hydrograph
- substitutes a near-unimodal PI one. For several basins, the seasonal contrast in discharge is
- 184 stronger in the LIG, e.g., for the Orinoco, Douro, Rhine, Ganges-Brahmaputra-Meghna,
- 185 Irrawaddy, Yangtze and Pearl. Furthermore, in many basins the peak of annual discharge is
- 186 shifted forward, by days up to weeks: in the Amazon, Orange, Zambesi, Mississippi, Saint
- 187 Lawrence, Douro, Danube, Rhine, Yangtze.
- 188 To represent changes in the annual timing of discharge, we inspect changes in the timing of the
- annual center of mass of flow (CMF) (Stewart et al., 2005) (bottom lines in Fig. 4). The CMF of
- 190 the LIG is anticipated by as much as 42 days in the case of the Niger, and postponed by as much
- as 36 days in the Irrawaddy. In many rivers of the Northern Hemisphere the CMF occurs later in
- 192 the LIG (Mackenzie, Mississippi, Saint Lawrence, Douro, Rhine, Danube, Ob, Irrawaddy,
- 193 Yenisei, Pearl), in many cases reflecting enhanced precipitation in summer and early autumn.
- 194 The Niger and the Yangtze are the only boreal rivers for which LIG CMF occurs substantially
- earlier. It must be noted that the Niger is also anomalous in that its LIG discharge is +200%
- larger. In the Southern Hemisphere, the CMF of LIG rivers only shifts substantially in the
- 197 Orange and Zambesi, where it occurs later, and in the Mekong and Murray-Darling, where it
- occurs earlier. Although the seasonal pattern changes widely in the Congo, its CMF is virtually the same. In other basing with much higher LIC discharge (Nile and Jubbe Shahalla) the CMF
- the same. In other basins with much higher LIG discharge (Nile and Jubba-Shebelle), the CMF
- shifts by only 2 days.

201 **3.3 Extreme discharge and floods**

- 202 Global area-weighted average anomalies in annual maxima of flood metrics are more
- accentuated than anomalies in annual average precipitation, runoff and discharge (Fig. 1).
- 204 Anomalies in annual maximum of flood volume are larger than flood area. Globally, LIG
- simulations display +11% (with +5 to +21% inter-model spread) flood area and +21% (+10 to
- +43%) flood volume. Especially in the Northern Hemisphere, the positive anomalies are very
- strong, with +39% (+24 to +57%) flood area and +82% flood volume, with very large inter-model
- spread for the latter: +45 to +127%. For the Southern Hemisphere, anomalies are -17% (-20 to -
- 15%) for flood area and -27% (-34 to -24%) for flood volume. The much larger anomalies of
- floods metrics cannot be attributed to changes in extreme precipitation (not shown), as these are
- even smaller than changes in mean precipitation. Geographic patterns of anomalies in flood area

- and flood volume at the 100-year return period (Fig. S13) diverge in many regions from
- anomalies in runoff (Fig. 2) and discharge (Fig. 3), mainly over northern Asia, North America
- and India. Also, they are more spatially heterogeneous, pointing to the relevance of sub-basin
- processes to modeled floods. To assess the link between precipitation intensity and hydrological
- extremes, we calculate annual maximum precipitation in consecutive intervals of 5, 15 and 30
- days (Fig. S14). In the Northern Hemisphere, geographical coincidence in the sign of anomaly is
 higher between flood area (or volume) and 5-day maximum precipitation than between flood
- area (or volume) and average precipitation (Fig. S13). This indicates that, in the model, extremes
- in boreal flooding are driven by intense precipitation over multiple days rather than by average
- 221 precipitation.
- For discharge and flood area in the same river basins analyzed above, the ensemble-averaged
- extreme values increase from return periods of 2-year to 100-year in a similar fashion (Fig. 5;
- flood volume is omitted because the shape of its curves is comparable to flood area). For most
- basins, patterns of extremes of intense precipitation are very similar for 5, 15 and 30-day
- intervals, and mostly also resemble patterns of extreme discharge and flood area (Fig. S15).
- 227 Notable deviations from this similarity emerge: 1) in the Mississippi, where LIG discharge and
- flood are lower than PI, whereas extremes of intense precipitation are virtually the same across
- simulations; 2) in the Saint Lawrence and Flinders, where LIG discharge extremes are slightly
- lower, whereas LIG flood area extremes are much lower.
- 231

232 **3.4 Comparison to proxies of discharge/runoff**

- 233 We revise proxy studies that report patterns of LIG runoff and discharge, to compare to the
- modeling results. We select mostly records of marine sediments under the influence of either
- discharge downstream from main river mouths or broadly of runoff from the adjacent land.
- Often, the interpretation of such records is dubious, because of the presence of multiple
- 237 mechanisms that may concur to explain the proxy signal, such as strong sea level variations of
- the glacial-interglacial cycles (e.g., Kujau et al., 2010) and potential shifts in the location of river mouths that are poorly constrained topographically. We find published proxies for 32 sites, of
- which 23 are suitable for comparison with models (Table S1). The modeled discharge agrees
- 241 with the proxies on the sign of LIG anomaly at 15 sites: the west coast of North America, the
- north and west coasts of South America, at several sites on the northern, eastern and southern
- coasts of Africa, at the southeast of India, and at western Australia (Fig. 3). Disagreement occurs
- over the Mississippi basin and downstream its river mouth, at the northern coast of South
- America (where model resolution is likely inadequate to capture small scale gradients), the
- western coast of Northern Africa, the eastern Mediterranean region, over the Limpopo basin, and at a site in Indonesia.
- 247 248

249 **4 Discussion and Conclusions**

250 Because reconstructing climatic and hydrological signals from proxies is hard, it is tempting to

- extend the interpretation of proxies of, e.g., precipitation, to also represent hydrological variables
- as runoff, discharge and flood, or conversely. Although our model results indicate that for most
- areas the sign of anomaly in those variables coincides, the discrepancies that emerge for non-
- negligible land portions (Fig. 2, S11 and S13) provide a cautionary message for the interpretation
- 255 of proxy records. On the other hand, areas where modelled variables diverge and areas of

stronger anomaly could inform site selection for proxy reconstructions that help shed light into mechanisms of LIG hydroclimate.

In the only modeling studies that offer points of paleoclimatic comparison for our results, Aerts 258 et al. (2006) and Ward et al. (2007) simulated discharge for major rivers during the mid-259 Holocene, when insolation and warming anomalies were geographically comparable, though 260 smaller in magnitude, to those of the LIG. Their annually integrated anomalies agree in sign with 261 our LIG ones for the Ganges, Congo, Lena, Murray-Darling, Amazon, Zambesi and Nile. They 262 slightly disagree for the Danube, Rhine and Mekong, and completely disagree for the 263 Mississippi. Attributing discrepancies with those results is unattainable because the effect of 264 different climate forcing and very different modeling framework cannot be separated. By virtue 265 of the possible similarities in the geographic pattern of temperature anomalies, another term of 266 comparison for LIG discharge are the results of simulations for the end of this century (2070-267 2100) under high-emission scenarios, although key differences in forcing between these climates 268 (Bony et al., 2013) limit the merit of this comparison. Our LIG positive discharge anomalies 269 agree with future projections with CMIP3 models (van Vliet et al., 2013) over northeast Asia, 270 Alaska, central Africa and the Arabian Peninsula. LIG negative discharge anomalies agree over 271 southern Africa, parts of North America and of Europe. Glaring disagreement emerges: over 272 Northern Africa and the Mediterranean, over tropical South America, Southeast Asia and 273 274 particularly the Himalaya region. Compared to CMIP5-based projections, anomalies in LIG discharge hydrographs are similar for Rhine, Ganges, Yangtze, and different for Amazon, Niger, 275 Nile, Mississippi, Mackenzie, Lena (Krysanova et al., 2017). LIG floods are lower over many 276 parts of Europe, in agreement with CMIP3-based future projections (Arnell and Gosling, 2016) 277

but in disagreement with others based on downscaled CMIP5 results (Alfieri et al., 2015).

279 Precipitation is an uncertain product of global climate models (e.g., Huang et al., 2020; see also Text S1). Nevertheless, precipitation from an almost identical ensemble of climate models has 280 been validated by comparison to proxies (Scussolini et al., 2019). That study reports that climate 281 282 models seem to reasonably reproduce the main features of LIG precipitation, especially in the Northern Hemisphere. Besides, comparison of proxies with a similar ensemble of models shows 283 broad agreement in LIG Arctic amplification of warmer temperatures (Otto-Bliesner et al., 284 2020). Our proxy-model comparison on discharge and runoff supplies additional confidence in 285 286 the models' capabilities of reproducing past climate change, suggesting that even for a cascade of climate-hydrological-hydrodynamic models there is more agreement than disagreement with 287 proxies. It must be noted that there are inherent limits of this model-proxy comparison. Beyond 288 those raised by Scussolini et al. (2019), an additional limit derives from the fact that LIG 289 simulations are carried out with a current river network, land cover and sea levels. Although 290 291 these were likely different in the LIG, improvements in this direction are postponed until global datasets for this period will emerge. Further, although we found more proxies than were found 292 for Holocene discharge (Aerts et al., 2006), these are fewer than for LIG precipitation (Scussolini 293 et al., 2019), and the number of suitable comparisons is too small to draw conclusions about the 294 geographic pattern of model-proxy agreement. Nevertheless, with growing interest and with 295 accelerated development in the fields of paleohydrology and paleo floods (Baker, 2013; Wilhelm 296 et al., 2017; Wilhelm et al., 2018), it is realistic that the coverage and resolution of proxies for 297 runoff, discharge and flooding will increase, enabling more extensive comparison with the 298 models presented here. Additionally, the above-mentioned forms of validation with proxies 299 enable selecting models that best reproduce observations for the LIG, and that can therefore be 300 assumed to better capture the internal feedbacks of the climate system in a warmer climate. With 301

ad-hoc methodologies, this could in turn enable differential weighting of models in the context of
 ensemble studies (Eyring et al., 2019).

Lastly, our hydrological results inform the study of the LIG history of ecosystems and humans at 304 the continental scale. For example, humid LIG conditions have been inferred for sectors of North 305 Africa that were crucial to pre-historic human migrations (Larrasoana et al., 2013). The timing of 306 307 human dispersal from Africa is not well constrained, with current hypotheses based on genomics and archeology suggesting migrations in the time window 130-50 ka, via the Bab el Mandeb 308 strait or the Sinai Peninsula (López et al., 2015), and pioneer hydrodynamic studies indicating 309 possible LIG migration to the Mediterranean along a western route (Coulthard et al., 2013). For 310 127 ka, increased precipitation emerges from proxies and models over the Sahel, Sahara, Arabian 311 Peninsula, Levant and Middle-East, with further-reaching and longer monsoon seasons 312 (Scussolini et al., 2019). We here simulate higher LIG annual runoff and discharge over North 313 Africa and the southwestern Arabian Peninsula. All this points to the existence of a river network 314

- and to greening of key regions that may have sustained the path of human tribes migrating across
- and out of the continent.
- 317

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635 Figure captions

- **Figure 1**. Summary of area-weighted global and hemispheric percentage anomalies between Last
- Interglacial and pre-industrial simulations, for each model and for the ensemble mean. Precipitation is
 calculated over land only. Values are averaged across the entire time-series, from daily values
- calculated over land only. Values are averaged across the entire time-series, from daily val
 (precipitation, runoff, discharge) and from annual maxima (flood area and flood volume).
- **Figure 2**. Ensemble anomaly in annual mean precipitation (a) and in surface runoff from model PCR-
- 640 **Figure 2.** Ensemble anomaly in annual mean precipitation (a) and in surface runoil from model PCR-641 GLOBWB (b). Areas for which more than two models (out of eight) disagree with the sign of the
- anomaly in precipitation and runoff are hatched. Also shown (c) are areas where the sign of anomalies in
- 642 precipitation and runoff coincides or diverges, in a discrete color scale; white indicates that either
- percentage anomaly is comprised between -2% and +2%; grey indicates no runoff values.
- **Figure 3**. Ensemble anomaly in river discharge from model CaMa-Flood, along with river discharge from
- 646 published proxies, in markers. Hatching as per Fig. 2. Green (purple) stars and diamonds indicate positive
- (negative) anomalies from the proxies. Stars (diamonds) indicate agreement (disagreement) with the
- 648 model ensemble in the sign of anomaly. The arrow indicates the location of the proxy record in the
- 649 Mississippi basin. Details and references of proxy records are in Table S1. Discharge from model PCR-
- 650 GLOBWB is shown in Fig. S8 for reference.
- **Figure 4**. Average annual hydrographs of discharge at points near the mouth of major river basins. X-
- axes are days in a 'water-year' from October 1^{st} to September 30^{th} . Left-hand y-axis is the ensemble mean
- value of absolute discharge, for Last Interglacial (solid black lines) and pre-industrial climates (dashed
- black lines). Right-hand y-axis is the percentage anomaly between the two climates, blue for positive
- (higher discharge during LIG), and red for negative. Individual models are in thin lines, and ensemble
- 656 means in thick lines. Axis range is -100% to 100%. The vertical lines at the bottom of each panel 657 represent the timing of the annual center of mass of flow, for LIG (solid line) and PI (dashed line). The
- represent the timing of the annual center of mass of flow, for LIG (solid line) andangular calendar is applied to the LIG data.
 - **Figure 5**. Extremes of discharge (a) and of flood area (b) for main river basins (shown in Fig. S5), for a set of return periods from 2-year to 100-year. Individual models are in thin lines and ensemble means in thick lines. Discharge is calculated for each basin in proximity of the river mouth; flood area is summed
 - 662 for the whole basin.