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**Amplification of Elevation-Dependent Temperature Variability Since the Last
Glacial Maximum**

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The mechanisms of recent Elevation-Dependent Warming (EDW) remain debated because nearly all data sources are limited to past decades and subject to anthropogenic effects. Here, we study how temperature changed along the elevation gradient around the world since the Last Glacial Maximum (LGM) and aim to shed lights on the mechanisms of EDW and implications for the future climate change in alpine regions. We present a unique network of 192 quantitative terrestrial temperature records along elevation gradient up to ~5000 m to study the past Elevation-Dependent Temperature Amplification (EDTA) since LGM. EDTA is exemplified by much stronger temperature variability at high-elevation sites during climate transitions of millennial- to centennial-scales. The spatiotemporal patterns of EDTA indicate that the surface albedo, caused by changes in glacier and vegetation coverage, played the most important role, which resulted in steeper lapse rate during the LGM and flatter in the Mid-Holocene. This suggests that alpine regions experienced much colder environments in glacial and much warmer in

41 **interglacial periods. This also implies that the mountain regions would warm much**
42 **faster in the context of current global change. The study emphasizes the need to**
43 **reassess and reevaluate alpine climate change mechanisms, and to reconsider the**
44 **mitigation and adaptation implementation strategies under the future global**
45 **warming scenarios.**

46
47 There is growing consensus from meteorological observations, reanalysis data,
48 remotely sensed imagery, and climate models that the high-elevation regions have
49 experienced accelerated warming compared to low-elevation environments over past
50 decades, known as the Elevation-Dependent Warming (EDW). EDW severely affects the
51 stability of alpine cryosphere and ecosystems^{1,2} and has been reported in alpine regions
52 with elevation higher than 500 m above sea level (a.s.l), including the High Mountain
53 Asia, Rocky Mountains, Andes Mountains, Kilimanjaro and European Alps etc¹. The
54 Tibetan Plateau (TP), for example, the highest and largest highland on earth, has
55 experienced much faster warming than the global average in recent decades^{3,4}, with more
56 evident warming in winter, followed by mean annual temperature, and summer
57 temperature⁵. Further, tree-ring width and maximum latewood density from the TP
58 suggests that the onset of a decrease in summer-to-winter temperature difference started
59 in the 1870s⁶. These changes may have increased spring-summer precipitation and
60 intensified the hydrological cycle, increased glacier instability and associated hazards⁷,

61 posing severe threats to freshwater resources in the South and East Asia^{8,9}. It may imply
62 also a highly climate instability that might affect the Asia's water towers for the global
63 mean warming of 1.5 - 2 °C (the Paris Agreement climate target) and much higher
64 warming rates above pre-industrial levels at the end of the twenty-first century.

65
66 A series of factors have been proposed as mechanisms for the EDW, including
67 snow-albedo feedback, cloud-radiation, as well as water vapor and radiative fluxes, via
68 monitoring net flux of energy to the surface along an elevation gradient¹. However, due to
69 few available data sources, the short-term observational evidence in the context of high
70 anthropogenic greenhouse gas emission may hamper in-depth understanding of the
71 mechanisms for EDW, which makes it an open question. A large number of terrestrial
72 temperature reconstructions and syntheses have been reported since the LGM¹⁰⁻¹⁵, which
73 provide a unique opportunity to assess past changes in temperature along elevation
74 gradients at various time and space scales spanning the past 21 thousand years. A
75 previous study focused on four lakes at different elevations on Mt. Kenya (East Africa)
76 found that the lapse rate was significantly steeper at the Last Glacial Maximum (LGM)
77 compared to modern times¹⁶. This implies that the alpine regions may have experienced a
78 much colder climate than lower elevations. Here, we use a unique paleoclimatic dataset
79 of quantified terrestrial temperature reconstructions to study the past changes in
80 temperature along elevation gradient around the world since the LGM. We aim to study

the Elevation-Dependent Temperature Amplification (EDTA) at climate transitions on orbital-, millennial-, and centennial- scales, including LGM to the Holocene Thermal Maximum (HTM), HTM to the Late Holocene (LH), the Medieval Climate Anomaly (MCA) to Little Ice Age (LIA), and compare with modern EDW.

Data and Methods

We compiled three global datasets consisting of 192 quantitative terrestrial temperature records since the LGM. We selected quantitative temperature reconstructions with precise age controls, high temporal resolution, and explicit temperature implications that cover different intervals. The dataset includes temperature records from long chain alkenones (LCAs), glycerol dialkyl glycerol tetraethers (GDGTs), chironomidae (midge), and pollen (Fig. 1, Methods and Supplementary Data). There are 30 records covering the transition of LGM-HTM, with elevation range of 0-3194 meters above sea level (m a.s.l.), 126 records at the HTM-LH period with elevation range of 0-5059 m a.s.l., and 36 records for the MCA-LIA with elevation range of 54-4450 m a.s.l., respectively (see Methods and Supplementary Data). The original temperature reconstructions were not recalibrated due to the lack of global transfer functions for each proxy indicator. According to the original publications, ~39% of the records reflect annual mean temperature, and ~61% reflect summer temperature (Supplementary Dataset 1). For all records we calculated the temperature change across the three transitions by averaging

temperature at time slices of 1000 years for LGM, HTM, LH, and 300 years for MCA and LIA (Figure S1) using a moving average-based slide window algorithm. We also calculated the lapse rate for temperature reconstructions at LGM, HTM and LH, in order to compare with modern observations (see details in Supplementary Methods).

Results and Discussion

Records at high-elevation sites show much larger amplitudes of temperature variability than low-elevation during transitions of different timescales, including the LGM-HTM at orbital scale, the HTM-LH at millennial scale, and the MCA-LIA at centennial scale (Fig 2 and Fig. S3). Temperature differences (ΔT) for all records between LGM and HTM ($\Delta T_{LGM-HTM}$), HTM and LH (ΔT_{HTM-LH}), MCA and LIA ($\Delta T_{MCA-LIA}$) were plotted against the elevation (Fig. S3). The composite dataset clearly shows significant trends in elevation-dependent temperature changes at the three transitions (Fig. 2), with stronger temperature increases at LGM-HTM, greater temperature decreases at HTM-LH and MCA-LIA at high elevation regions compared to low elevations, suggesting EDTA is a prevailed phenomenon in geological periods. Further, during the transition of LGM to HTM, the temperature increased by 3.8 ± 1.2 °C at sea level, while it increased by 8.1 ± 1.2 °C (see Supplementary Methods for details on the calculation) at 3000 m a.s.l. as an example for alpine regions, based on the linear regression in Fig. 2. During the transition of HTM to LH, the temperature decreased by 0.8 ± 0.9 °C at sea level, while it decreased

121 4.3 ± 0.9 °C in regions with elevations of 3000 m a.s.l. It is noteworthy that the
122 temperature amplification based on the various proxy indicators differs significantly at
123 high-elevation sites. Among all proxies, LCAs is ranked as the most sensitive proxy,
124 while the chironomidae as the least sensitive, which likely results from inherent response
125 of individual proxy to temperature variation (Fig. S3).

126
127 By grouping various proxy records together, we calculated temperature stacks at
128 different elevations by averaging the records (see Methods for details) and found that the
129 ΔT increased with elevation (Fig. S4). For example, during the transition of HTM-LH, ΔT
130 increased from 0.7 ± 0.1 °C at 0-1km to 2.8 ± 0.9 °C at elevation >4 km. Notably, the
131 Tibetan Plateau (averaged at 4500 m a.s.l.) experienced 2~3 times of temperature
132 variability compared with the average elevation of the world's continents (875 m a.s.l.)¹⁷
133 during the three transitions. The amplitudes in EDTA are comparable to the modern
134 observations on the Tibetan Plateau¹⁸. Though EDTA at the three transitions represents
135 temperature variability at orbital, millennial (0.8 °C/1000 yr) and centennial scales
136 (0.1 °C /100 yr), the modern EDW (0.35 °C/10 yr, annual mean temperature) occurs
137 during the period from 1970 to 2014¹⁸, which implies that the alpine regions are more
138 sensitive in temperature variability in the context of current global warming.

139
140 We estimated the surface temperature lapse rate, Γ , at the LGM, HTM and LH,

using the mean annual temperature records with elevation gradients in the middle
 latitudes of the Northern Hemisphere (25-55° N), and obtained $\Gamma_{LGM} = -3.94 \pm$
 3.98 °C/km, $\Gamma_{HTM} = -2.16 \pm 6.70$ °C/km, and $\Gamma_{LH} = -3.14 \pm 6.79$ °C/km, respectively (Fig.
 3). It is not surprising that Γ at the LGM, HTM and LH are smaller than the modern
 average free-air Γ value of 6.5 °C/km (the saturated adiabatic lapse rate)¹⁹, because the
 air parcels unlikely follow the adiabatic processes strictly in a large area across 30
 degrees in latitude. We calculated Γ during 1970-2000 (Γ_{Modern}) at the same locations as
 the records, using the reanalysis temperature data in WorldClim²⁰, the sea surface
 temperature from HadISST1²¹, and obtained $\Gamma_{Modern} = -2.26 \pm 4.30$ °C/km. It is interesting
 to observe that the Γ_{LGM} is larger than Γ_{Modern} , which agrees with the results of the
 Kilimanjaro mountains¹⁶. The greater Γ_{LGM} and smaller Γ_{HTM} comparing with Γ_{Modern}
 suggest that the high-elevation regions would be much colder during the LGM and
 warmer during the HTM. This further supports the prevalence of EDTA in the past.

The EDTA at the three transitions also show clear zonal patterns (Fig. 4 and Fig.
 S5). The ΔT for all proxy records were sub-grouped based on latitudes, including low
 latitudes (25° S~25° N), middle (25° N~55° N), and high latitudes (>55° N). During the
 LGM-HTM transition, the strongest EDTA was observed for summer temperatures in
 high latitudes (though the elevation of the highest record is only 720 m a.s.l.), followed
 by relatively weak EDTA for summer and mean annual temperature in middle latitudes.

The EDTA behave differently during the HTM-LH and MCA-LIA, with the strongest EDTA for summer temperature in middle latitudes, followed by mean annual temperatures in middle latitudes and summer temperatures in high latitudes (Fig. S5). The patterns of EDTA based on climate records since LGM are quite different from modern observations in alpine regions, with the strongest modern EDW for winter temperatures¹. The difference in the zonal patterns between past records and modern observations likely results from 1) lack of sufficient winter temperature records since the LGM, 2) quite different climate background between geological times and current global warming, and 3) different timescales from orbital, millennial- to interannual scales.

We calculated the ΔT from the TraCE-21ka simulation outputs across the world, in order to compare with the EDTA revealed by the records. The model outputs capture the polar amplifications very well, as exemplified in previous studies^{22,23}, and the simulations also reveal elevation-dependent temperature amplification to some extent (Fig. S6, S7). The slight discrepancy in the elevation-dependent temperature variability between climate reconstructions and TraCE-21ka models may result from 1) most proxy indicators reveal near-surface or localized temperature variation, while the model performed the temperature changes using a large spatial distribution CCSM3 simulation (T31_gx3v5 resolution)²⁴, and 2) the forcings affecting EDTA may not be fully addressed in the models.

The current EDW has been mainly attributed to snow-albedo feedback^{25,26}, though multiple forcings, including cloud-radiation interactions^{27,28}, water vapor²⁹, aerosols³⁰, anthropogenic black carbon, CO₂ concentration³¹ and underlying land cover estimate³² cannot be excluded. From the compilation of the quantitative terrestrial temperature reconstructions, the most evident EDTA in high latitudes at the transition of LGM-HTM, and in middle latitudes at HTM-LH likely suggest that the albedo may contribute to the occurrence of EDTA in high-elevation regions. During the transition of LGM-HTM, the high latitude regions experienced dramatic changes in glacier coverage at all elevations, which were mainly affected by orbital forcing and concentration of greenhouse gases. It is not surprising that the summer temperature showed the most significant changes in high elevations due to changes in glacier albedo feedback. During the transition of HTM-LH, the summer temperature in middle latitudes revealed stronger EDTA, which would be mainly affected by changes in vegetation-albedo feedback. Pollen-based reconstruction for the Northern Hemisphere indicates the biome changed much more significantly in the middle latitudes (ca. 46% of all available sites) than high latitudes (approximately 25% of all available sites)³³ (Fig. S8), which was mainly affected by movement of the Intertropical Convergence Zone driven by summer insolation. Calculations of the effects of various forcings on temperature variability agree with our assumptions that greenhouse gases and ice sheet variation dominate orbital scale³⁴, and

orbital-driven insolation variations contributes mostly to millennial scale during Holocene (Fig. S9).

Summary

Syntheses of quantitative temperature records since the Last Glacial Maximum indicate that the Elevation-Dependent Temperature Amplification (EDTA) in alpine regions across the world not only occurs in the context of current global warming, but was also relevant in geological periods. The high-elevation regions were much colder during glacial periods, and much warmer during interglacial periods than previously thought. The reasons might be attributed to the changes in land surface albedo related to glacier and vegetation coverage.

This has implications for paleoclimate studies, which requires in-depth understanding of alpine climate changes. The rate of the current warming in high elevation regions, in the context of anthropogenic global change, is likely much faster than that in the geological periods, indicating that the alpine regions may face much faster warming in the near future. This forces us to reassess whether the 2 °C projection is appropriate for high elevation environments in the context of current global warming. Policy makers need to reevaluate the mitigation and adaptation strategies in alpine regions under the high greenhouse gas emissions scenario.

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Author contributions: J.H., F.L. and F.C. designed the research; J.H., F.L., Z.S., K.Y., X.H., M.D., W.D. performed the data analysis; J.C. performed the model simulation; X.C. performed biome reconstruction. E.X. and J.L. improved the manuscript with constructive comments and suggestions. F.L., J.H., E.X. and F.C. led the writing of the paper and all authors contributed to the interpretation of the results and to the text.

Competing interests: Authors declare no competing interests.

Data and materials availability: All data and methods needed to evaluate the conclusions in this paper are present in the Supplementary Materials.

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342 Figure 1

345 **Figure 1. Spatiotemporal distribution of terrestrial temperature records since LGM.**

346 (A) Map showing the locations of the temperature records based on GDGTs, LCAs,
 347 pollen and midge proxy indicators. (B) Distribution of the records by elevations in 0.5km
 348 intervals (left) and by latitude in 5° steps (Right). (C) Temporal availability of
 349 temperature records based on proxy indicators. LCAs represents long-chain alkenones,
 350 GDGTs stands for glycerol dialkyl glycerol tetraethers.

352 Figure 2

353

354

355 **Figure 2. Dependence of temperature changes on elevation around the world across**

356 **important transitions since the Last Glacial Maximum.** The terrestrial temperature

357 records were sub-grouped at important climate transitions of LGM-HTM (solid circles in

358 grey), HTM-LH (open circles in red), and MCA-LIA (solid circles in blue).

359 Shading represents 95% bootstrap confidence intervals with 5000 replicates.

360

361

362 Figure 3.

363

364

365 **Figure 3. Schematic comparison of the lapse rate for the mean annual temperatures**
366 **in the middle latitudes of the Northern Hemisphere (25-55° N) at LGM, HTM, LH**
367 **and Modern.** Solid and dash lines in grey represent the lapse rate at LGM, solid line in
368 pink represents lapse rate at HTM, solid line in blue for LH, solid line in green for
369 modern. As the highest record during LGM goes back to 3194 m a.s.l., the lapse rate was
370 linearly extended to higher elevation for comparison. The modern lapse rate was
371 calculated at the same locations for the records for the periods of 1970-2000 AD, using
372 the reanalysis temperature data in WorldClim and the sea surface temperature from
373 HadISST1.

374

Figure 4

Figure 4. 3-D view of variability of temperature changes versus elevations and latitudes at three transitions, (A) LGM-HTM, (B), HTM-LH, and (C) MCA-LIA.

Note that amplitudes of temperature changes vary with elevation and latitudes at three transitions (see details in Fig. S5).

Supplementary Files

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