*Earth's Future*

Supporting Information for to

**Projected Changes in Mountain Precipitation under $CO_2$-induced warmer climate**

Kad et al.

## Contents of this file

**Supplementary Methods**

**Temperature lapse rate ($^{o}$C km$^{-1}$)**

The atmospheric lapse rate is defined as the temperature changes with height in the atmosphere (from the surface to 100 hPa). It is obtained by least-squares linear regression of temperature to emanate lapse rates.

**Moisture advection (g kg$^{-1}$ day$^{-1}$)**

The net moisture advection ($Q_{adv}$) is a sum of the vertical moisture advection and horizontal moisture advection, using a robust physical framework. The vertical moisture advection can split into its dynamic component related to atmospheric circulation change pattern. The thermodynamic component relates to its change in moisture content controlled by the Clausius-Clapeyron relation.

$$\Delta Q_{adv} = (\Delta V_{dynamic} + \Delta V_{thermodynamic}) + \Delta H$$

$$\Delta Q_{adv} = -\left(\Delta\omega.\frac{\partial\overline{q}}{\partial p}\right) - \left(\overline{\omega}.\frac{\partial\Delta q}{\partial p}\right) - \Delta(V_h.\nabla q)$$

**Definition of precipitation extremes**

We use the following indices to examine the precipitation extreme events (Calculated over equilibrated last 20 years of each simulation).

**Table S1.** Precipitation extremes indices (Karl et al., 1999) were used to define extremes events.

| Type | Indices | Name | Definition | Unit |
|---|---|---|---|---|
| Absolute | SDII | Simple daily intensity index | Annual precipitation per total number of wet days | mm day$^{-1}$ |
| | Rx1day | Highest 1-day precipitation | Maximum precipitation in 1-day | mm |
| | Rx5day | Highest 5-day precipitation | Maximum precipitation within 5-day | mm |
| Threshold | R10 | Heavy rainy days | Number of days when precipitation more or equal to 10mm | day |
| | R20 | Very heavy rainy days | Number of days when precipitation more or equal to 20mm | day |

## Supplementary Figures

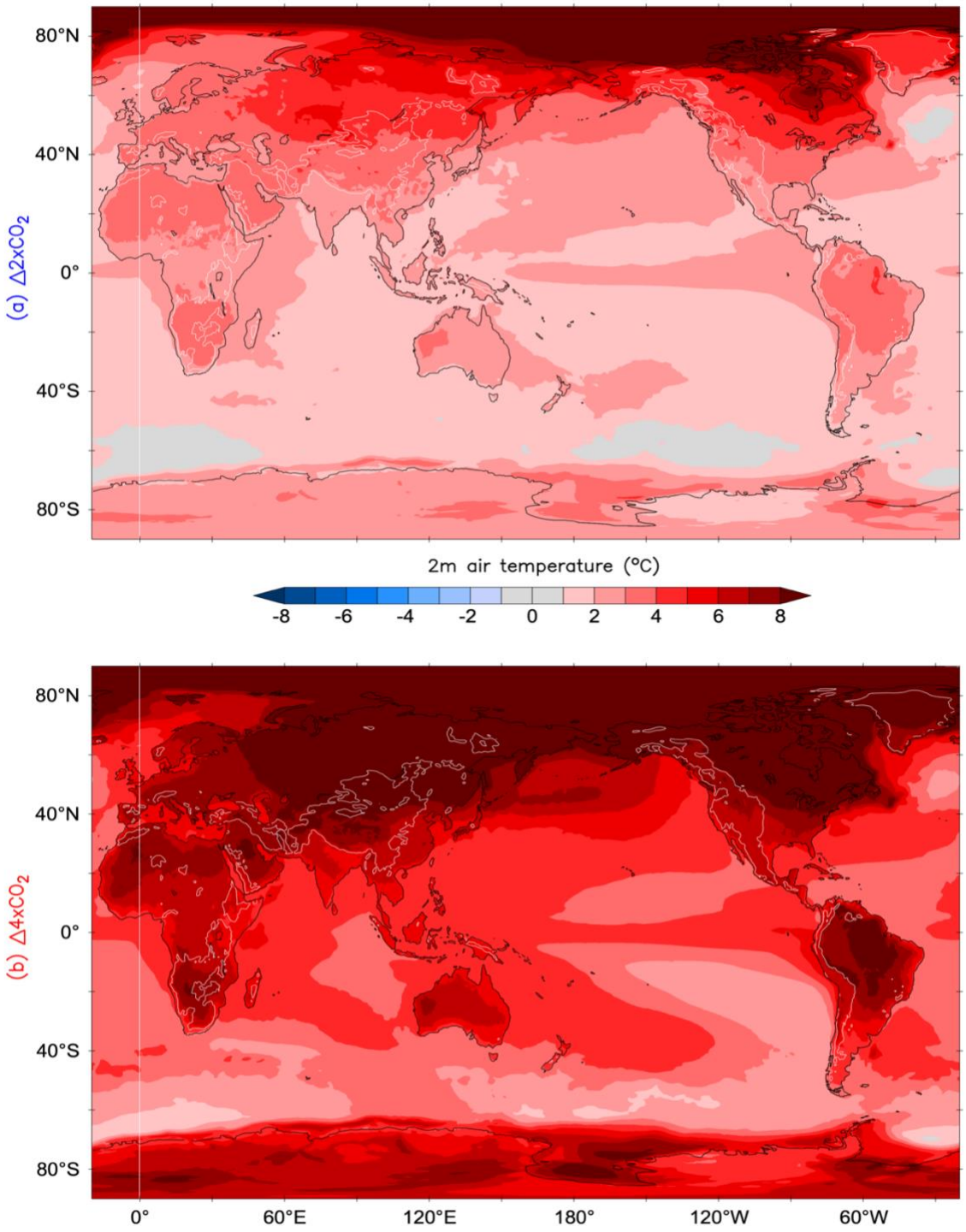


**Fig. S1. Global mountain system warming in response to $CO_2$ perturbation**. Change in 2 m air temperature between (a) 2x$CO_2$ and PD and (b) 4x$CO_2$ and PD. White contour presents global mountain regions (excluding antarctica) with the elevation is higher than 1km.

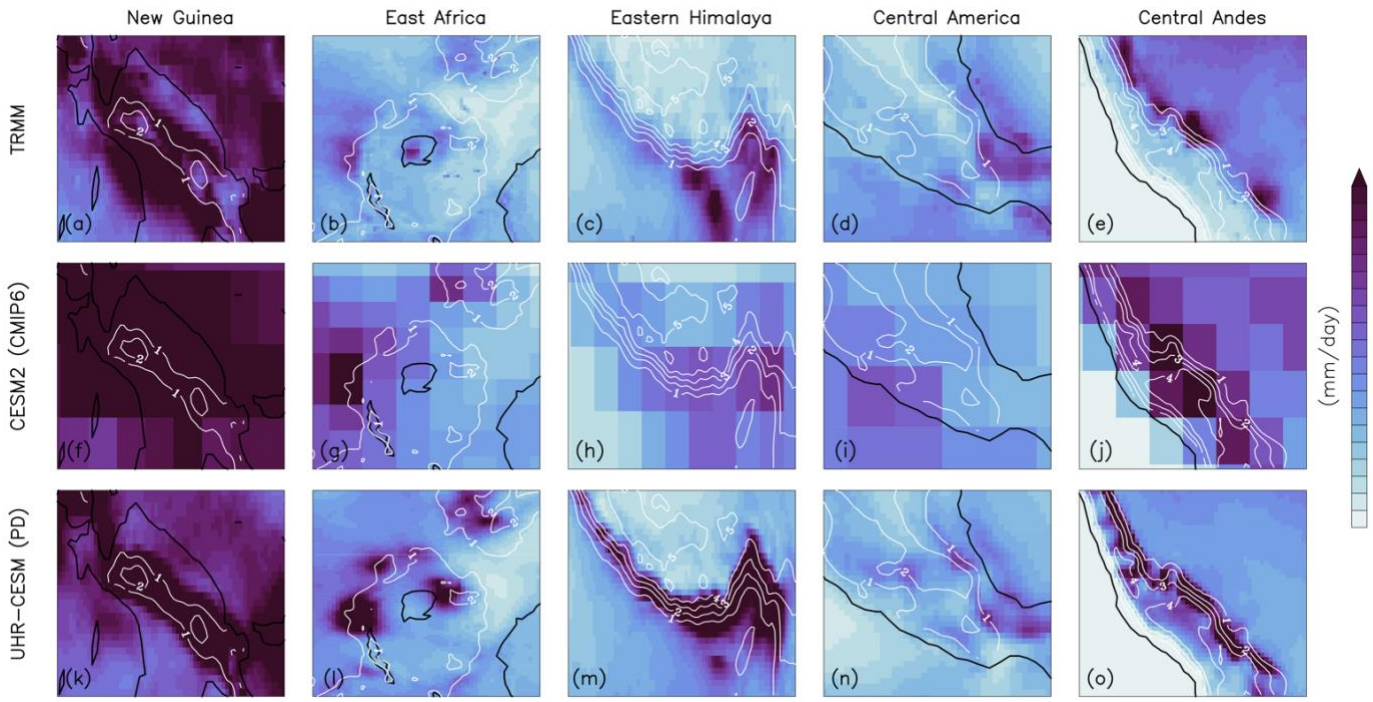


**Fig. S2. Annual mean precipitation in observation and model simulation.** Annual mean precipitation climatology over chosen mountains from (a-e) satellite product, (f-j) CESM2 simulation having about 100 km nominal resolution, and (k-o) PD simulation having about 25 km resolution from UHR-CESM. The satellite dataset was obtained from the Tropical Rainfall Measurement Mission (TRMM, http://disc.sci.gsfc.nasa.gov/)(Huffman et al., 2010) 3B43 (this data merges the TRMM 3B42 product adjusted with the GPCC rain gauge) during 2000-2019 and the CESM2 model data from Coupled Model Intercomparison Project Phase 6 (CMIP6, https://www.cesm.ucar.edu/projects/CMIP6/)(Danabasoglu et al., 2020) during 1996-2015. The white contour shows an elevation orography of 1 km interval from the UHR-CESM for consistency and comparison.

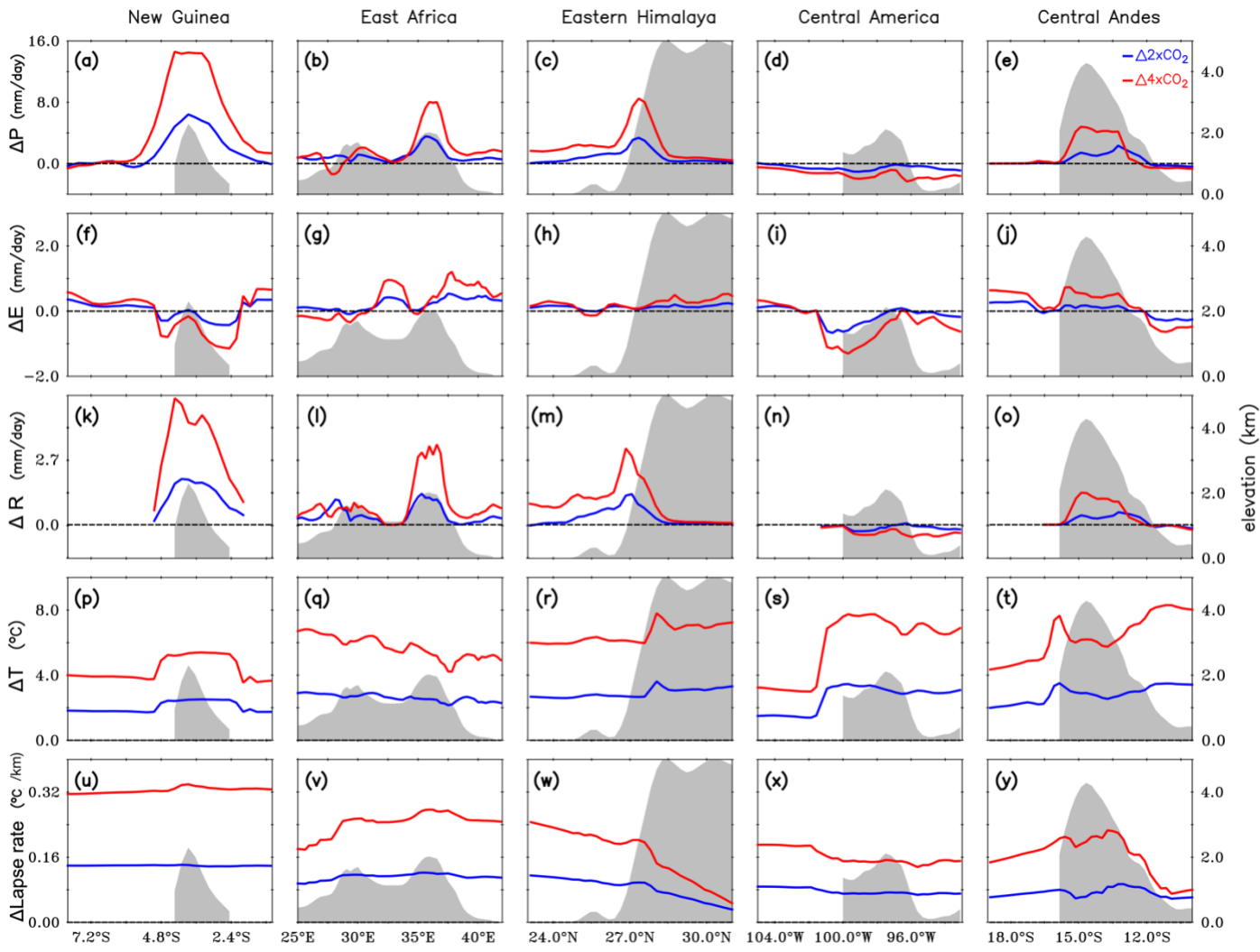


**Fig. S3. Changes in various parameters over selected major mountain regions in response to $CO_2$ perturbation.** Cross-section of precipitation (a-e), evaporation at surface (f-j), surface runoff (k-o), temperature (p-t), and lapse rate (u-y). The blue line indicates changes with respect to $2xCO_2$ anomalies, and the red line indicates changes with $4xCO_2$ anomalies. Shaded grey color represents orography.

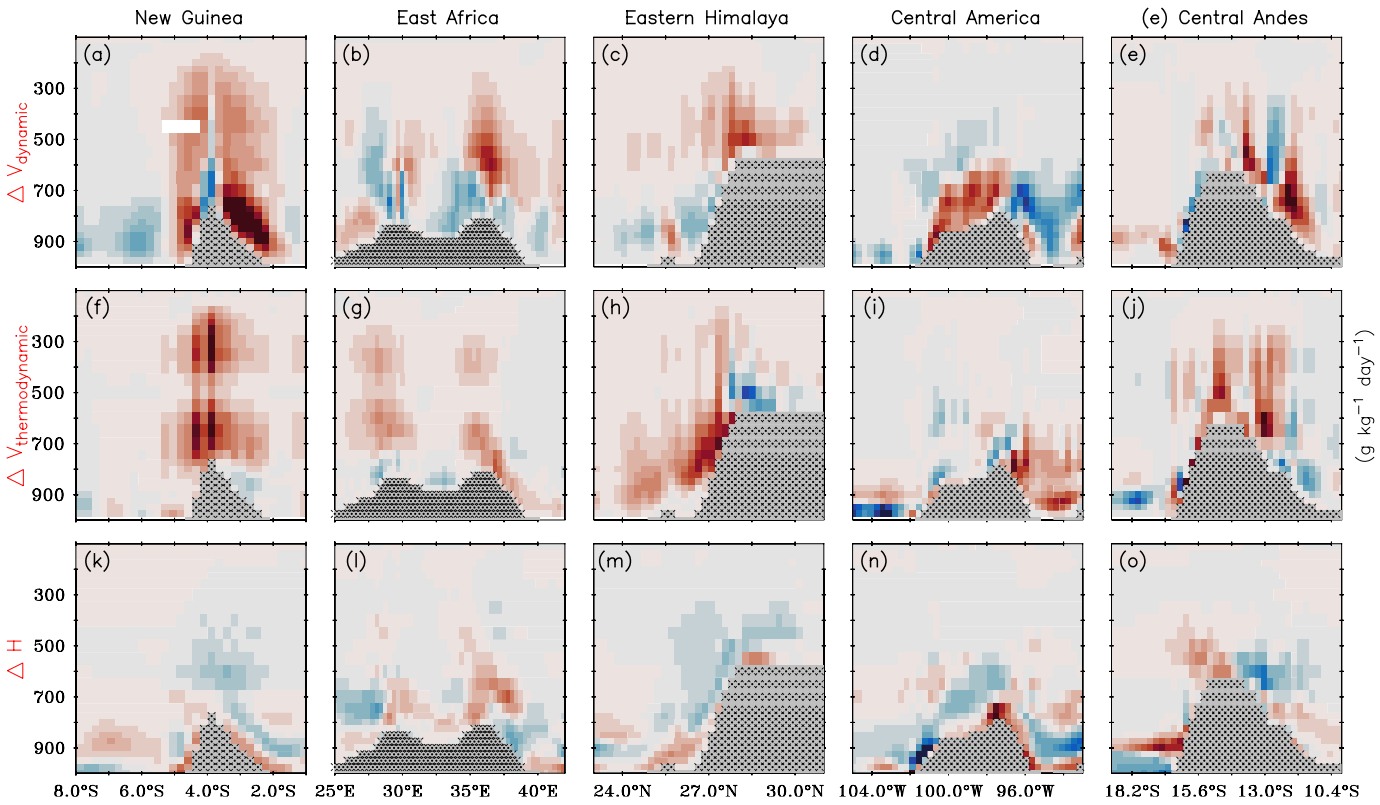


**Fig. S4. Vertical structure of anomalous moisture advection in response to 4x$CO_2$.** Shading denotes projected change in moisture advection over New Guinea, East Africa, Eastern Himalayas, Central America, and Central Andes. (a)-(e) Change in vertical dynamic moisture advection, (f)-(j) change in vertical thermodynamic moisture advection, and (k)-(o) change in horizontal moisture advection, respectively.

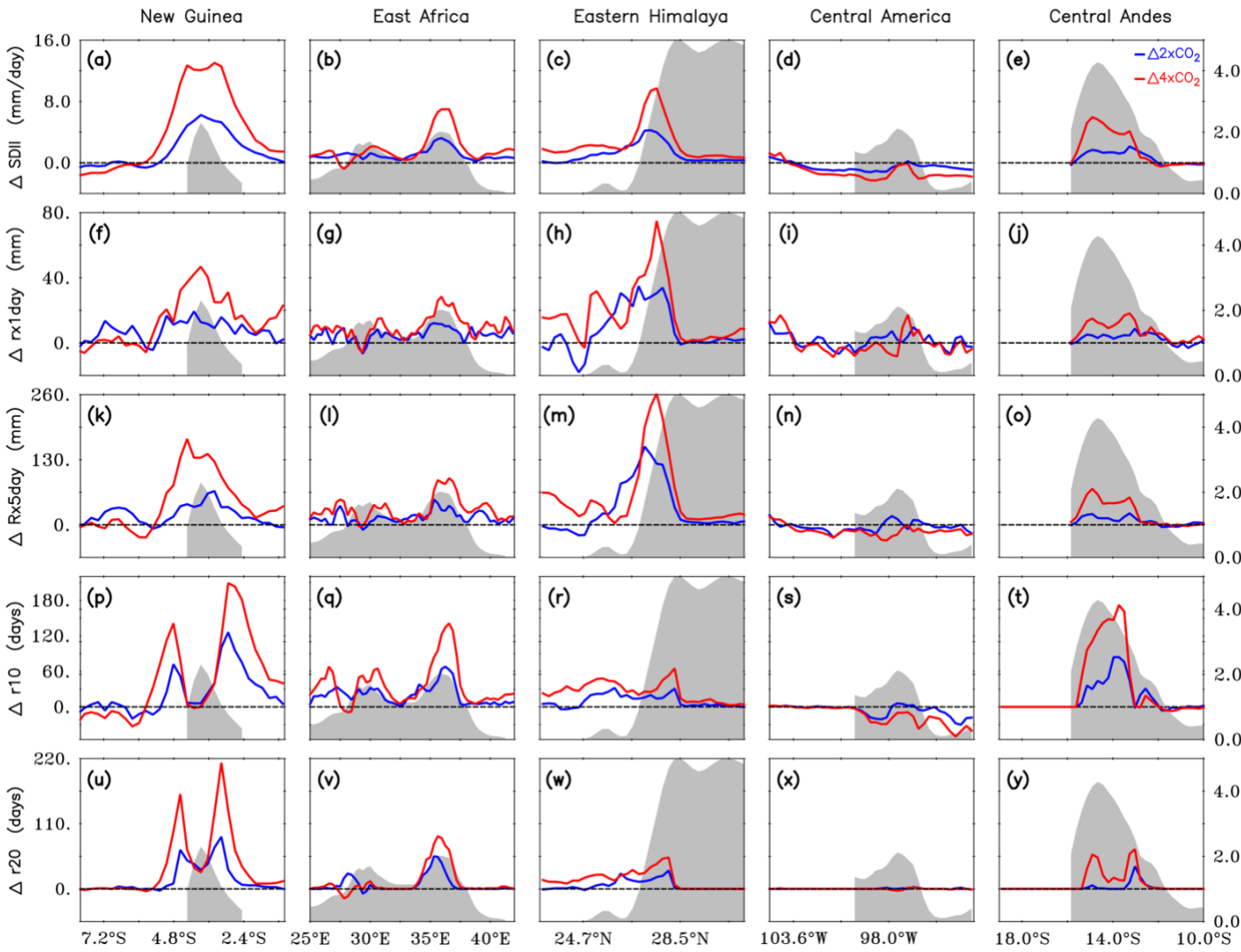


**Fig. S5. Changes in various extreme precipitation indices.** Cross-section of SDII (a-e), Rx1day (f-j), Rx5day (k-o), R10 (p-t), and R20 (u-y) shown with shaded grey color elevation orography (for more details in supplementary Table 1). The blue line indicates changes with respect to 2x$CO_2$ anomalies, and the red line indicates changes with 4x$CO_2$ anomalies.

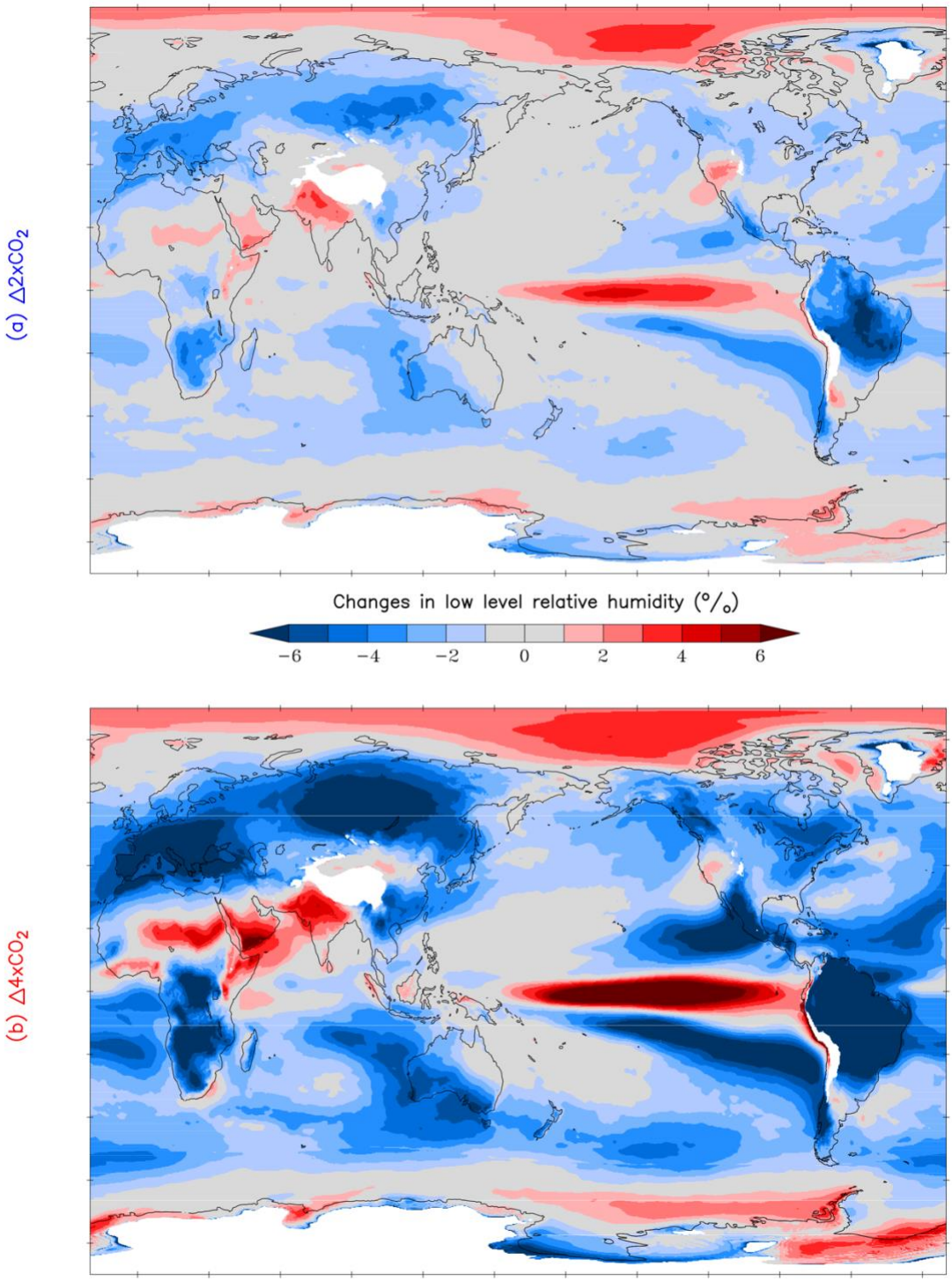


**Fig. S6. Relative humidity response to $CO_2$ perturbation**. The low-level relative humidity is defined mean of 750 hPa to 1000 hPa model pressure level.

**Supplementary References**

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., et al. (2020). The Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(2). https://doi.org/10.1029/2019MS001916

Huffman, G. J., Adler, R. F., Bolvin, D. T., & Nelkin, E. J. (2010). The TRMM Multi-satellite Precipitation Analysis (TMPA). In *Satellite Rainfall Applications for Surface Hydrology*. https://doi.org/10.1007/978-90-481-2915-7_1

Karl, T. R., Nicholls, N., & Ghazi, A. (1999). CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes - Workshop summary. In *Climatic Change* (Vol. 42). https://doi.org/10.1023/A:1005491526870