Supporting Information for South Asian Summer Monsoon Precipitation is Sensitive to Southern Hemisphere Subtropical Radiation Changes

Dipti Hingmire[1], Haruki Hirasawa[1], Hansi Singh[1,5], Philip J. Rasch[2],

Sookyung Kim[3,6], Subhashis Hazarika[3,6], Peetak Mitra[3,4], Kalai Ramea[3,5]

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada

[2]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA

[3]Palo Alto Research Corporation, Palo Alto, CA, USA

[4]Excarta, Palo Alto, CA, USA

[5]Planette Inc., San Francisco, CA, USA

[6]SRI International, Palo Alto, CA, USA

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Description of observations and reanalysis data

Monthly observation data used in this study includes precipitation from the Global Precipitation Climatology Project version 2.3 (GPCP; Adler et al. (2018)), Sea Surface Temperature (SST) data from Extended Reconstructed Sea Surface Temperature (ERSST), version 4 (Huang et al., 2015) and Top Of Atmosphere (TOA) radiation fluxes from Clouds and the Earth's Radiant Energy System Energy Balanced and Filled (CERES-EBAF) version 4.2 (Loeb et al., 2018). Gridded reanalyzed upper-air circulation products used in the study were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 (Hersbach et al., 2020). To calculate biases in the CESM2 we used 11 historical simulations from CMIP6 archive. The biases are calculated as the climatological mean difference between model and observations for the period 1979-2014, except for TOA radiation fluxes where we use climatology of 2004-2014, as the CERES instrument was launched in 1999.

CMIP6 Data

We used historical monthly data from 11 ensemble members of CESM2 (Danabasoglu et al., 2020) participating in CMIP6 to analyse the existing CESM2 biases. To calculate multimodel regression of SASM precipitation biases onto net TOA biases we used 32 CMIP6 (Eyring et al., 2016) ESMs as listed in table S1.

Figure Descriptions

Figures S1 to S8 provide additional support and insights on the findings detailed in the main text. The F_{TOA} response of fixing CDNC to 150 cm^{-3} for Atlantic and 75 cm^{-3} in other experiments is shown in Figure S1. Fixing CDNC produces a reduction of 4-12 Wm^{-2} in F_{TOA} radiation over the SH subtropical region (panels e-h Figure S1). Figure S2 shows the existing biases in the CESM2 with GPCP for different monsoon regions of the world. The CESM2 have biases in simulating climatological mean precipitation for other monsoon regions as well. Figures S3 to S7 show precipitation response of the radiation reduction experiments over other monsoon regions. For West African monsoon during May-June and July to September, the Atlantic experiment improves the Sahel precipitation bias by small amount while as other experiments have negligible effects (Figures S3 and S4). All the experiments show worsening of biases of southern hemisphere monsoons such as Australian monsoon and East/South African monsoon in December-February, (Figures S5 and S6) with exception of South American monsoon for which the Atlantic experiment shows improvement in precipitation biases over Brazil (Figure S7). Figure S8 depicts the relationship between Root Mean Square Errors (RMSE, calculated with GPCP for precipitation and CERES-EBAF for radiation) in net TOA and SASM precipitation for CMIP6 multimodel ensemble. The models having higher RMSE in SASM precipitation show errors in SH subtropical net TOA as well.

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Table S1. CMIP6 models used in this study

CMIP6 model	Ensemble member	CMIP6 model	Ensemble member
ACCESS-CM2	r1i1p1f1	E3SM-1-1	r1i1p1f1
ACCESS-ESM1-5	r1i1p1f1	E3SM-1-1-ECA	r1i1p1f1
AWI-CM-1-1-MR	r1i1p1f1	EC-Earth3-Veg-LR	r1i1p1f1
AWI-ESM-1-1-LR	r1i1p1f1	FGOALS-g3	r1i1p1f1
BCC-CSM2-MR	r1i1p1f1	GFDL-CM4	r1i1p1f1
BCC-ESM1	r1i1p1f1	GFDL-ESM4	r1i1p1f1
CESM2	r1i1p1f1	GISS-E2-1-G-CC	r1i1p1f1
CESM2-FV2	r1i1p1f1	INM-CM4-8	r1i1p1f1
CESM2-WACCM	r1i1p1f1	IPSL-CM6A-LR	r1i1p1f1
CESM2-WACCM-FV2	r1i1p1f1	MIROC-ES2L	r1i1p1f2
CMCC-CM2-SR5	r1i1p1f1	MIROC6	r1i1p1f1
CNRM-CM6-1	r1i1p1f2	MPI-ESM1-2-LR	r1i1p1f1
CNRM-CM6-1-HR	r1i1p1f2	MRI-ESM2-0	r1i1p1f1
CNRM-ESM2-1	r1i1p1f2	NESM3	r1i1p1f1
CanESM5-CanOE	r1i1p2f1	NorESM2-MM	r1i1p1f1
TaiESM1	r1i1p1f1	SAM0-UNICON	r1i1p1f1

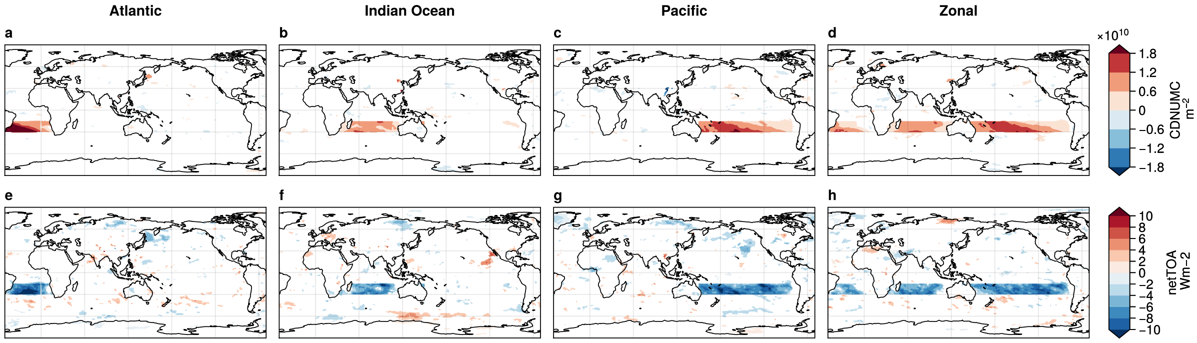

Figure S1. **Fixed-SST response:** Applied CDNC perturbations (cm^{-3}; a-d) and annual mean changes in F_{TOA} radiation (W m^{-2}; e-h) in fixed-SST simulations over different regions - (a,e) Atlantic, (b,f) Indian Ocean, (c,g) Pacific and (d,h) Zonal. Only significant ($p < 0.05$) changes are shown in colour.

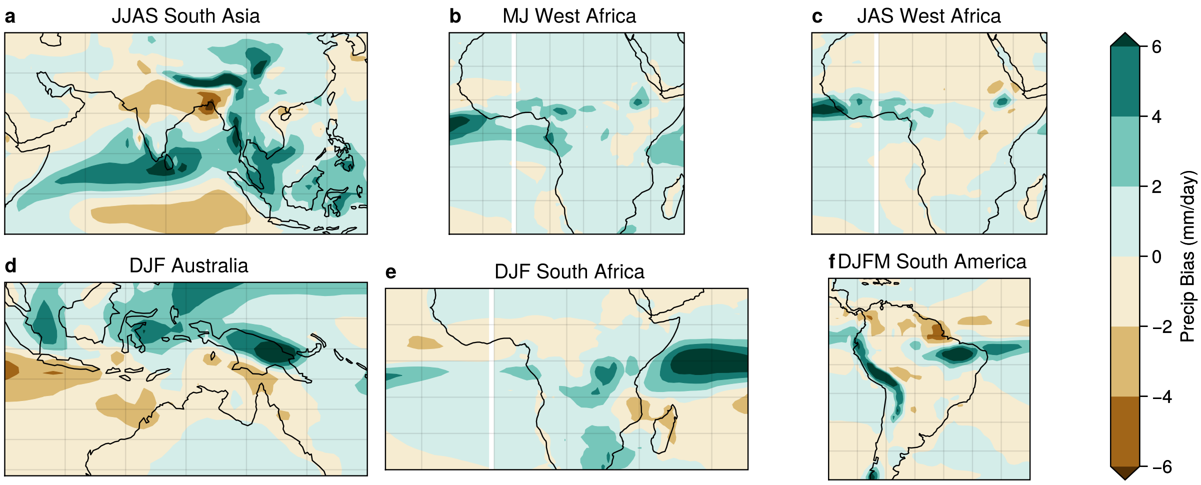

Figure S2. Existing biases in CESM2: Ensemble mean bias of CESM2 Precipitation with GPCP (mm/day) for a. June-September (JJAS) over South Asia, b. May-June (MJ) over West Africa, c. July-September (JAS) over West Africa, d. December-February (DJF) over Australia, e. DJF over South Africa and f. December-March (DJFM) over South America.

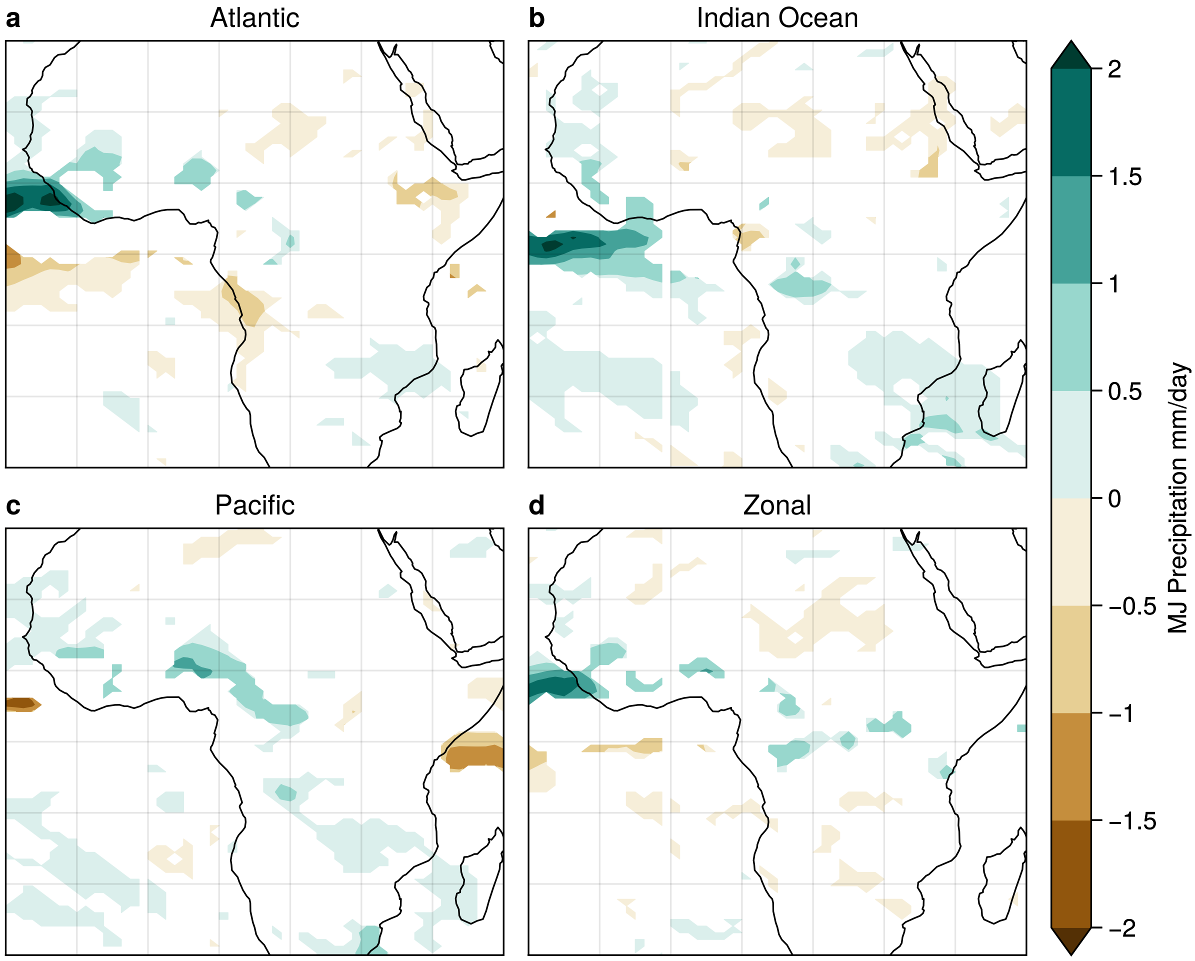

Figure S3. West African precipitation response: MJ precipitation response (mm/day) (at simulation period 121-150 years) in fully coupled simulation for experiments a. Atlantic, b. Indian Ocean, c. Pacific and d. Zonal. Non-significant responses (at level of significance 0.05) are masked in white.

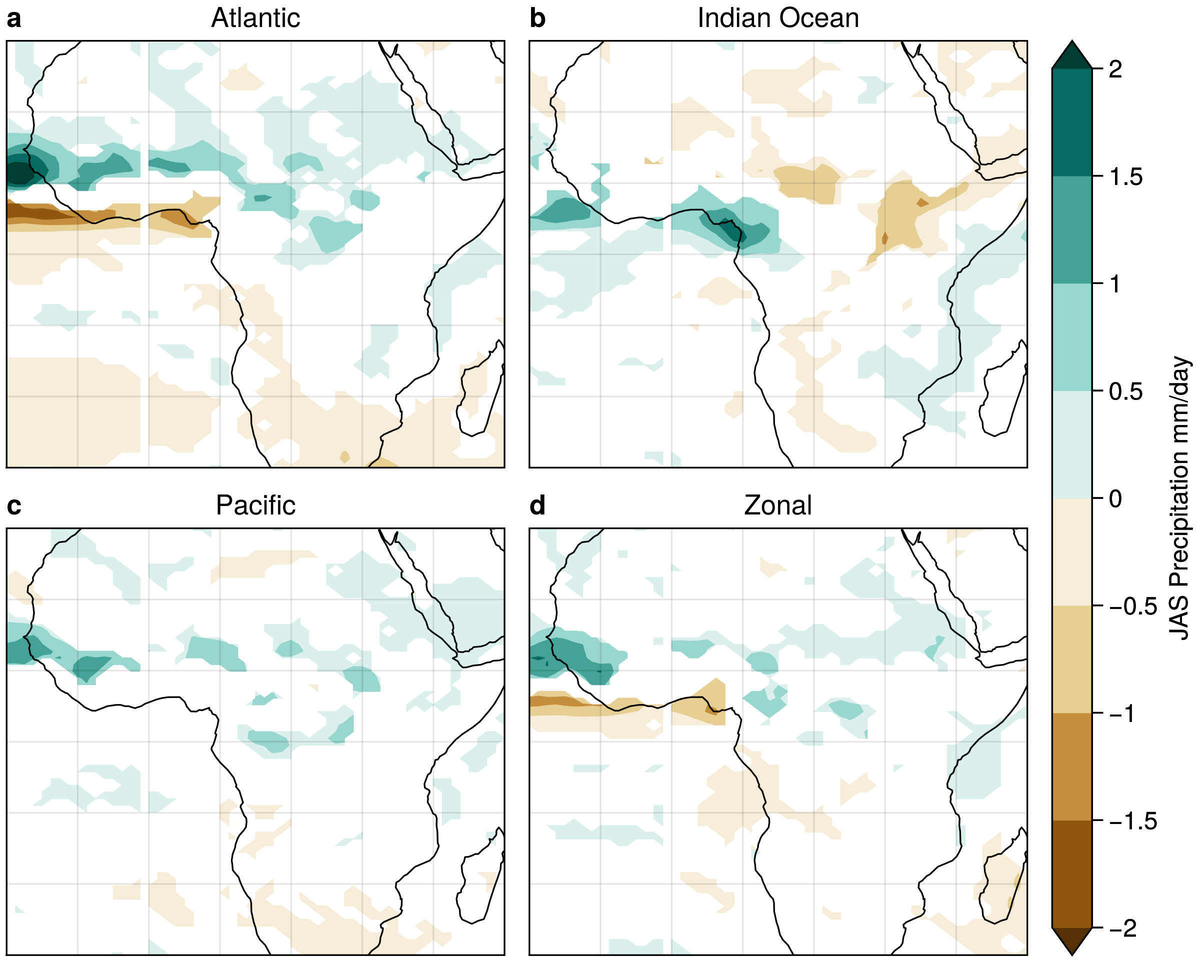

Figure S4. West African precipitation response: JAS precipitation response (mm/day) (at simulation period 121-150 years) in fully coupled simulation for experiments a. Atlantic, b. Indian Ocean, c. Pacific and d. Zonal. Non-significant responses (at level of significance 0.05) are masked in white.

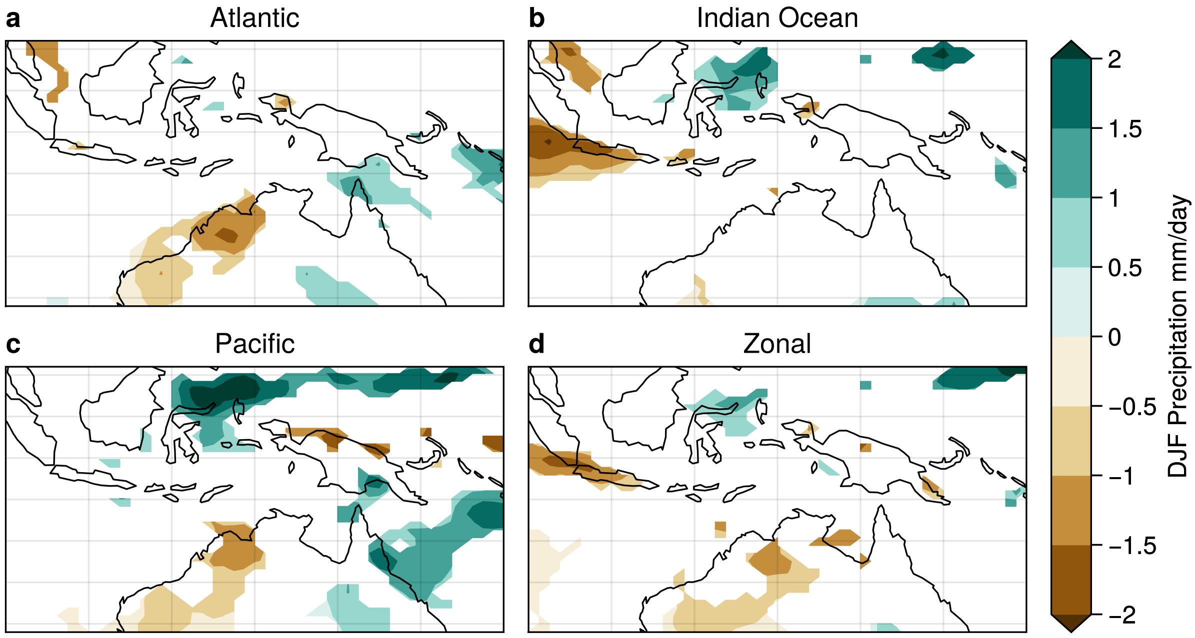

Figure S5. Australian monsoon precipitation response: DJF precipitation response (mm/day) (at simulation period 121-150 years) in fully coupled simulation for experiments a. Atlantic, b. Indian Ocean, c. Pacific and d. Zonal. Non-significant responses (at level of significance 0.05) are masked in white.

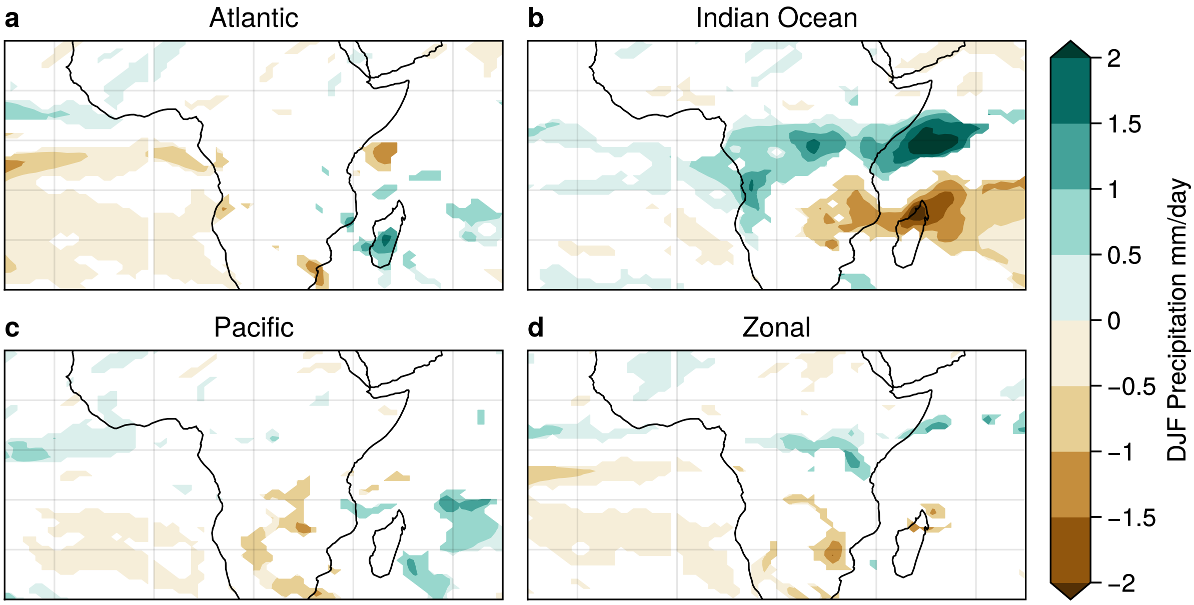

Figure S6. East African monsoon precipitation response: DJF precipitation response (mm/day) (at simulation period 121-150 years) in fully coupled simulation for experiments a. Atlantic, b. Indian Ocean, c. Pacific and d. Zonal. Non-significant responses (at level of significance 0.05) are masked in white.

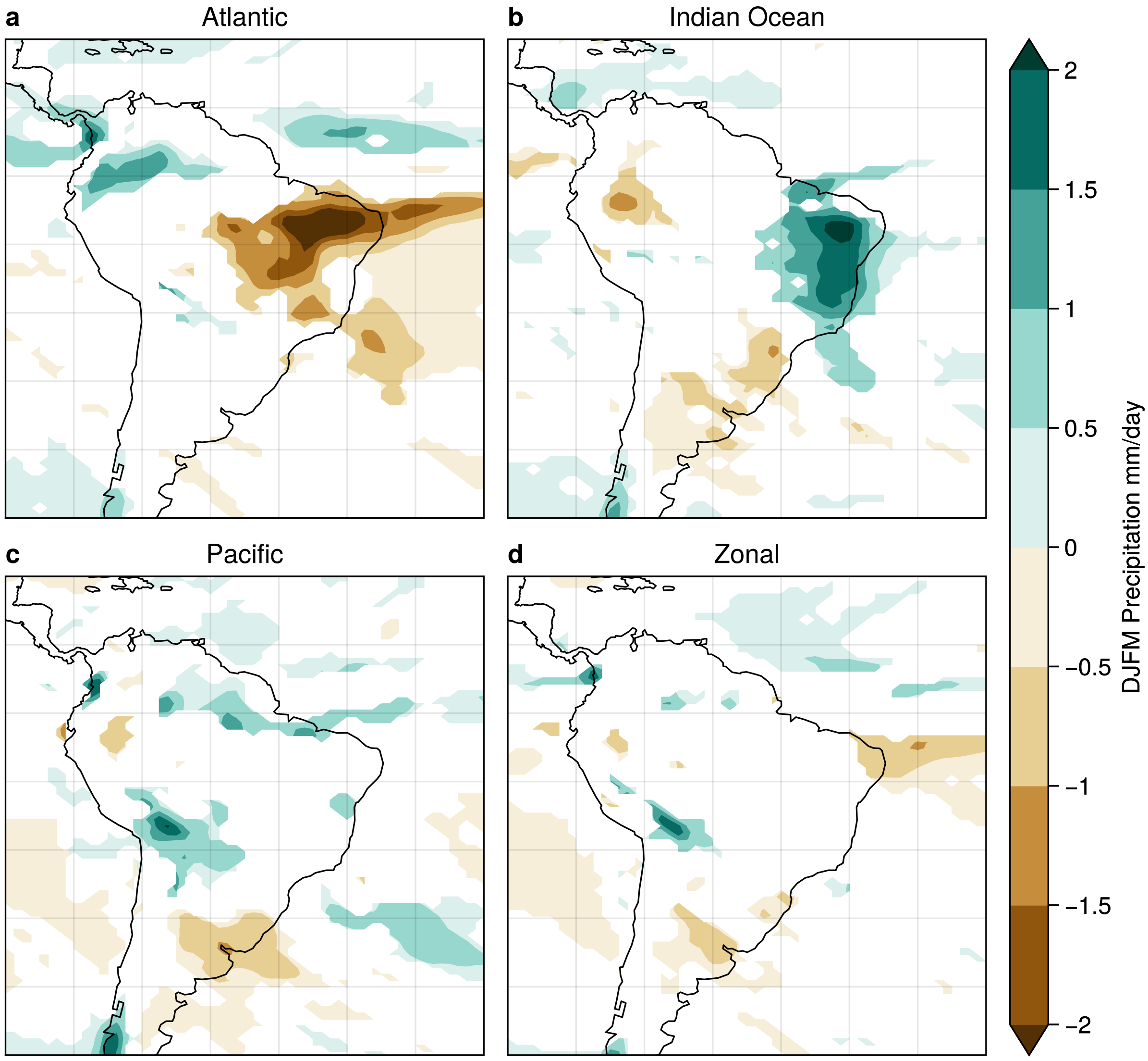

Figure S7. South American monsoon precipitation response: DJFM precipitation response (mm/day) (at simulation period 121-150 years) in fully coupled simulation for experiments a. Atlantic, b. Indian Ocean, c. Pacific and d. Zonal. Non-significant responses (at level of significance 0.05) are masked in white.

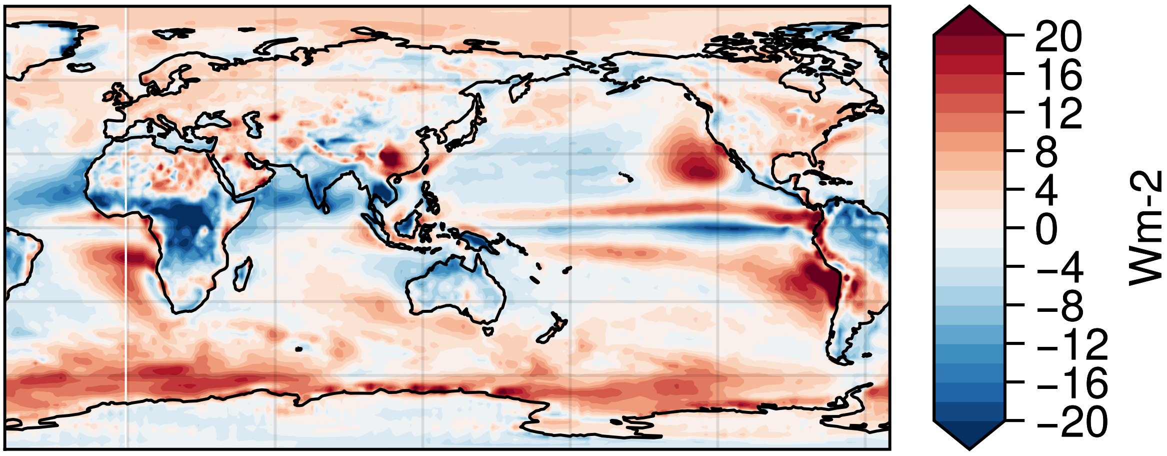

Figure S8. Regression of net TOA Root Mean Square Errors (RMSE) (W m^{-2}) and SASM precipitation RMSE (mm day^{-1}) in the CMIP6 multi-model ensemble evaluated when SASM precipitation RMSE is two standard deviations above the multi-model mean.