

Supplementary Materials

Spatial patterns of CMIP6-projected climate change across Andean–Amazonian ecoregions of northeastern Peru

Supplementary Tables S1–S8 and Figure S1

Historical reference period: 1985–2014
Future periods: 2031–2060 and 2071–2100
Scenarios: SSP2-4.5 and SSP5-8.5

Table S1. Data sources and preprocessing used in the study.

Dataset	Role in study	Variables / information	Period used	Spatial support	Processing
NEX-GDDP-CMIP6 v2.0	Historical climate simulations and future climate projections	tas; pr; rsds	1985-2014; 2031-2060; 2071-2100	0.25 degree native NEX-GDDP-CMIP6 grid	Daily tas and rsds aggregated to annual means; daily pr accumulated to annual totals; 30-year climatological means calculated; fields bilinearly remapped to the 0.01 degree analysis grid for spatial alignment
CHELSA v2.1	External gridded reference for historical climate evaluation	Temperature; precipitation; incoming shortwave solar radiation	1985-2014	CHELSA native grid; evaluated on a common 0.25 degree grid	Monthly temperature and solar radiation temporally weighted by number of days per month; monthly precipitation accumulated to annual totals; annual values averaged over 1985-2014; spatially harmonized to a common 0.25 degree grid for historical evaluation
SERNANP ecoregion spatial data	Spatial delineation of the three ecoregions analyzed	TSHBF; TSDBF; MGS	Not applicable	Vector polygons	Ecoregion polygons clipped to the Amazonas department; used for ecoregional extraction and area-based analyses
Amazonas departmental boundary	Spatial mask defining the study area	Amazonas department boundary	Not applicable	Vector polygon	Used for spatial masking, clipping, and area calculations within the study domain

Note: The 0.01° analysis grid was used for spatial alignment and ecoregional extraction. Bilinear interpolation from the native 0.25° NEX-GDDP-CMIP6 grid does not increase the effective spatial resolution of the original climate information.

Table S2. Historical evaluation of the five NEX-GDDP-CMIP6 models and their arithmetic multi-model ensemble against CHELSA v2.1 for 1985–2014.

Variable	Model	NEX	CHELSA	Bias	MAE	RMSE	r
Temperature	CESM2	21.23	19.71	1.52	1.71	2.18	0.942
Temperature	IPSL-CM6A-LR	22.06	19.71	2.35	2.40	2.81	0.944
Temperature	MIROC6	21.78	19.71	2.07	2.15	2.59	0.944
Temperature	MPI-ESM1-2-HR	21.88	19.71	2.17	2.24	2.67	0.944
Temperature	MRI-ESM2-0	21.82	19.71	2.11	2.19	2.62	0.944
Temperature	Ensemble	21.75	19.71	2.04	2.13	2.57	0.943
Precipitation	CESM2	1450.19	1903.12	-452.93	534.88	658.53	0.660
Precipitation	IPSL-CM6A-LR	1464.73	1903.12	-438.39	524.94	647.14	0.661
Precipitation	MIROC6	1474.52	1903.12	-428.60	528.67	649.04	0.658
Precipitation	MPI-ESM1-2-HR	1523.31	1903.12	-379.81	506.83	618.02	0.661
Precipitation	MRI-ESM2-0	1521.24	1903.12	-381.88	517.61	627.40	0.658
Precipitation	Ensemble	1486.80	1903.12	-416.32	520.90	639.30	0.660
Solar radiation	CESM2	230.01	197.70	32.31	32.31	32.95	0.324
Solar radiation	IPSL-CM6A-LR	230.24	197.70	32.54	32.54	33.18	0.310
Solar radiation	MIROC6	229.63	197.70	31.93	31.93	32.58	0.314
Solar radiation	MPI-ESM1-2-HR	229.30	197.70	31.61	31.61	32.26	0.324
Solar radiation	MRI-ESM2-0	228.58	197.70	30.88	30.88	31.54	0.335
Solar radiation	Ensemble	229.55	197.70	31.86	31.86	32.50	0.321

Note: Values are area-weighted spatial statistics evaluated over 72 common-grid cells (approximately 39,272.42 km²). Bias = NEX-GDDP-CMIP6 minus CHELSA. MAE = mean absolute error; RMSE = root mean square error; r = area-weighted spatial Pearson correlation coefficient. Units: °C for temperature, mm yr⁻¹ for precipitation, and W m⁻² for solar radiation.

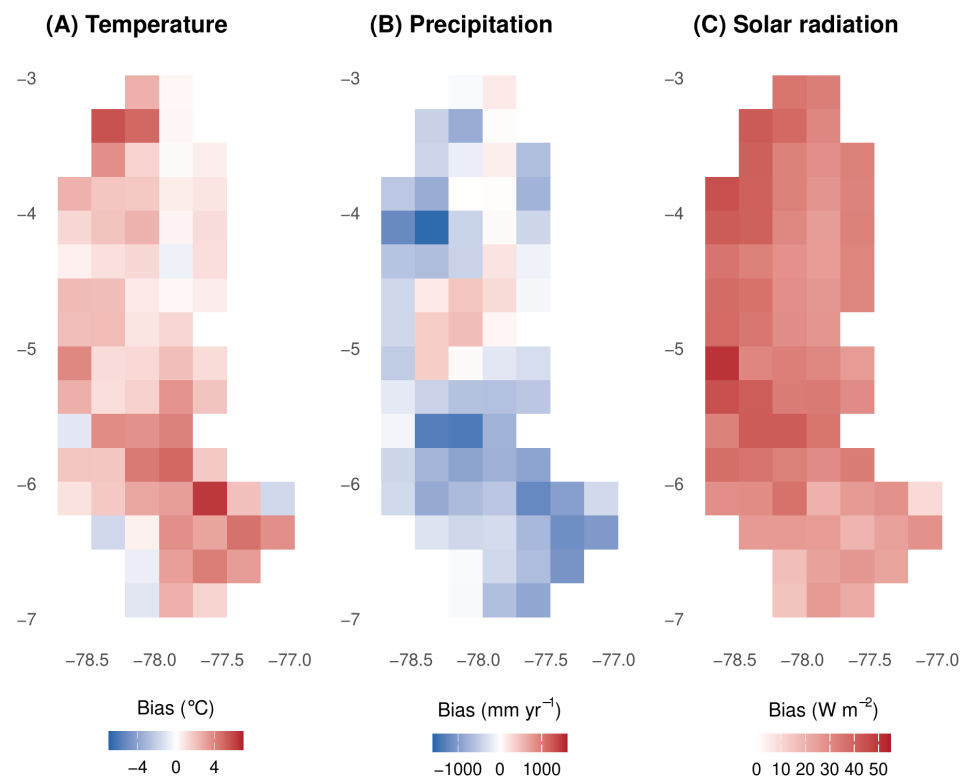


Figure S1. Spatial distribution of historical bias between the NEX-GDDP-CMIP6 multi-model ensemble (NEX-MME) and CHELSA v2.1 for 1985-2014: (A) near-surface air temperature, (B) annual precipitation, and (C) incoming shortwave solar radiation. Bias was calculated as NEX-MME minus CHELSA; therefore, positive values indicate overestimation and negative values indicate underestimation.

Table S3. Sensitivity of projected climate changes to the use of the arithmetic multi-model mean versus the multi-model median.

Variable	Scenario	Period	Mean	Median	Mean absolute difference	Same sign (%)
Temperature	SSP2-4.5	2031-2060	1.20	1.22	0.03	100.0
Temperature	SSP5-8.5	2031-2060	1.53	1.58	0.07	100.0
Temperature	SSP2-4.5	2071-2100	2.11	1.95	0.16	100.0
Temperature	SSP5-8.5	2071-2100	3.96	3.58	0.39	100.0
Precipitation	SSP2-4.5	2031-2060	3.95	1.71	2.25	97.1
Precipitation	SSP5-8.5	2031-2060	6.02	4.50	1.99	100.0
Precipitation	SSP2-4.5	2071-2100	10.61	9.80	1.65	100.0
Precipitation	SSP5-8.5	2071-2100	16.77	12.91	4.62	100.0
Solar radiation	SSP2-4.5	2031-2060	0.75	0.94	0.25	100.0
Solar radiation	SSP5-8.5	2031-2060	1.07	1.43	0.37	100.0
Solar radiation	SSP2-4.5	2071-2100	1.18	1.47	0.38	97.0
Solar radiation	SSP5-8.5	2071-2100	2.07	2.26	0.32	98.2

Note: Ensemble mean and median represent spatially averaged projected changes relative to 1985–2014. Temperature is expressed in °C, precipitation in %, and solar radiation in W m⁻². Same sign indicates the percentage of grid cells for which both ensemble estimators project the same direction of change.

Table S4. Leave-one-model-out sensitivity of projected precipitation change to the composition of the five-model ensemble.

Scenario	Period	Excluded model	Full ensemble (%)	Leave-one-out (%)	Difference (pp)
SSP2-4.5	2031-2060	CESM2	3.95	5.15	1.20
SSP2-4.5	2031-2060	IPSL-CM6A-LR	3.95	0.88	-3.07
SSP2-4.5	2031-2060	MIROC6	3.95	3.61	-0.34
SSP2-4.5	2031-2060	MPI-ESM1-2-HR	3.95	5.10	1.15
SSP2-4.5	2031-2060	MRI-ESM2-0	3.95	5.02	1.07
SSP5-8.5	2031-2060	CESM2	6.02	7.23	1.21
SSP5-8.5	2031-2060	IPSL-CM6A-LR	6.02	3.42	-2.60
SSP5-8.5	2031-2060	MIROC6	6.02	5.13	-0.89
SSP5-8.5	2031-2060	MPI-ESM1-2-HR	6.02	7.22	1.20
SSP5-8.5	2031-2060	MRI-ESM2-0	6.02	7.10	1.08
SSP2-4.5	2071-2100	CESM2	10.61	10.03	-0.58
SSP2-4.5	2071-2100	IPSL-CM6A-LR	10.61	7.26	-3.35
SSP2-4.5	2071-2100	MIROC6	10.61	10.80	0.19
SSP2-4.5	2071-2100	MPI-ESM1-2-HR	10.61	13.27	2.66
SSP2-4.5	2071-2100	MRI-ESM2-0	10.61	11.69	1.08
SSP5-8.5	2071-2100	CESM2	16.77	17.42	0.65
SSP5-8.5	2071-2100	IPSL-CM6A-LR	16.77	6.55	-10.22
SSP5-8.5	2071-2100	MIROC6	16.77	17.45	0.68
SSP5-8.5	2071-2100	MPI-ESM1-2-HR	16.77	22.55	5.78
SSP5-8.5	2071-2100	MRI-ESM2-0	16.77	19.87	3.10

Note: Full ensemble represents the spatially averaged precipitation change calculated from all five GCMs. Leave-one-out represents the corresponding change after excluding the indicated model. Difference is expressed in percentage points (pp).

Table S5. Temperature - area-weighted ecoregional climate statistics.

Ecoregion	Variable	Unit	Scenario	Period	Mean	Spatial SD
TSHBF	Temperature	°C	Historical	1985-2014	21.98	3.23
TSHBF	Temperature	°C	SSP2-4.5	2031-2060	23.18	3.23
TSHBF	Temperature	°C	SSP5-8.5	2031-2060	23.51	3.24
TSHBF	Temperature	°C	SSP2-4.5	2071-2100	24.10	3.24
TSHBF	Temperature	°C	SSP5-8.5	2071-2100	25.95	3.26
TSDBF	Temperature	°C	Historical	1985-2014	20.23	3.41
TSDBF	Temperature	°C	SSP2-4.5	2031-2060	21.41	3.41
TSDBF	Temperature	°C	SSP5-8.5	2031-2060	21.72	3.40
TSDBF	Temperature	°C	SSP2-4.5	2071-2100	22.28	3.41
TSDBF	Temperature	°C	SSP5-8.5	2071-2100	24.07	3.40
MGS	Temperature	°C	Historical	1985-2014	14.14	1.14
MGS	Temperature	°C	SSP2-4.5	2031-2060	15.36	1.13
MGS	Temperature	°C	SSP5-8.5	2031-2060	15.67	1.13
MGS	Temperature	°C	SSP2-4.5	2071-2100	16.24	1.13
MGS	Temperature	°C	SSP5-8.5	2071-2100	18.05	1.13

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity among raster cells and does not represent temporal variability or inter-model uncertainty.

Table S5 (continued). Precipitation - area-weighted ecoregional climate statistics.

Ecoregion	Variable	Unit	Scenario	Period	Mean	Spatial SD
TSHBF	Precipitation	mm yr ⁻¹	Historical	1985-2014	1553.98	596.84
TSHBF	Precipitation	mm yr ⁻¹	SSP2-4.5	2031-2060	1613.39	615.05
TSHBF	Precipitation	mm yr ⁻¹	SSP5-8.5	2031-2060	1640.91	621.10
TSHBF	Precipitation	mm yr ⁻¹	SSP2-4.5	2071-2100	1697.92	622.26
TSHBF	Precipitation	mm yr ⁻¹	SSP5-8.5	2071-2100	1781.98	640.63
TSDBF	Precipitation	mm yr ⁻¹	Historical	1985-2014	786.46	72.53
TSDBF	Precipitation	mm yr ⁻¹	SSP2-4.5	2031-2060	815.06	73.82
TSDBF	Precipitation	mm yr ⁻¹	SSP5-8.5	2031-2060	837.04	73.73
TSDBF	Precipitation	mm yr ⁻¹	SSP2-4.5	2071-2100	895.31	75.11
TSDBF	Precipitation	mm yr ⁻¹	SSP5-8.5	2071-2100	953.23	82.15
MGS	Precipitation	mm yr ⁻¹	Historical	1985-2014	787.77	17.04
MGS	Precipitation	mm yr ⁻¹	SSP2-4.5	2031-2060	830.88	20.44
MGS	Precipitation	mm yr ⁻¹	SSP5-8.5	2031-2060	868.01	25.12
MGS	Precipitation	mm yr ⁻¹	SSP2-4.5	2071-2100	934.39	29.80
MGS	Precipitation	mm yr ⁻¹	SSP5-8.5	2071-2100	1034.68	46.87

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity among raster cells and does not represent temporal variability or inter-model uncertainty.

Table S5 (continued). Solar radiation - area-weighted ecoregional climate statistics.

Ecoregion	Variable	Unit	Scenario	Period	Mean	Spatial SD
TSHBF	Solar radiation	W m ⁻²	Historical	1985-2014	229.11	3.02
TSHBF	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	229.88	2.87
TSHBF	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	230.22	2.81
TSHBF	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	230.37	2.61
TSHBF	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	231.35	2.27
TSDBF	Solar radiation	W m ⁻²	Historical	1985-2014	234.26	0.96
TSDBF	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	234.72	0.87
TSDBF	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	234.86	0.81
TSDBF	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	234.55	0.75
TSDBF	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	234.59	0.56
MGS	Solar radiation	W m ⁻²	Historical	1985-2014	233.81	0.71
MGS	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	234.45	0.68
MGS	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	234.62	0.66
MGS	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	234.32	0.65
MGS	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	234.25	0.50

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity among raster cells and does not represent temporal variability or inter-model uncertainty.

Table S6. Temperature - projected changes by ecoregion relative to 1985–2014.

Ecoregion	Variable	Unit	Scenario	Period	Change	Spatial SD
TSHBF	Temperature	°C	SSP2-4.5	2031-2060	1.21	0.04
TSHBF	Temperature	°C	SSP5-8.5	2031-2060	1.54	0.03
TSHBF	Temperature	°C	SSP2-4.5	2071-2100	2.12	0.04
TSHBF	Temperature	°C	SSP5-8.5	2071-2100	3.98	0.10
TSDBF	Temperature	°C	SSP2-4.5	2031-2060	1.19	0.01
TSDBF	Temperature	°C	SSP5-8.5	2031-2060	1.49	0.02
TSDBF	Temperature	°C	SSP2-4.5	2071-2100	2.06	0.03
TSDBF	Temperature	°C	SSP5-8.5	2071-2100	3.84	0.05
MGS	Temperature	°C	SSP2-4.5	2031-2060	1.21	0.01
MGS	Temperature	°C	SSP5-8.5	2031-2060	1.53	0.01
MGS	Temperature	°C	SSP2-4.5	2071-2100	2.10	0.02
MGS	Temperature	°C	SSP5-8.5	2071-2100	3.91	0.02

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity in projected change within each ecoregion.

Table S6 (continued). Precipitation - projected changes by ecoregion relative to 1985–2014.

Ecoregion	Variable	Unit	Scenario	Period	Change	Spatial SD
TSHBF	Precipitation	%	SSP2-4.5	2031-2060	3.94	0.73
TSHBF	Precipitation	%	SSP5-8.5	2031-2060	5.88	1.20
TSHBF	Precipitation	%	SSP2-4.5	2071-2100	10.13	2.63
TSHBF	Precipitation	%	SSP5-8.5	2071-2100	16.00	4.47
TSDBF	Precipitation	%	SSP2-4.5	2031-2060	3.65	0.96
TSDBF	Precipitation	%	SSP5-8.5	2031-2060	6.48	2.00
TSDBF	Precipitation	%	SSP2-4.5	2071-2100	13.95	2.72
TSDBF	Precipitation	%	SSP5-8.5	2071-2100	21.36	5.07
MGS	Precipitation	%	SSP2-4.5	2031-2060	5.47	0.35
MGS	Precipitation	%	SSP5-8.5	2031-2060	10.17	0.91
MGS	Precipitation	%	SSP2-4.5	2071-2100	18.59	1.40
MGS	Precipitation	%	SSP5-8.5	2071-2100	31.28	3.35

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity in projected change within each ecoregion.

Table S6 (continued). Solar radiation - projected changes by ecoregion relative to 1985–2014.

Ecoregion	Variable	Unit	Scenario	Period	Change	Spatial SD
TSHBF	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	0.77	0.21
TSHBF	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	1.11	0.30
TSHBF	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	1.25	0.50
TSHBF	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	2.24	0.86
TSDBF	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	0.46	0.11
TSDBF	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	0.60	0.16
TSDBF	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	0.29	0.22
TSDBF	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	0.32	0.49
MGS	Solar radiation	W m ⁻²	SSP2-4.5	2031-2060	0.64	0.05
MGS	Solar radiation	W m ⁻²	SSP5-8.5	2031-2060	0.81	0.08
MGS	Solar radiation	W m ⁻²	SSP2-4.5	2071-2100	0.51	0.10
MGS	Solar radiation	W m ⁻²	SSP5-8.5	2071-2100	0.44	0.25

Note: TSHBF = Tropical and Subtropical Humid Broadleaf Forests; TSDBF = Tropical and Subtropical Dry Broadleaf Forests; MGS = Montane Grasslands and Shrublands. Spatial SD describes spatial heterogeneity in projected change within each ecoregion.

Table S7. Area classified as climate-change hotspots by ecoregion under SSP5-8.5 for 2071–2100.

Variable	Scenario	Period	Ecoregion	P75 threshold	Hotspot area (km²)	Hotspot area (%)
Temperature	SSP5-8.5	2071-2100	TSHBF	4.04	9754.17	27.4
Temperature	SSP5-8.5	2071-2100	TSDBF	4.04	0.00	0.0
Temperature	SSP5-8.5	2071-2100	MGS	4.04	0.00	0.0
Precipitation	SSP5-8.5	2071-2100	TSHBF	18.59	7680.15	21.6
Precipitation	SSP5-8.5	2071-2100	TSDBF	18.59	1622.86	53.8
Precipitation	SSP5-8.5	2071-2100	MGS	18.59	427.72	100.0
Solar radiation	SSP5-8.5	2071-2100	TSHBF	2.69	9767.20	27.4
Solar radiation	SSP5-8.5	2071-2100	TSDBF	2.69	0.00	0.0
Solar radiation	SSP5-8.5	2071-2100	MGS	2.69	0.00	0.0

Note: Hotspots were defined as grid cells exceeding the 75th percentile of projected change across the Amazonas department. Threshold units are °C for temperature, % for precipitation, and W m⁻² for solar radiation. This is a relative spatial classification and not an ecological impact or risk threshold.

Table S8. Inter-model spread and directional agreement under SSP5-8.5 for 2071–2100 relative to 1985–2014.

Variable	Unit	Change min	Change max	Spread min	Spread max	40%	60%	80%	100%
Temperature	°C	3.74	4.21	0.91	1.19	0.0	0.0	0.0	100.0
Precipitation	%	8.40	36.62	14.49	48.94	0.0	22.6	70.5	6.9
Solar radiation	W m ⁻²	-0.73	4.41	1.03	4.82	1.8	56.1	40.7	1.3

Note: Directional agreement indicates the percentage of valid grid cells at which 2/5 (40%), 3/5 (60%), 4/5 (80%), or 5/5 (100%) of the selected GCMs agreed on the direction of projected change. Directional agreement does not represent model accuracy, probability, or statistical confidence.