HEAT ANALYSIS APPENDIX

Kerala, India

April 2024

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Methodology

CHELSA-downscaled Monthly Climatologies

To develop high-resolution (1 km) heat projections for Kerala State, we downscaled maximum temperature outputs from 17 global climate models (GCMs) that participated in CMIP6 for two scenarios, SSP5-8.5 and SSP2-4.5. The downscaling was achieved using a statistical downscaling method known as the CHELSA method (Karger, 2022) which perturbs a high-resolution reference dataset (Karger et al., 2017) by projected deltas. We used a modified version of the CHELSA method described in Lute (2023). More specifically, we computed changes in the monthly climatologies of maximum temperature from each GCM between a reference period (1981–2010) and a period of interest (we used 1990–2020, 2020–2040, and 2040–2060, labeled as hist, 2030, and 2050, respectively). These deltas were interpolated to the 1-km spatial resolution CHELSA reference grid and then added to the CHELSA reference data, which represents the period 1981–2010. The resulting data is monthly climatologies of maximum temperature for 17 GCMs, three time periods, and two future scenarios at 1-km spatial resolution across Kerala.

Intermodel Variability and Model Subsetting

Preliminary analyses indicated that the 8 GCMs with higher native spatial resolution (~1° or less) had lower intermodel spread than the full GCM ensemble, and generally had lower intermodel spread than the average of 100 random samples of the same size (n=8) from the full set (n=17; Figures A1–A9). Therefore, a subset of higher-resolution models was used to prepare the final table (Table A1) and figures (Figures 1–3; Figures A10-A18). These models were those that had native spatial resolutions of ~1° or less (n=8) and included CNRM-CM6-1, CNRM-CM6-1-HR, CNRM-ESM2-1, EC-Earth3-Veg-LR, GFDL-CM4, MIROC6, MPI-ESM1-2-HR, and MRI-ESM2-0. In both cases (higher-resolution subset and full ensemble), the intermodel spread was higher for the later (2050) time period, as expected.

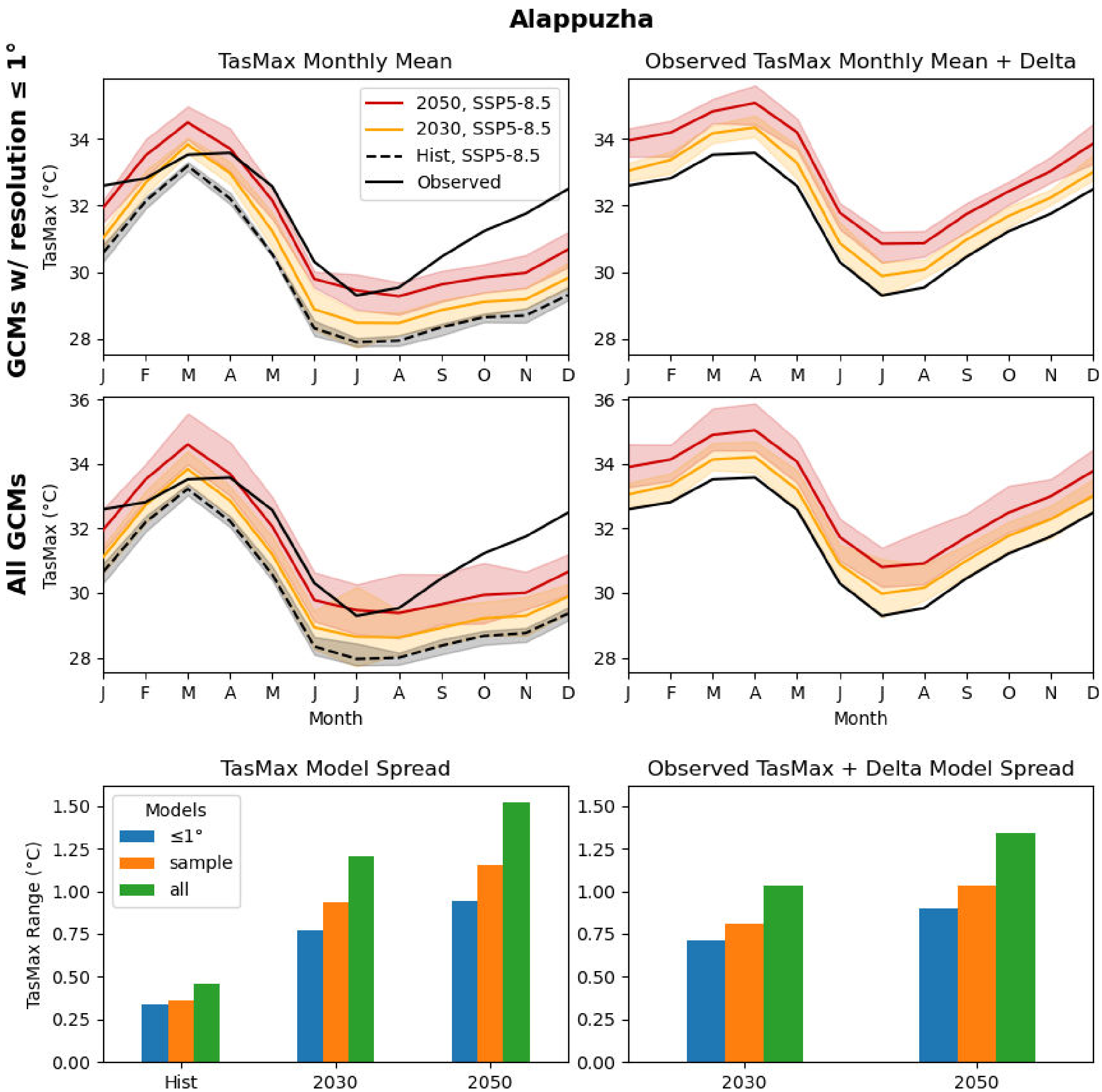

Figure A1. Comparison of intermodel spread at the Alappuzha station. The top row shows the seasonal cycle using observations (1990–2020, solid black line) and the higher-resolution model subset for three time periods under the SSP5-8.5 scenario; the intermodel range is shaded. The same is shown in the middle row, but using the full model ensemble. The bottom row compares the intermodel spread between the full ensemble (n=17), the higher-resolution subset (n=8), and the mean of 100 random samples of 8 models from the 17 models. The left column uses the CHELSA-downscaled data. The right column uses the CHELSA-downscaled data adjusted to observations.

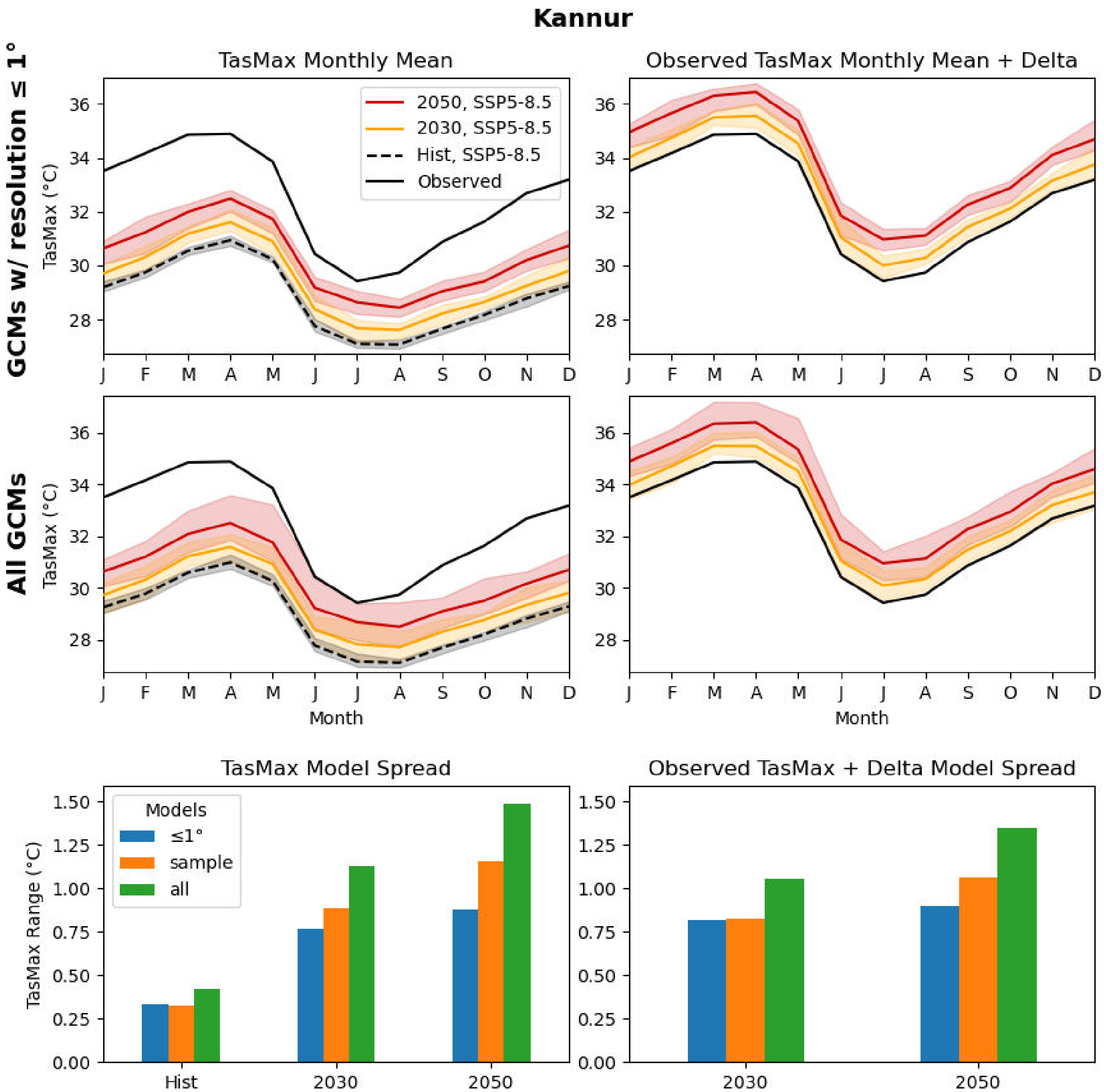

Figure A2. Comparison of intermodel spread at the Kannur station.

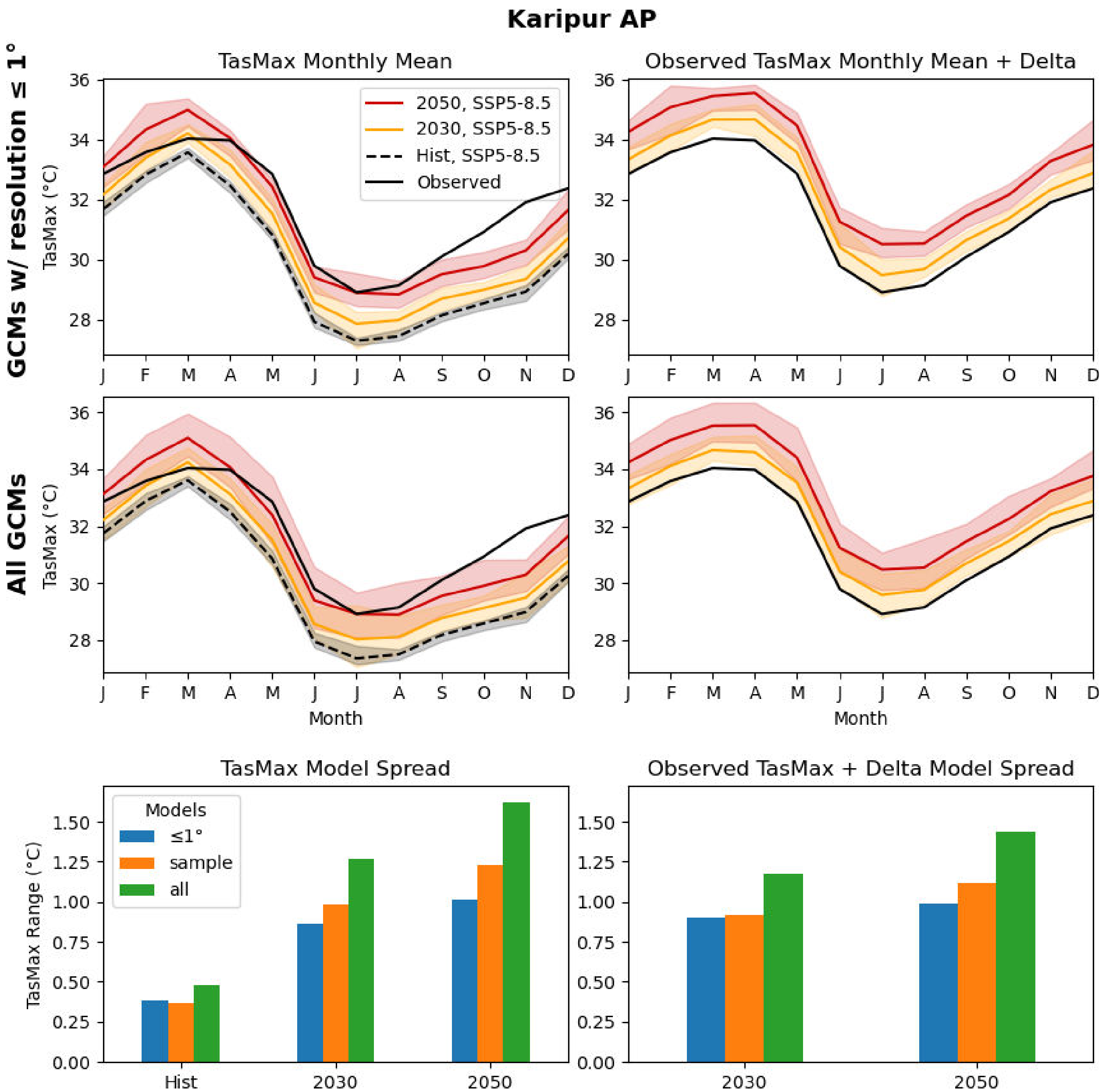

Figure A3. Comparison of intermodel spread at the Karipur Airport station.

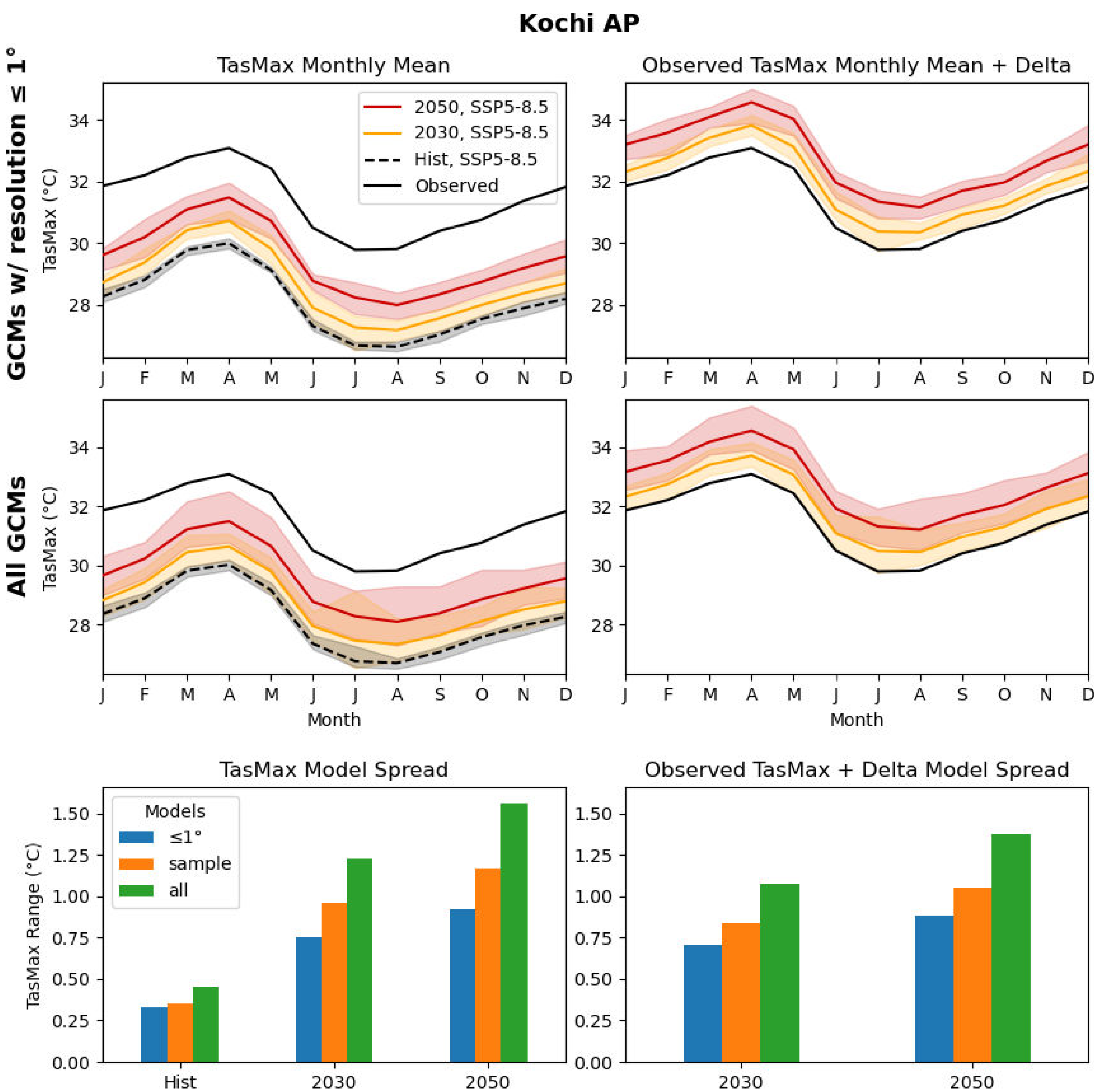

Figure A4. Comparison of intermodel spread at the Kochi Airport station.

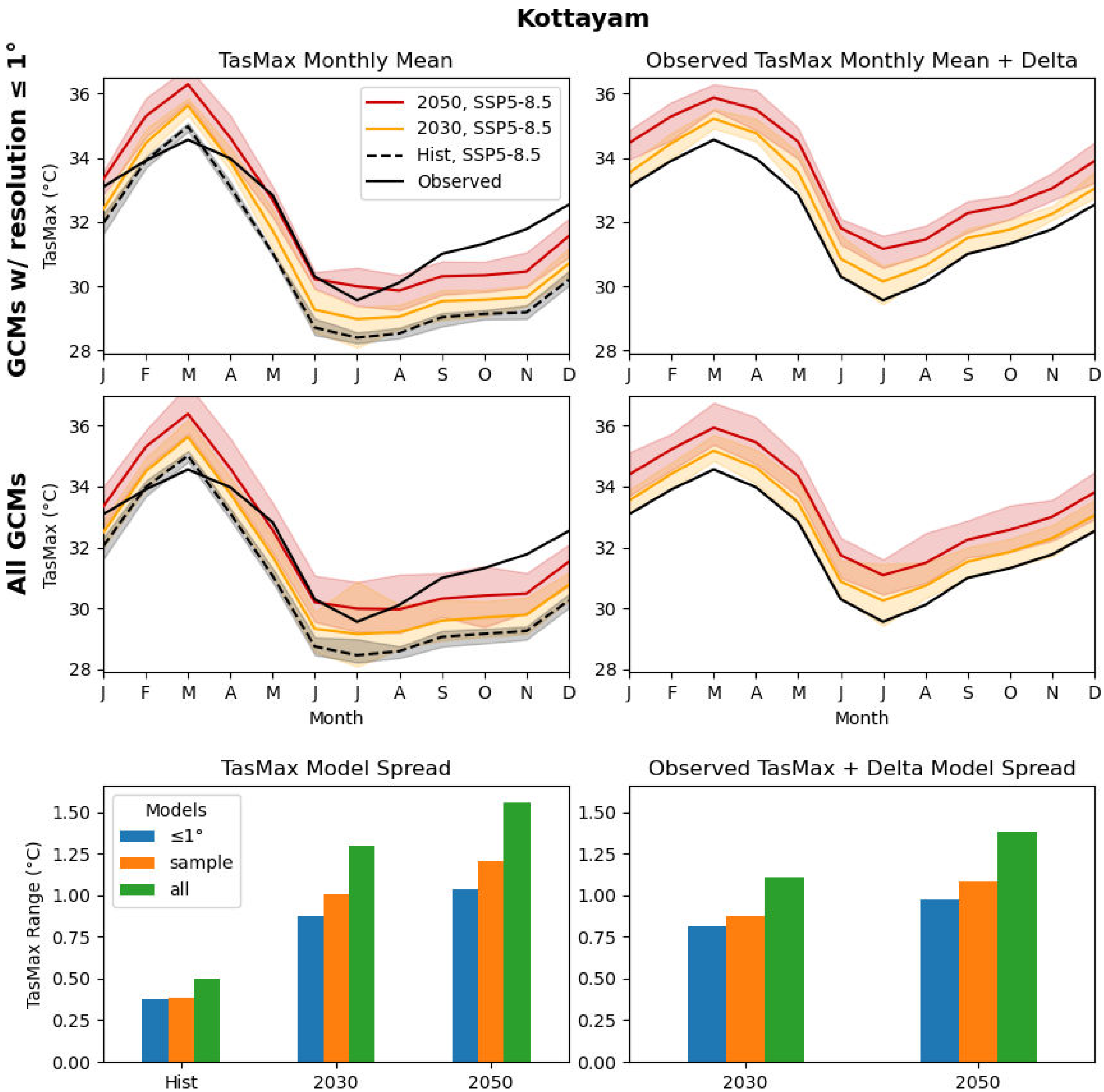

Figure A5. Comparison of intermodel spread at the Kottayam station.

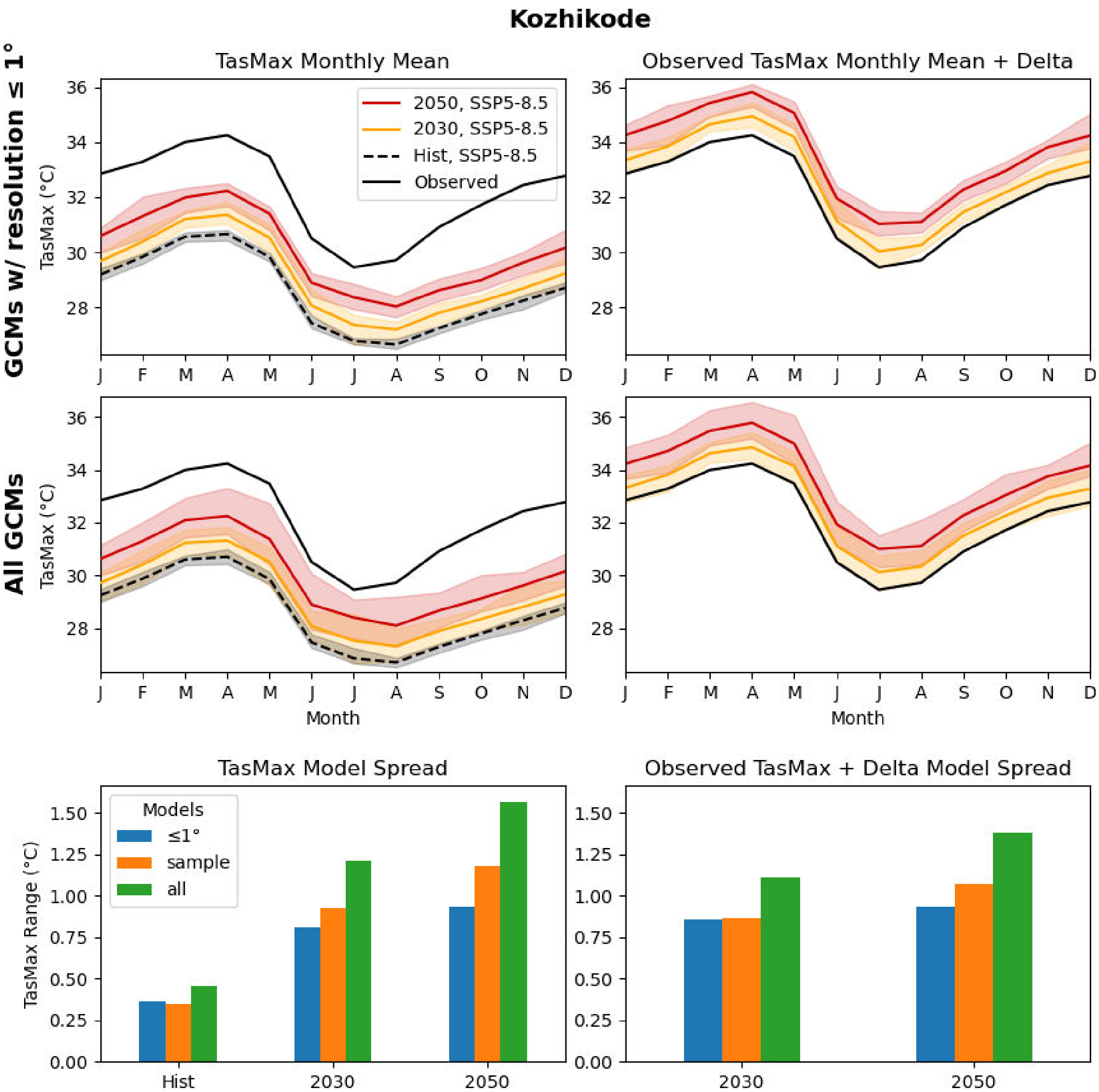

Figure A6. Comparison of intermodel spread at the Kozhikode City station.

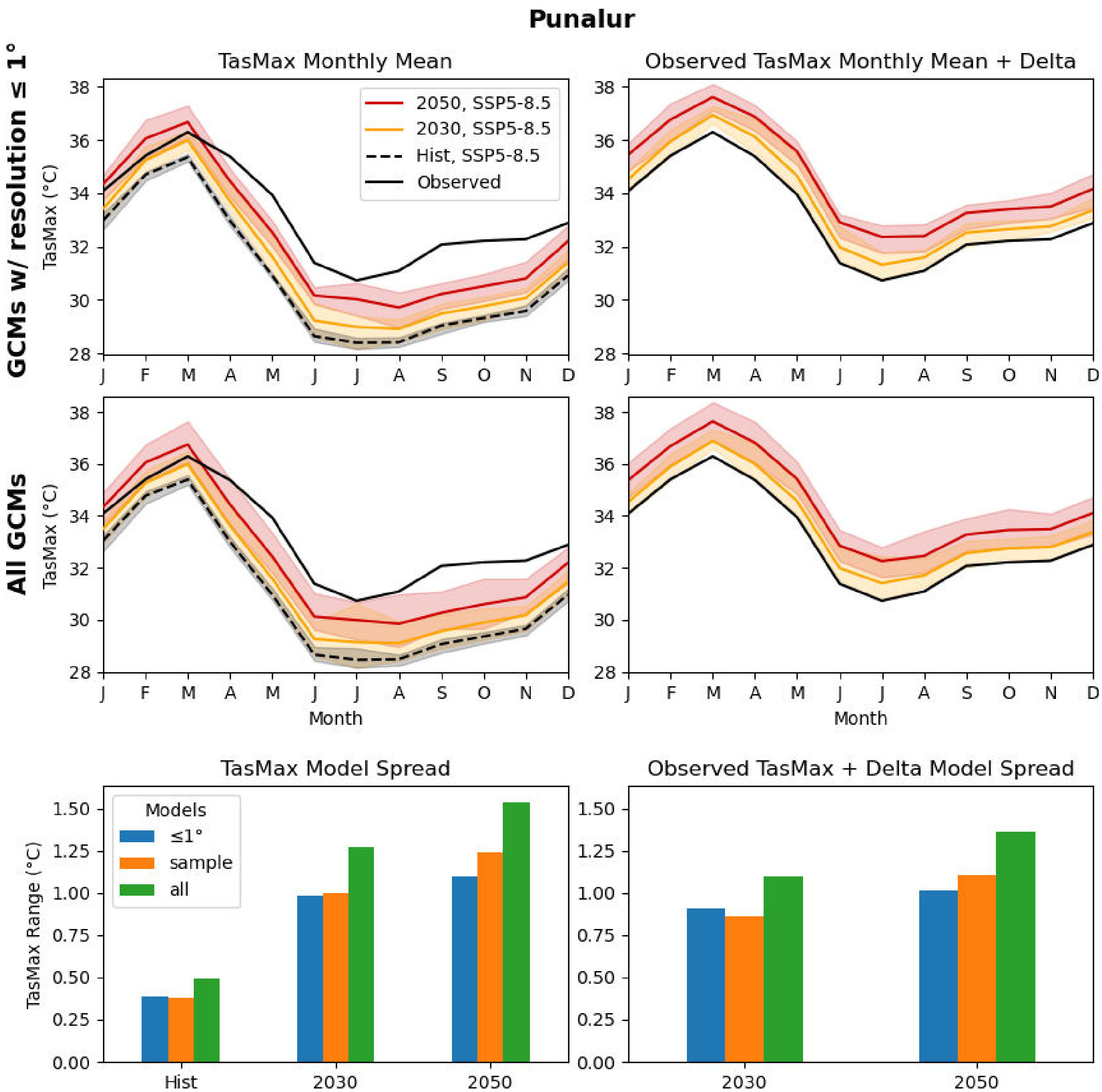

Figure A7. Comparison of intermodel spread at the Punalur station.

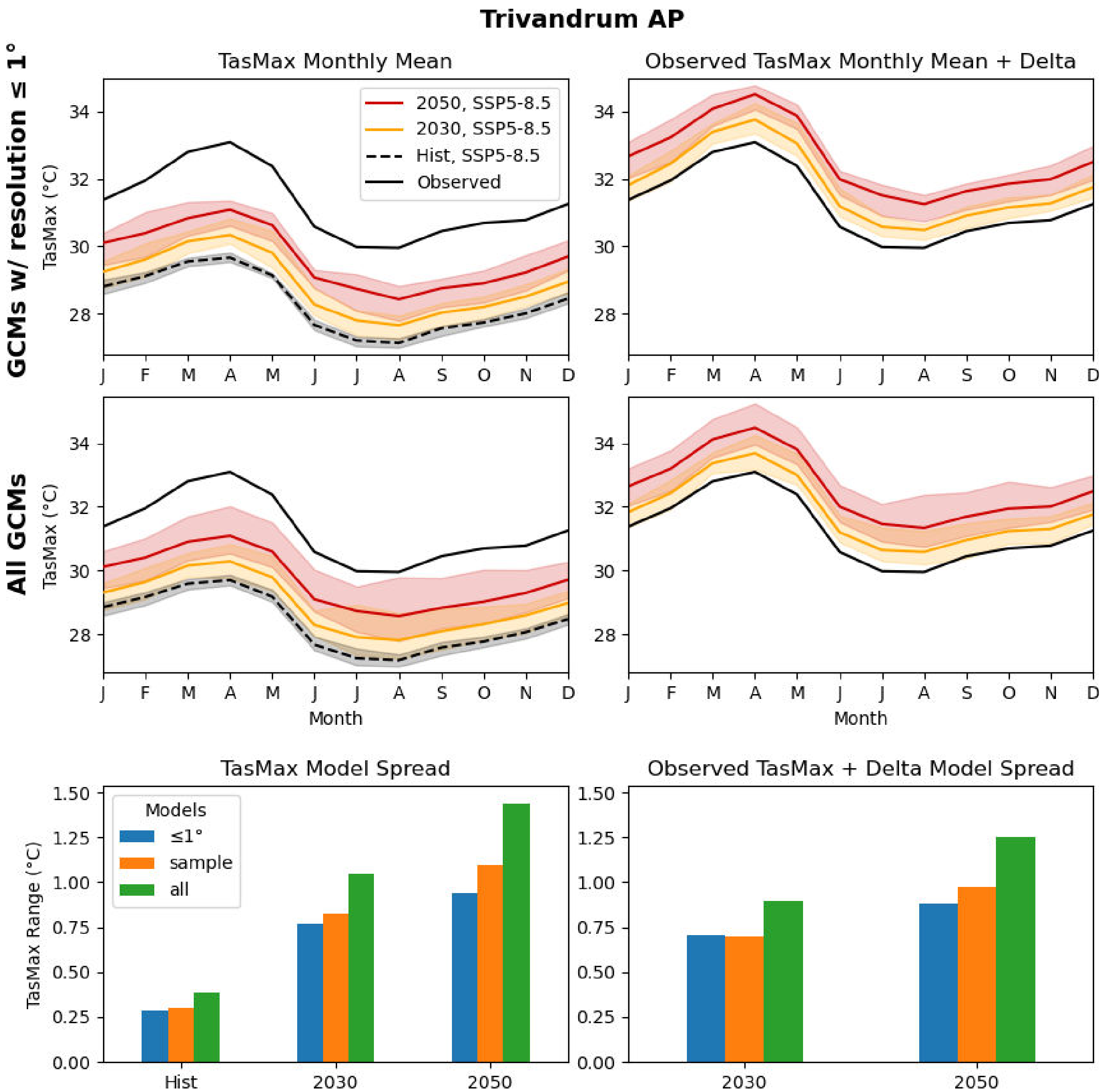

Figure A8. Comparison of intermodel spread at the Trivandrum Airport station.

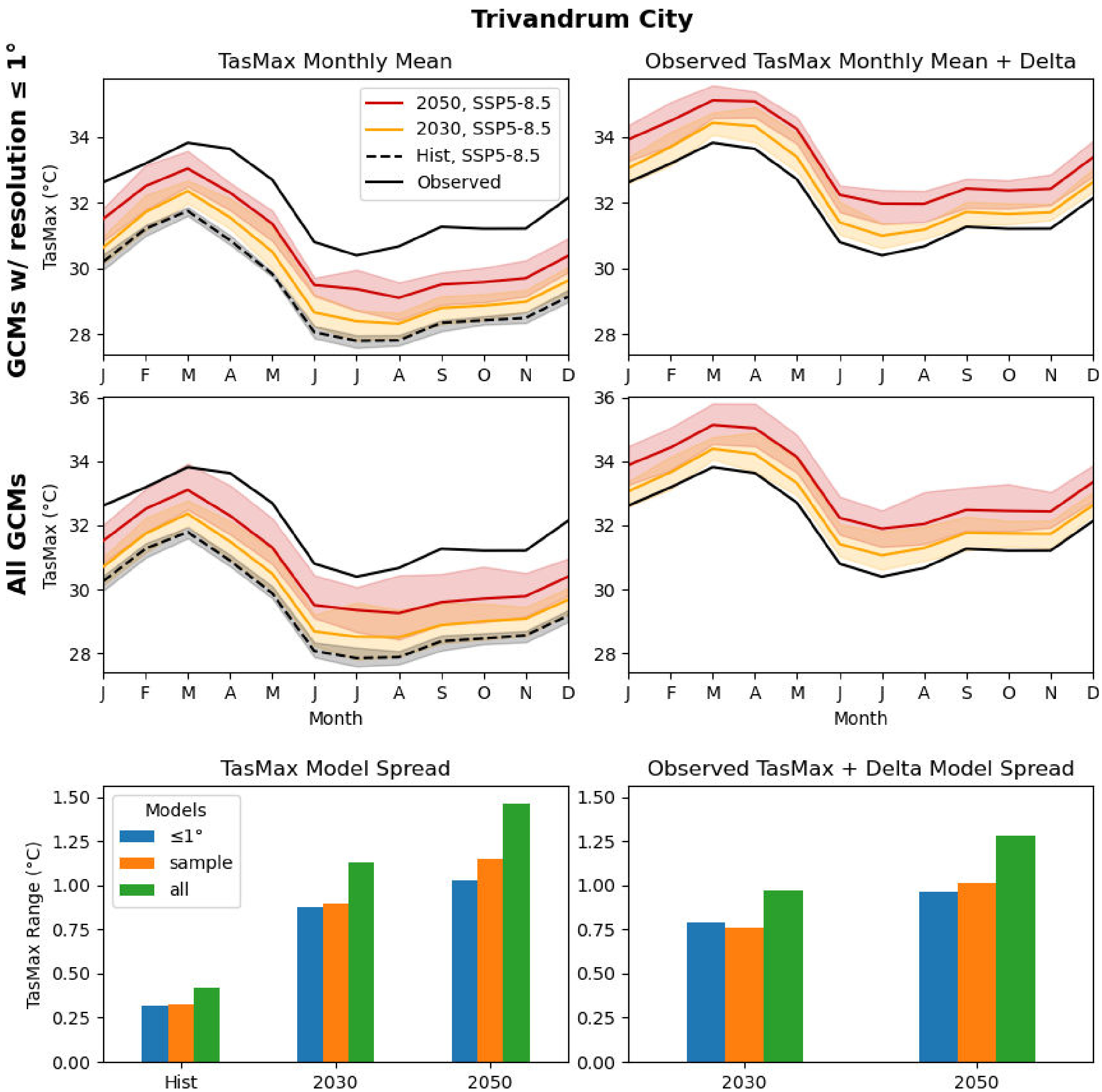

Figure A9. Comparison of intermodel spread at the Trivandrum City station.

Projected Seasonal Change

Comparison of the downscaled model output (from the higher-resolution subset[1]) with the observations showed that the models were underestimating the historical temperature climatology (Figures A10-A18, left). To more accurately represent the future seasonal cycle, the *delta method* for bias adjustment was used, in which the delta between each projected scenario-time period combination (e.g., SSP2-4.5, 2050) and the modeled historical climatology was added to the observed climatology (Figures A10-A18, right). The annual mean $T_{as,max}$ and delta for each station is listed in Table A1.

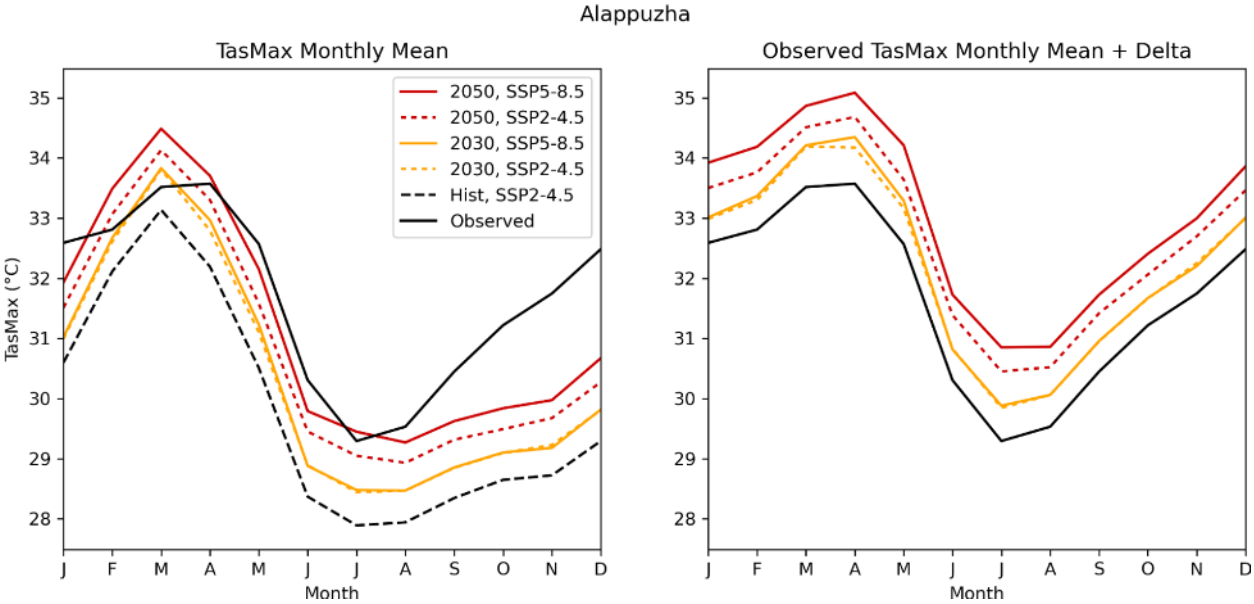

Figure A10. $T_{as,max}$ seasonal cycle at Alappuzha. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

[1] This was also true using the full model ensemble (Figures A1-A9).

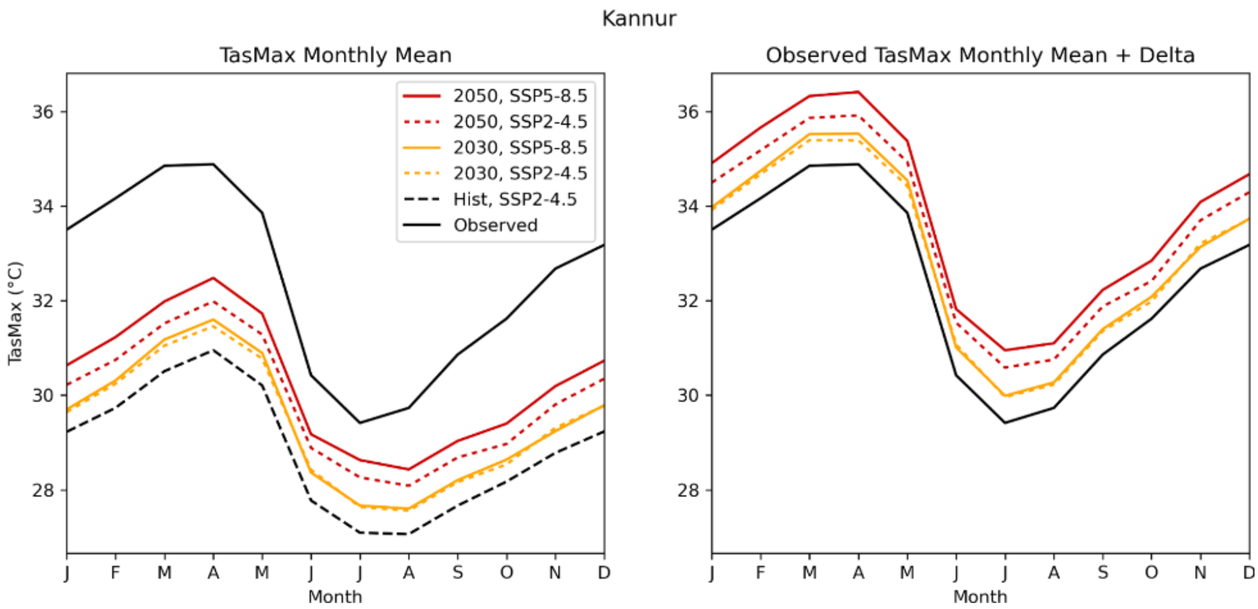

Figure A11. $T_{as,max}$ seasonal cycle at Kannur. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

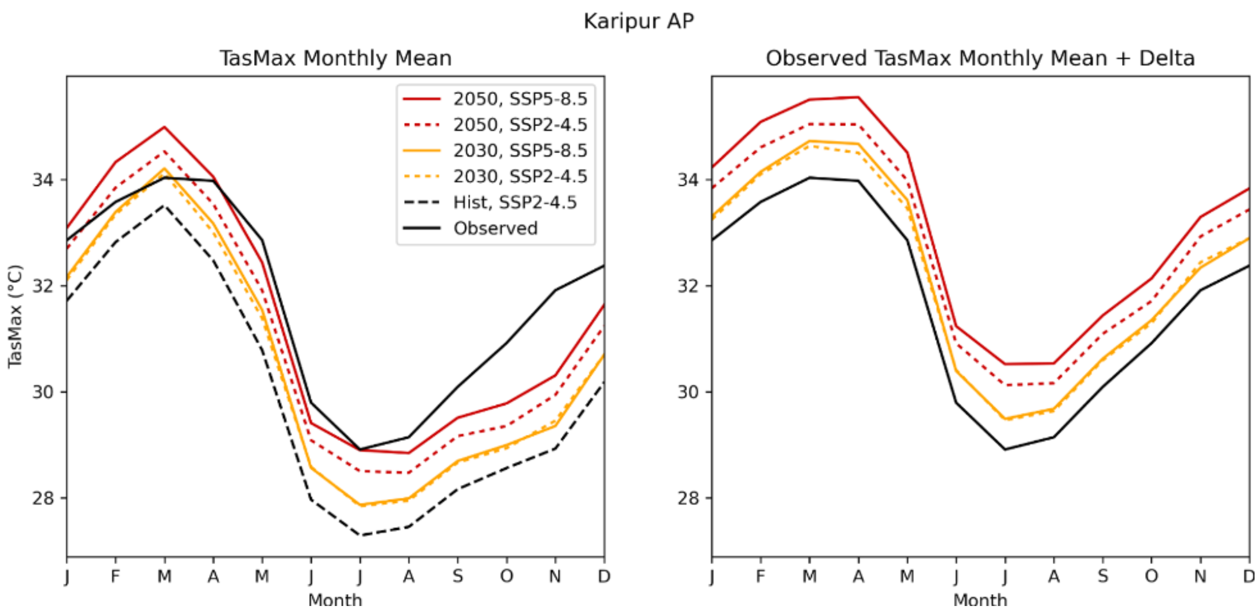

Figure A12. $T_{as,max}$ seasonal cycle at Karipur Airport. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

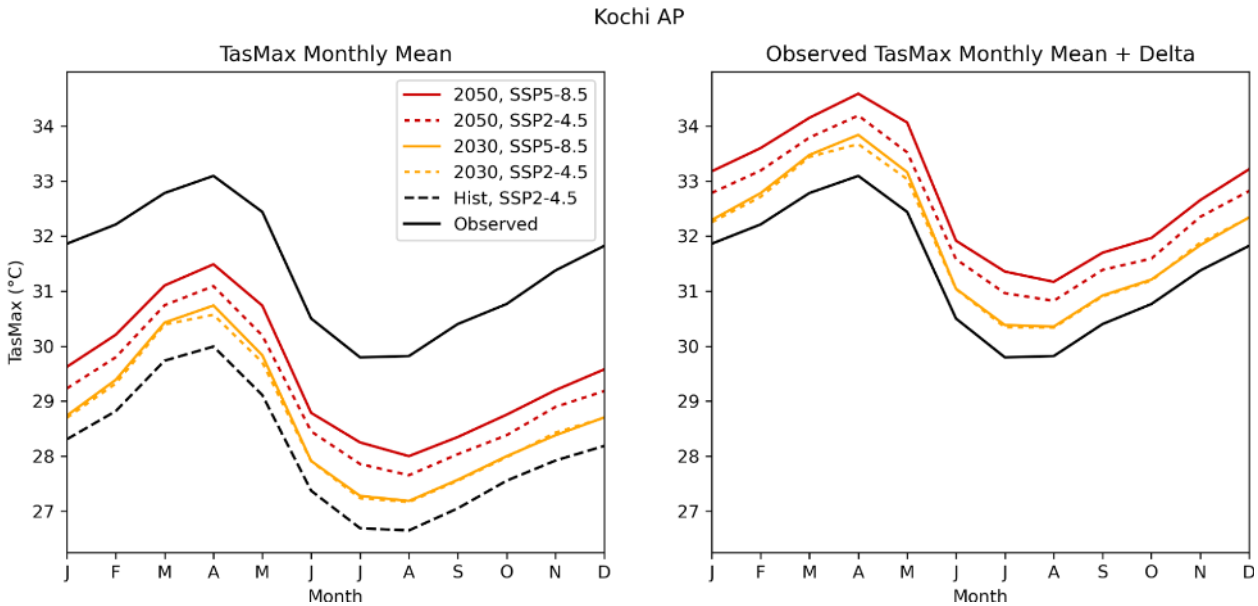

Figure A13. $T_{as,max}$ seasonal cycle at Kochi Airport. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

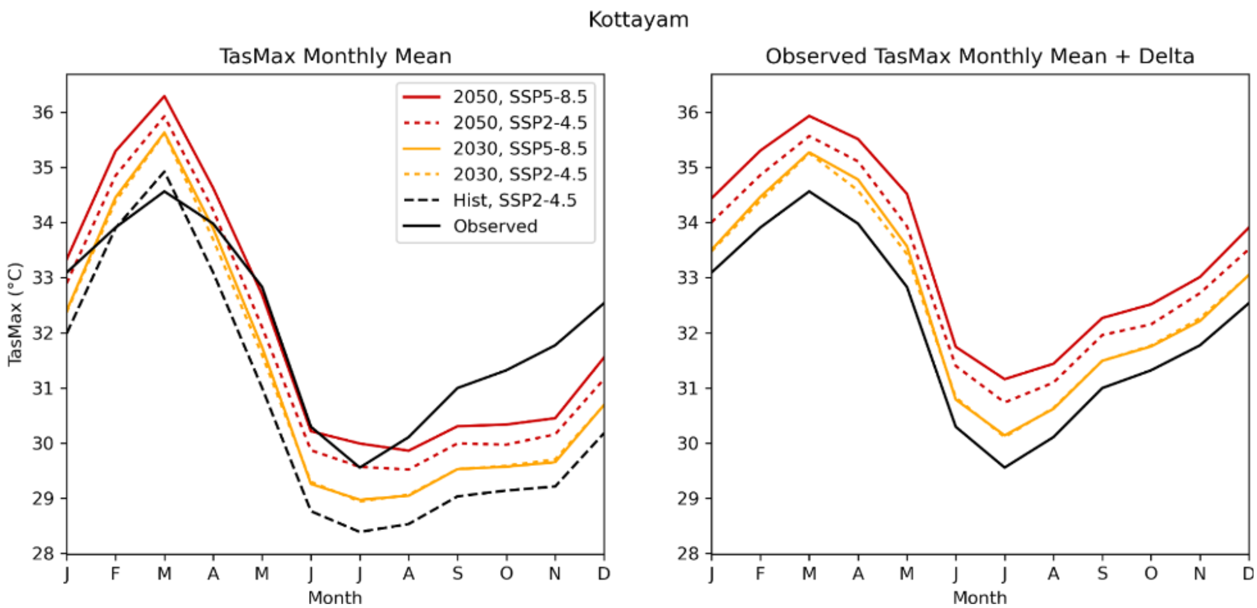

Figure A14. $T_{as,max}$ seasonal cycle at Kottayam. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

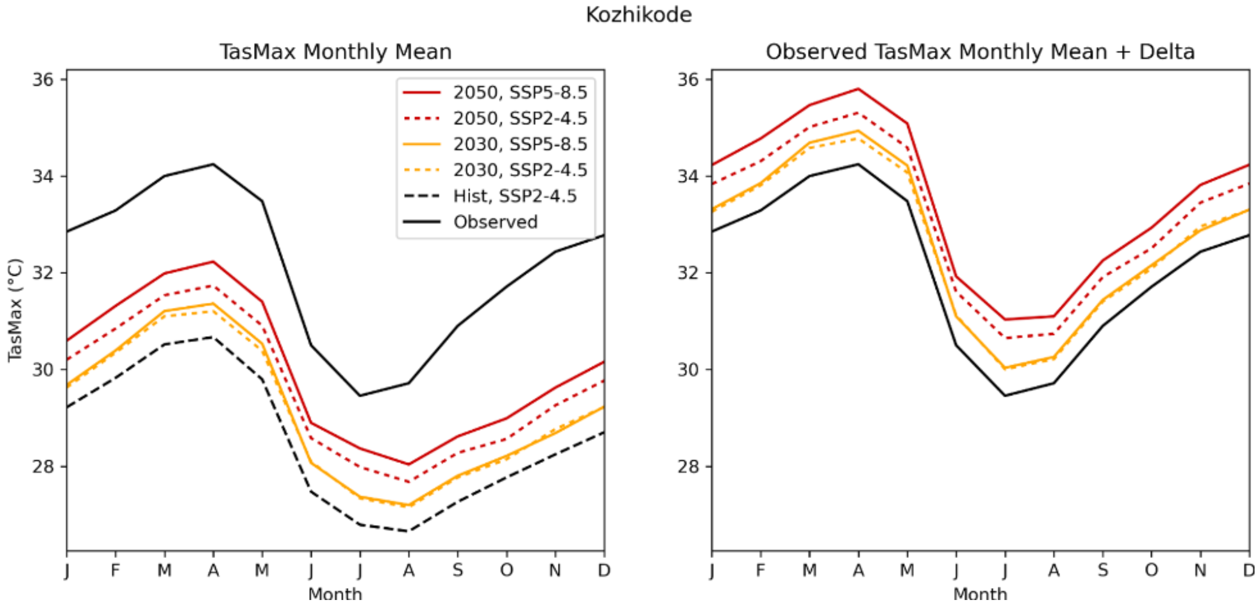

Figure A15. $T_{as,max}$ seasonal cycle at Kozhikode. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

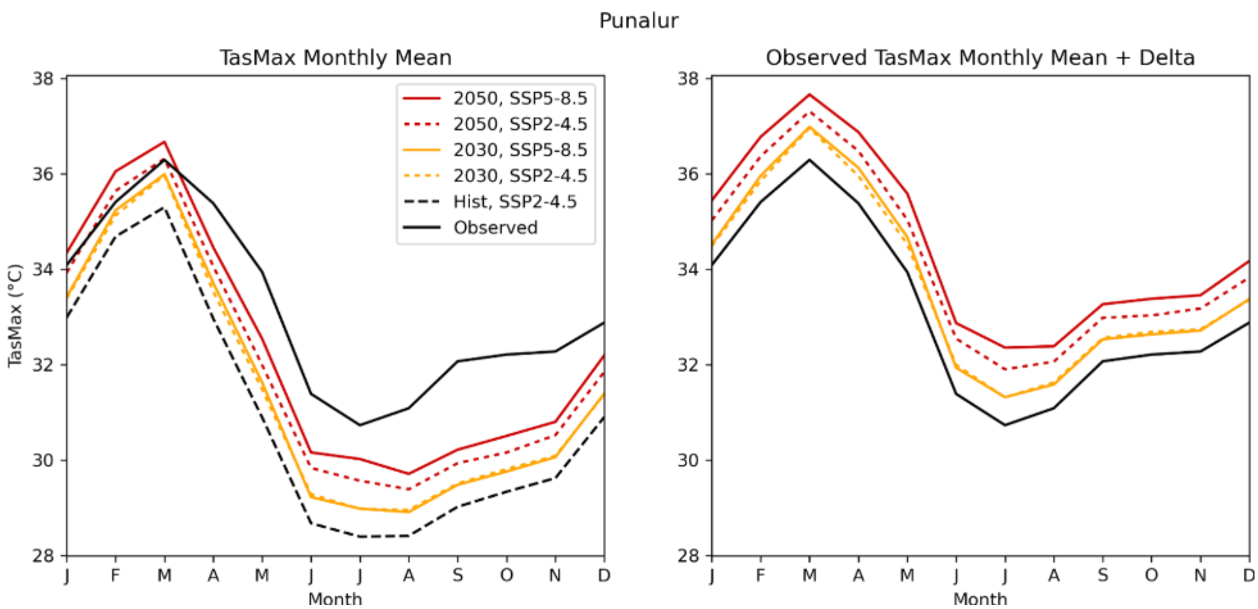

Figure A16. $T_{as,max}$ seasonal cycle at Punalur. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

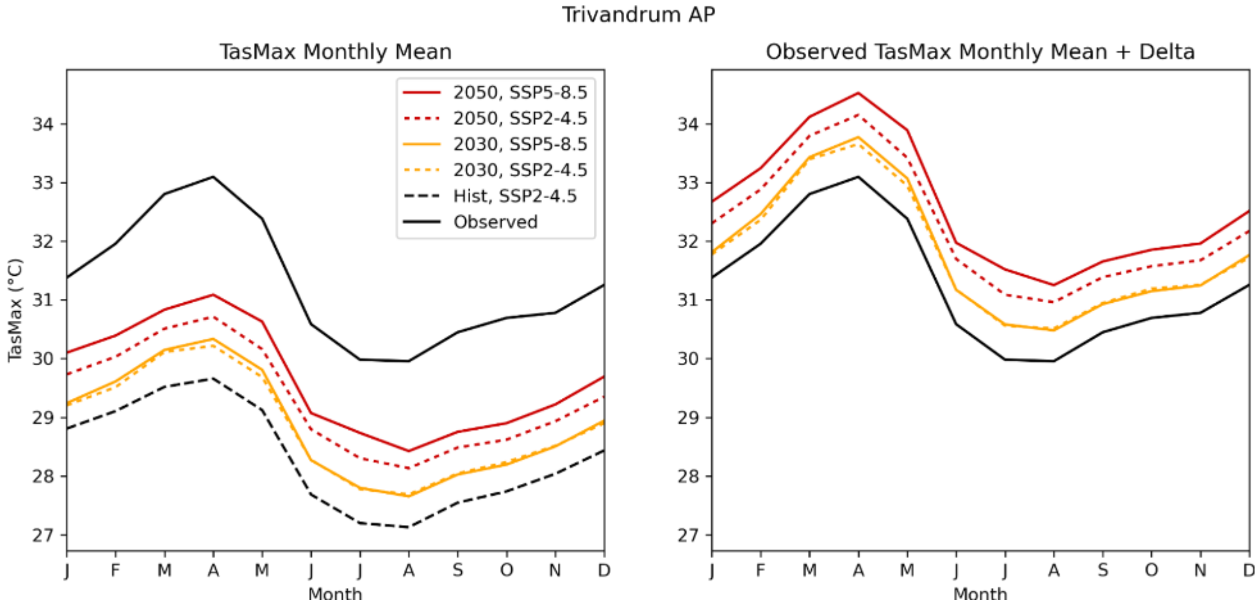

Figure A17. $T_{as,max}$ seasonal cycle at Trivandrum Airport. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

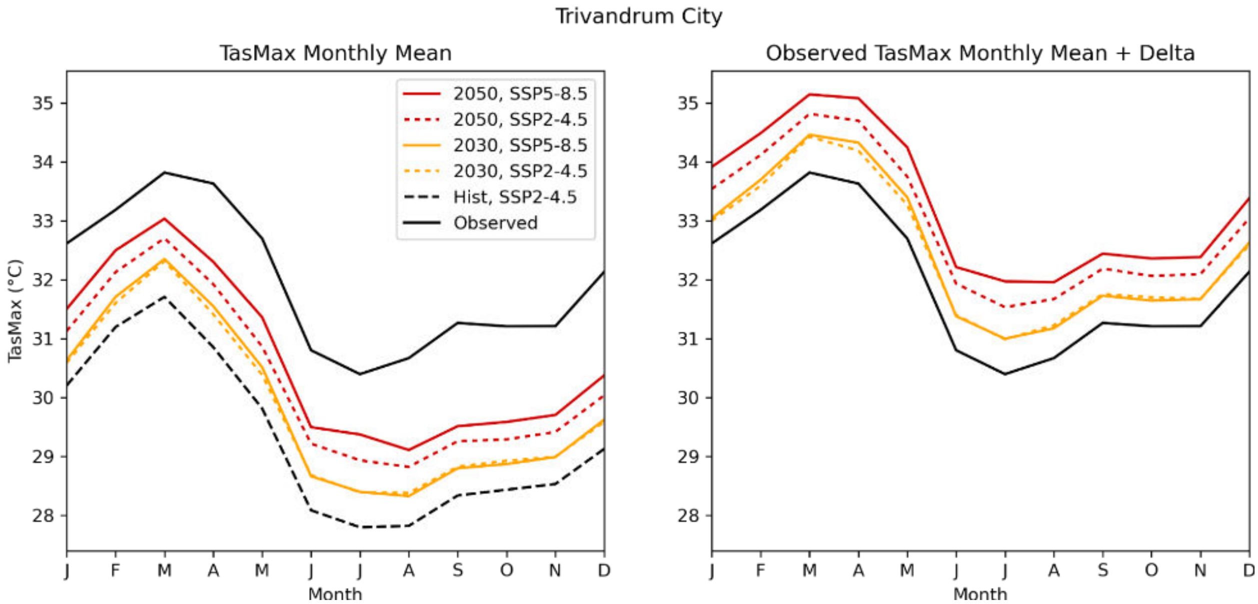

Figure A18. $T_{as,max}$ seasonal cycle at Trivandrum City. Observed (1990–2020, solid black line) and modeled seasonal cycle (left); the modeled seasonal cycle adjusted to observations using the delta method (right).

Table A1. Observed annual mean $T_{as,max}$ (°C) at each station and the projected annual mean delta (°C) for the near-term (2030, 2020–2040) and mid-century (2050, 2040–2060) time periods, under the SSP2-4.5 and SSP5-8.5 scenarios.

Station	Observations	2030 SSP2-4.5	2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5
Alappuzha	31.67	0.53	0.56	1.00	1.38
Kannur	32.43	0.51	0.56	1.03	1.44
Karipur AP	31.71	0.52	0.57	1.04	1.45
Kochi AP	31.41	0.52	0.56	1.01	1.39
Kottayam	32.08	0.53	0.56	1.01	1.40
Kozhikode	32.11	0.52	0.57	1.03	1.44
Punalur	33.15	0.52	0.55	1.00	1.37
Trivandrum City	31.97	0.51	0.54	0.98	1.33
Trivandrum AP	31.28	0.52	0.55	0.98	1.32

CHELSA-downscaled W5E5 Daily Data

Daily maximum temperature data for 1971–2100 from 19 CMIP6 climate models were bilinearly interpolated to a 1-km grid and then bias-adjusted using phase 3 of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) version 2.5 methodology (ISIMIP3BASD v2.5) (Lange, 2019; Lange, 2021). High-resolution, 1-km CHELSA-W5E5 reanalysis data (Karger et al., 2021; Karger et al., 2022) for 1985–2014 were selected as the observation dataset for bias-adjustment.

Distribution Plots

Kernel density estimates for daily maximum temperatures for February–May were plotted to visualize changes in the distribution between time periods for eight locations in Kerala. The 95th percentile maximum temperatures (temperatures that are met or exceeded, on average, about 18 days per year) were labeled to highlight changes in extreme heat (Figures 4 and 5).

References

Karger, D., Conrad, O., Böhner, J. et al. Climatologies at high resolution for the earth's land surface areas. *Sci Data* 4, 170122 (2017). https://doi.org/10.1038/sdata.2017.122

Karger, D. (2023). *chelsa_cmip6* [Python package]. https://gitlabext.wsl.ch/karger/chelsa_cmip6/-/tree/master/ (original work published 2022)

Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), *Geosci. Model Dev.*, 12: 3055–3070.

Lange, S. (2021). ISIMIP3BASD (2.5.0). Zenodo. https://doi.org/10.5281/zenodo.4686991.

Lute, A.C. (2023). *Downscaling Global Climate Model Data with CHELSA* [Google doc]. https://drive.google.com/file/d/16Cytimboal5YIqqVUGGB4UNpzCIWvPYK/view

The impacts of climate change on the frequency and severity of physical hazards are putting many communities at risk. As the threat of climate change grows, so too does the need for accessible information, tools, and expertise to support climate-resilient decision making across multiple scales, from communities to countries. Woodwell Climate Research Center believes there is a need to localize and customize climate risk assessments. This information is critical for local government leaders as they make planning decisions, but it is not available to all communities. Woodwell Climate believes that this science should be freely and widely available. To address this gap, Woodwell Climate works with communities across the world, including the State of Kerala, India, to provide community climate risk assessments, free of charge.

Naegele, A.C., Lute, A.C., and Gassert, K.N. (2024). *Heat Analysis for Kerala, India*.
https://woodwellclimate.org/assessments/kerala

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