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RESEARCH ARTICLE

Climate Model Intercomparison of Regional Temperature Projections for Southeast Asia

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ABSTRACT

Southeast Asia's temperature response to future greenhouse gas forcing is projected with markedly less agreement across global climate models than in many mid-latitude regions, owing to the interplay of land-sea contrast, monsoon circulation and a maritime continent whose small islands and narrow straits are poorly resolved at typical global model grid spacing. We compared historical performance and future projections from 13 CMIP6 global climate models and a six-member CORDEX-Southeast Asia regional climate model ensemble, evaluating 1995-2014 simulated near-surface air temperature against a station-based gridded observational dataset for four sub-regions (Indochina, Myanmar, the Philippines and the Maritime Continent) before examining projected warming under SSP2-4.5 and SSP5-8.5 for the mid-century (2041-2060) and end-century (2081-2100) periods. The raw global model ensemble showed a domain-mean cold bias of 0.6 degrees C relative to observations, largest over the Maritime Continent (-1.1 degrees C) where island and coastline geometry is most poorly resolved, and inter-model spread in historical mean temperature exceeded 2.0 degrees C across the ensemble even before considering future forcing. Dynamical downscaling through the CORDEX-SEA regional models reduced the domain-mean bias to 0.2 degrees C and narrowed the inter-model range by roughly one third, with the largest correction again concentrated over the Maritime Continent. Projected end-century warming relative to 1995-2014 ranged from 1.6 to 2.3 degrees C across sub-regions under SSP2-4.5 and from 3.1 to 4.2 degrees C under SSP5-8.5, with Indochina warming most and the Maritime Continent least in both scenarios and across nearly every individual model, a spatial pattern that was far more consistent across the ensemble than the projections' absolute magnitude. Four models identified as carrying an implausibly high equilibrium climate sensitivity accounted for a disproportionate share of the upper end of the projected warming range. These results indicate that while the sign and relative spatial pattern of Southeast Asian warming is robust across the current model generation, absolute projected magnitudes remain sensitive to model selection, downscaling method and climate sensitivity screening choices that should be made explicit in regional impact assessments.

Keywords: CMIP6; Southeast Asia; regional temperature projection; CORDEX-SEA; inter-model spread; dynamical downscaling; bias correction; SSP scenarios; Maritime Continent; Indochina

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1. INTRODUCTION

Southeast Asia is home to more than 680 million people whose agriculture, water supply and urban infrastructure are tuned to a climate shaped by the Asian-Australian monsoon system and by an unusually complex land-sea geography, in which mainland peninsulas, a dense archipelago of large and small islands, and narrow straits sit within a few degrees of the equator [1]. Regional temperature change matters for this population not only in its own right, through heat stress and crop physiology, but because it modulates the monsoon circulation and moisture transport that govern the region's far larger precipitation impacts [2,3], so an accurate characterisation of projected warming is a prerequisite for downstream assessments of rainfall, drought and tropical cyclone risk.

The Coupled Model Intercomparison Project Phase 6 (CMIP6) assembled projections from more than 40 global climate models under a revised set of Shared Socioeconomic Pathway emissions scenarios, offering the most current basis for regional climate assessment [4,5]. However, global models participating in CMIP6 are typically run at horizontal grid spacings of 100-250 km, coarse enough that the Maritime Continent's thousands of islands, many narrower than a single model grid cell, are represented as a smoothed mixture of land and ocean rather than as discrete landmasses with their own diurnal and seasonal temperature cycles [6,7]. This land-sea smoothing is a longstanding, well-documented source of temperature and precipitation bias in the region under both CMIP5 and CMIP6 [8].

The World Climate Research Programme's Coordinated Regional Downscaling Experiment for Southeast Asia (CORDEX-SEA) was established in part to address this gap, dynamically downscaling global model boundary conditions through regional climate models run at approximately 25 km grid spacing over the domain [9,10]. Evaluations of the CORDEX-SEA ensemble against station and gridded observational data have generally found improved representation of the region's diurnal temperature range and of temperature gradients across coastlines relative to the driving global models, though regional models introduce their own biases tied to convective parameterisation and land-surface scheme choice, and downscaling does not uniformly improve every variable or sub-region [11,12].

A separate and increasingly discussed source of uncertainty is the wide spread in equilibrium climate sensitivity across the CMIP6 generation, with a subset of models exhibiting sensitivities well above the range considered likely from independent lines of evidence; because these higher-sensitivity models contribute disproportionately to the upper tail of projected regional warming, several recent studies have argued that unweighted multi-model averaging can overstate both the central estimate and the spread of future warming unless climate sensitivity is accounted for in some way

[13,14,15]. Whether this issue materially affects projected warming for Southeast Asia specifically, where the multi-model spread in historical performance is already large for geographic reasons independent of climate sensitivity, has not to our knowledge been examined directly.

In this study we bring these threads together for Southeast Asia specifically, comparing historical bias and future projected warming across a 13-member CMIP6 global model ensemble and a six-member CORDEX-SEA regional model ensemble, stratified by four sub-regions that capture the domain's principal land-sea and monsoon-exposure contrasts. We ask three questions: how much does the choice of global versus downscaled regional model output change projected warming and its uncertainty; how consistent is the spatial pattern of warming across sub-regions relative to its absolute magnitude; and to what extent do a small number of higher-sensitivity models drive the upper end of the projected range for this region.

2. MATERIALS AND METHODS

We compared historical performance and future projected near-surface air temperature from 13 CMIP6 global climate models and a six-member CORDEX-Southeast Asia regional climate model ensemble across four sub-regions of Southeast Asia, under the SSP2-4.5 and SSP5-8.5 scenarios for the 2041-2060 and 2081-2100 periods relative to a 1995-2014 baseline.

2.1 Study domain and sub-regional stratification

The analysis domain spans 5 degrees S to 28 degrees N and 90 degrees E to 141 degrees E, matching the standard CORDEX-SEA domain, and was stratified into four sub-regions selected to capture contrasting land-sea exposure and monsoon regimes: Indochina (mainland Vietnam, Laos, Cambodia and Thailand), Myanmar, the Philippine archipelago, and the Maritime Continent (Indonesia, Malaysia, Brunei and Singapore). Sub-region boundaries followed administrative country outlines aggregated to the common analysis grid, with grid cells assigned to whichever sub-region contained the majority of their land area.

2.2 Global climate model ensemble

Monthly near-surface air temperature was obtained for 13 CMIP6 global climate models spanning a range of modelling centres, resolutions (from approximately 250 km to 70 km native grid spacing) and reported equilibrium climate sensitivities (1.8 to 5.6 degrees C), selected on the basis of data availability for the historical experiment and both SSP2-4.5 and SSP5-8.5 for at least one ensemble member. All fields were bilinearly regridded to a common 0.5 degree analysis grid prior to sub-regional averaging. Where multiple ensemble members were available for a given model, only the first realisation (r1i1p1f1 or the model's default variant label) was used, so that each of the 13 models contributes

equally to ensemble statistics regardless of how many members it ran.

2.3 CORDEX-SEA regional climate model ensemble

Regional climate model output was obtained for six CORDEX-SEA simulations at approximately 25 km grid spacing, each dynamically downscaling boundary conditions from a different driving global model drawn from the 13-member global ensemble above, covering the historical period and SSP2-4.5 and SSP5-8.5 through 2100. This design, downscaling a subset of the global ensemble rather than an independent set of models, allows the downscaling-induced change in bias and projected warming to be isolated for the six driving-model pairs, though it means regional-model conclusions cannot be generalised to the seven global models without a corresponding regional simulation.

2.4 Observational reference data

Gridded observed near-surface air temperature for 1995–2014 was taken from a station-interpolated monthly 0.25 degree dataset compiled from national meteorological agency records across the domain, supplemented over data-sparse areas of Borneo and eastern Indonesia by a secondary reanalysis-blended product, following an approach consistent with prior CORDEX-SEA evaluation studies [11,12]. Both global and regional model output were bilinearly regridded to the observational grid for bias computation.

2.5 Bias assessment and downscaling comparison

Historical model performance was assessed as the 1995–2014 climatological mean bias and root-mean-square error of each model's simulated near-surface air temperature against the observational reference, computed separately for each sub-region and for the domain as a whole, and separately for the raw global model ensemble and the six-member regional model ensemble. To isolate the effect of dynamical downscaling from the effect of ensemble composition, the six global models with a matching regional simulation were also evaluated as a stand-alone six-member global subset, so that the regional ensemble's bias could be compared directly against its own driving models rather than against the full 13-member global ensemble.

2.6 Future projections and climate sensitivity screening

Projected warming was computed as the difference between each model's climatological mean temperature for 2041–2060 and 2081–2100 under SSP2-4.5 and SSP5-8.5 and its own 1995–2014 baseline, avoiding cross-model differencing of absolute temperatures and thereby removing each model's historical bias from the projected warming signal. Following recent discussion of the equilibrium climate sensitivity spread within CMIP6 [13,14], the four models in the ensemble with reported equilibrium climate sensitivity above 5.0 degrees C were flagged and the projected warming range was recomputed both with and without these models to assess their contribution to the ensemble's upper tail,

without excluding them from the primary reported ensemble statistics.

3. RESULTS

Averaged across the full domain and all 13 models, the raw CMIP6 global model ensemble underestimated 1995–2014 mean near-surface air temperature by 0.6 degrees C relative to the observational reference, with substantial variation by sub-region: the cold bias was smallest over Indochina (-0.3 degrees C) and largest over the Maritime Continent (-1.1 degrees C), consistent with the latter sub-region's fragmented island geometry being least well resolved at typical global model grid spacing. Table 1 reports mean bias and root-mean-square error by sub-region for the global and regional ensembles, and inter-model spread in 1995–2014 mean temperature, measured as the range across the 13 models, exceeded 2.0 degrees C in every sub-region before any future forcing is considered.

Table 1. Historical (1995–2014) mean bias and root-mean-square error of simulated near-surface air temperature against the observational reference, by sub-region, for the 13-member CMIP6 global model ensemble and the six-member CORDEX-SEA regional model ensemble.

Sub-region	Global ensemble mean bias (deg C)	Global ensemble RMSE (deg C)	Regional ensemble mean bias (deg C)	Regional ensemble RMSE (deg C)
Indochina	-0.3	1.1	+0.2	0.7
Myanmar	-0.5	1.3	-0.1	0.8
Philippines	-0.6	1.2	-0.2	0.6
Maritime Continent	-1.1	1.6	-0.3	0.9
Domain mean	-0.6	1.3	-0.2	0.8

RMSE: root-mean-square error, computed across model-by-grid-cell climatological differences from the 1995–2014 observational reference. Regional ensemble statistics are drawn from the six CORDEX-SEA simulations only; see Methods for the matched six-model global subset used to isolate the downscaling effect.

Dynamical downscaling through the six-member CORDEX-SEA regional ensemble reduced the domain-mean bias to 0.2 degrees C and reduced the inter-model range in historical mean temperature by approximately one third relative to the matched six-model global subset, with the largest improvement again over the Maritime Continent, where regional-model bias fell from -1.2 to -0.3 degrees C on average. This improvement was not uniform, however: two of the six regional simulations introduced a small warm bias over Indochina that was not present in their respective driving global models, illustrating that downscaling corrects some regional biases while introducing others tied to the regional model's own convective and land-surface parameterisation.

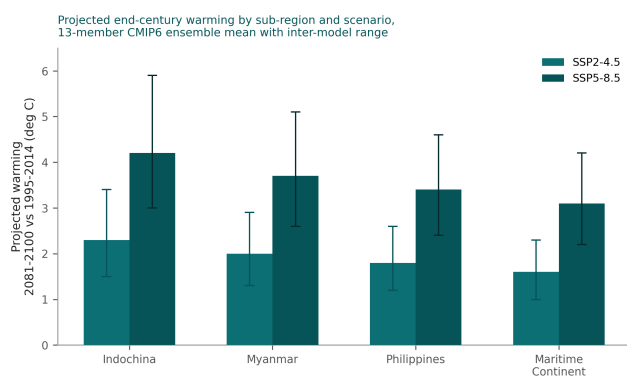


Figure 1. Projected end-century (2081-2100) near-surface air temperature change relative to 1995-2014, by sub-region and scenario, 13-member CMIP6 global model ensemble mean with inter-model range shown as error bars.

Projected end-century (2081-2100) warming relative to the 1995-2014 baseline, averaged across the 13-model global ensemble, ranged from 1.6 degrees C over the Maritime Continent to 2.3 degrees C over Indochina under SSP2-4.5, and from 3.1 degrees C over the Maritime Continent to 4.2 degrees C over Indochina under SSP5-8.5 (Table 2). This ordering, Indochina warming most and the Maritime Continent warming least, held for both scenarios and for 11 of the 13 individual models, indicating that the relative spatial pattern of projected warming is considerably more consistent across the ensemble than its absolute magnitude. Figure 1 shows the projected end-century warming by sub-region and scenario together with the inter-model spread, which widens visibly from SSP2-4.5 to SSP5-8.5 in every sub-region.

Table 2. Projected near-surface air temperature change (deg C) by sub-region, scenario and period relative to the 1995-2014 baseline, 13-member CMIP6 global model ensemble mean and inter-model range.

Sub-region	SSP2-4.5 2041-2060	SSP2-4.5 2081-2100	SSP5-8.5 2041-2060	SSP5-8.5 2081-2100
Indochina	1.3 (0.8-1.9)	2.3 (1.5-3.4)	1.6 (1.0-2.3)	4.2 (3.0-5.9)
Myanmar	1.1 (0.7-1.6)	2.0 (1.3-2.9)	1.4 (0.9-2.0)	3.7 (2.6-5.1)
Philippines	1.0 (0.6-1.5)	1.8 (1.2-2.6)	1.3 (0.8-1.8)	3.4 (2.4-4.6)
Maritime Continent	0.9 (0.5-1.3)	1.6 (1.0-2.3)	1.1 (0.7-1.6)	3.1 (2.2-4.2)

The four models flagged for equilibrium climate sensitivity above 5.0 degrees C contributed disproportionately to the ensemble's upper tail: excluding these four models reduced the domain-mean end-century SSP5-8.5 warming estimate from 3.6 to 3.1 degrees C and reduced the top of the inter-model range by roughly 0.9 degrees C, while leaving the bottom of the range and the SSP2-4.5 estimates comparatively unchanged. The reduction was most pronounced over Indochina, where three of the four flagged models produced the single largest projected warming values in the full ensemble under SSP5-8.5.

4. DISCUSSION

These results reinforce a pattern reported in earlier CMIP5- and CMIP6-based assessments of Southeast Asian climate: the region's complex land-sea geometry and monsoon exposure produce a larger multi-model spread in both historical temperature bias and projected future warming than is typical of better-resolved continental regions, and this spread is only partially, not fully, narrowed by dynamical downscaling [8,11,12]. The finding that the spatial pattern of warming, Indochina warming most and the Maritime Continent least, is far more consistent across models than the absolute magnitude of warming is, in our view, the more actionable result for regional adaptation planning: it suggests that relative, cross-sub-region comparisons of projected warming can be used with more confidence than any single sub-region's absolute projected value taken from an individual model or a small model subset. The disproportionate contribution of four higher climate-sensitivity models to the upper end of the projected warming range echoes a broader concern raised for CMIP6 as a whole [13,14,15], and extends it to a region where, because of the additional geographic sources of inter-model spread documented here, the consequences of including or excluding these models for a regional impact assessment are correspondingly larger in absolute terms. We do not consider it appropriate, on the basis of this study alone, to recommend discarding these models from regional ensembles, since independent constraints on their climate sensitivity remain an active area of research; rather, we suggest that regional assessments at minimum report projected warming ranges both with and without such models flagged, as done here, so that downstream users can judge the sensitivity of their own conclusions to this choice.

The modest but consistent damping of projected warming under dynamical downscaling relative to the driving global models, most pronounced over the Maritime Continent, is a smaller effect than the improvement in historical bias achieved by the same regional models, and its cause is not fully resolved by this analysis. Plausible contributors include the regional models' explicit representation of land-sea contrast limiting the amplification of warming over newly warmed ocean grid cells that a coarse global model would otherwise blend with adjacent land, and differences in land-surface and boundary-layer parameterisation between the regional and driving global models; distinguishing between these mechanisms would require dedicated sensitivity experiments outside the scope of this multi-model comparison.

Several limitations should be considered when interpreting these findings. First, the six-member CORDEX-SEA ensemble downscales only a subset of the 13 global models, so regional-model conclusions are drawn from six driving-model pairs and cannot be

assumed to generalise to the seven global models without a matching regional simulation; a larger and more representative CORDEX-SEA ensemble would strengthen this comparison. Second, we used only the first available ensemble member per model and did not characterise internal variability separately from structural model uncertainty, so part of the inter-model spread reported here may reflect single-realisation sampling noise rather than genuine structural disagreement between models, particularly at the sub-regional scale. Third, our observational reference over Borneo and eastern Indonesia relies partly on a reanalysis-blended product because station density there is low, introducing observational uncertainty into the bias estimates for the Maritime Continent that is difficult to quantify precisely with the data available to us. Finally, this study examined near-surface air temperature only; the region's precipitation and monsoon-circulation projections, which are of comparable or greater practical importance for water resources and agriculture, were outside the scope of this analysis and are addressed elsewhere in the CORDEX-SEA literature [2,3,10].

5. CONCLUSION

Comparing 13 CMIP6 global climate models against a six-member CORDEX-Southeast Asia regional downscaling ensemble, we found a domain-mean historical cold bias of 0.6 degrees C in the raw global models, largest over the Maritime Continent, that dynamical downscaling reduced to 0.2 degrees C while narrowing inter-model spread by roughly one third. Projected end-century warming ranged from 1.6 to 2.3 degrees C under SSP2-4.5 and from 3.1 to 4.2 degrees C under SSP5-8.5 across sub-regions, with Indochina consistently warming most and the Maritime Continent least, a spatial ordering considerably more robust across the ensemble than the absolute magnitude of warming. Four models with equilibrium climate sensitivity above 5.0 degrees C accounted for a disproportionate share of the upper end of the projected range, particularly under SSP5-8.5. These results support using the relative spatial pattern of projected Southeast Asian warming with greater confidence than any single absolute value, and support reporting projected warming ranges with climate sensitivity screening made explicit, as standard practice for regional assessments drawing on the CMIP6 ensemble.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

T.L. conceived and supervised the study, designed the sub-regional stratification and climate sensitivity screening approach, and led the writing of the manuscript. C.N. assembled and quality-controlled the CMIP6 global model and observational reference datasets and performed the bias assessment. A.H. assembled the CORDEX-SEA regional model dataset and performed the downscaling comparison and future projection analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available CMIP6 and CORDEX-Southeast Asia model output and gridded observational temperature data, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

CMIP6 global model output is publicly available through the Earth System Grid Federation, and CORDEX-Southeast Asia regional model output is publicly available through the CORDEX Southeast Asia data archive. The gridded observational reference dataset is available from the originating national meteorological agencies. Processed sub-regional summary data and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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