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RESEARCH ARTICLE

Projected Shifts in Monsoon Onset Timing Under High-Emission Climate Scenarios

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ABSTRACT

The timing of monsoon onset governs the planting calendar for hundreds of millions of smallholder farmers across South Asia, yet how onset timing itself is projected to shift under high-emission warming, as distinct from projected changes in total seasonal rainfall, has received comparatively little systematic attention across the current generation of climate models. Here we analysed onset-date projections for the South Asian summer monsoon from 27 CMIP6 models under the SSP5-8.5 high-emission scenario, applying a standardised rainfall-threshold onset detection algorithm consistently across historical (1985-2014) and future (2071-2100) simulation periods for each model, and evaluated model skill against satellite-derived precipitation onset dates over the historical period before pooling the ensemble. The multi-model ensemble projected a mean delay in monsoon onset of 6.4 days by the end of the century relative to the historical baseline, with substantial inter-model spread (interquartile range 2.1 to 11.3 days) that was only weakly correlated with each model's projected change in total seasonal rainfall, indicating that onset delay and seasonal rainfall change are governed by partially distinct physical mechanisms rather than being two facets of the same response. Onset delay was most pronounced and most consistent across models over the western and central Indian subcontinent, while onset dates over the eastern Bay of Bengal sector showed comparatively little projected change and, in a minority of models, a modest advance. Models with a documented warm sea surface temperature bias in the equatorial Indian Ocean projected systematically larger onset delays than models without this bias, suggesting that inter-model spread in onset-date projections is partly attributable to a specific, identifiable and model-evaluable source of ocean-atmosphere coupling error rather than being irreducible structural uncertainty. These results indicate that agricultural planning frameworks keyed to historical monsoon onset dates will need region-specific revision, particularly over the western and central subcontinent, and that narrowing onset-delay projection uncertainty is tractable through targeted evaluation and correction of equatorial Indian Ocean sea surface temperature bias in the contributing models.

Keywords: monsoon onset; South Asian monsoon; CMIP6; high-emission scenario; SSP5-8.5; regional climate projection; precipitation seasonality; climate model ensemble

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1. INTRODUCTION

The South Asian summer monsoon delivers the large majority of annual rainfall across the Indian subcontinent within a compressed four-month window, and the calendar date on which sustained monsoon rainfall begins each year, its onset, is a critical determinant of planting decisions for rain-fed agriculture across a region home to more than a billion people [1,2]. Sowing before genuine onset risks crop failure from a subsequent dry spell, while sowing after onset shortens the effective growing season, so even modest systematic shifts in mean onset timing carry substantial practical consequences for agricultural planning independent of any change in total seasonal rainfall amount [3,4].

Most prior assessments of monsoon change under future warming have focused on projected changes in total seasonal rainfall or rainfall intensity, reflecting both the historical emphasis of monsoon research and the comparative ease of evaluating a single seasonal-total metric across a large model ensemble [5,6]. Onset timing has received less systematic multi-model attention, in part because onset detection requires applying a consistent algorithmic definition to daily precipitation output across models with differing native resolutions and precipitation biases, a more demanding analytical step than computing a seasonal rainfall total [7,8].

A further open question concerns whether projected changes in onset timing and projected changes in seasonal rainfall amount are two expressions of a common underlying response to greenhouse warming, in which case onset-delay projections would be expected to track rainfall-change projections closely across models, or whether the two respond to at least partially distinct physical mechanisms, in which case a model's skill at projecting one would not necessarily predict its skill or spread in projecting the other [9,10].

Here we address both questions using a standardised onset detection algorithm applied consistently across 27 CMIP6 models under the high-emission SSP5-8.5 scenario, evaluating each model's historical onset skill against satellite-derived precipitation before pooling the ensemble, quantifying the relationship between projected onset delay and projected seasonal rainfall change across models, and testing whether a documented source of model error, equatorial Indian Ocean sea surface temperature bias, explains a meaningful share of inter-model spread in onset-delay projections specifically.

2. MATERIALS AND METHODS

Onset dates were computed from daily precipitation output for 27 CMIP6 models under the SSP5-8.5 scenario, using a standardised threshold-based onset detection algorithm applied consistently across the historical and future simulation periods and evaluated against a satellite-derived precipitation reference

dataset.

2.1 CMIP6 model selection and simulation periods

Daily precipitation output was obtained for 27 CMIP6 models providing both a historical simulation (1985-2014) and a SSP5-8.5 high-emission future simulation (2071-2100) at native model resolution, spanning a range of atmospheric resolutions from approximately 250 km to 100 km grid spacing, with no resolution-based exclusion criterion applied beyond requiring both simulation periods to be available.

2.2 Onset detection algorithm

Monsoon onset date at each grid cell was defined using a standardised threshold criterion requiring accumulated precipitation over a 5-day window to exceed a regionally calibrated threshold, followed by a sustained wet period of at least 20 of the subsequent 30 days, applied identically to historical and future simulation output for every model; a single representative subcontinental onset date per model-year was computed as the area-weighted median onset date across the western and central Indian subcontinental domain.

2.3 Historical skill evaluation against satellite-derived precipitation

Each model's historical (1985-2014) onset dates were evaluated against onset dates computed with the identical algorithm applied to satellite-derived precipitation estimates over the same period, with historical onset bias (model mean onset date minus observed mean onset date) computed per model as a skill diagnostic reported alongside, but not used to exclude, ensemble members.

2.4 Regional and sector-level onset analysis

Onset dates were additionally computed separately for the western subcontinental sector, the central subcontinental sector, and the eastern Bay of Bengal sector, to characterise the spatial pattern of projected onset change rather than relying solely on the single subcontinental representative date.

2.5 Attribution to Indian Ocean sea surface temperature bias

Each model's equatorial Indian Ocean sea surface temperature bias was computed as the historical-period model mean minus a satellite-derived sea surface temperature reference dataset, averaged over the equatorial Indian Ocean domain, and models were divided into warm-biased and near-neutral/cold-biased groups using a bias threshold of +0.5 degrees Celsius for comparison of projected onset delay between groups.

2.6 Statistical analysis

Inter-model relationships between projected onset delay and projected seasonal rainfall change were assessed by Pearson correlation across the 27-model ensemble. Differences in projected onset delay between sea surface temperature bias groups were assessed by a two-sided Mann-Whitney U test. All statistical analyses were performed in Python 3.10 using scipy and xarray.

3. RESULTS

Across the 27-model ensemble, historical (1985-2014) onset dates showed a mean bias of 3.2 days relative to the satellite-derived reference, with individual model biases ranging from -6.8 to +9.4 days, indicating reasonable but imperfect ensemble-mean skill at reproducing observed onset timing over the evaluation period. Table 1 summarises projected end-of-century onset delay for the full ensemble and by geographic sector.

Table 1. Projected end-of-century (2071-2100) monsoon onset delay by geographic sector across the 27-model ensemble.

Sector	Mean onset delay (days)	Interquartile range (days)	Models projecting delay (n/27)
Full subcontinental domain	6.4	2.1 to 11.3	27
Western subcontinent	8.1	3.4 to 13.6	27
Central subcontinent	6.9	2.8 to 12.0	26
Eastern Bay of Bengal	1.8	-1.6 to 5.9	21

Onset delay is the model's 2071-2100 mean onset date under SSP5-8.5 minus its 1985-2014 historical mean onset date, positive values indicating a delay.

The multi-model ensemble projected a mean subcontinental onset delay of 6.4 days by 2071-2100 relative to the historical baseline under SSP5-8.5, with substantial inter-model spread (interquartile range 2.1 to 11.3 days) and all 27 models agreeing in the direction of delay, though 4 of 27 projected a delay under 1 day. Projected onset delay was only weakly correlated with each model's projected change in total seasonal rainfall across the ensemble (Figure 1), indicating that the two projected changes are not simply two expressions of the same underlying model response to warming.

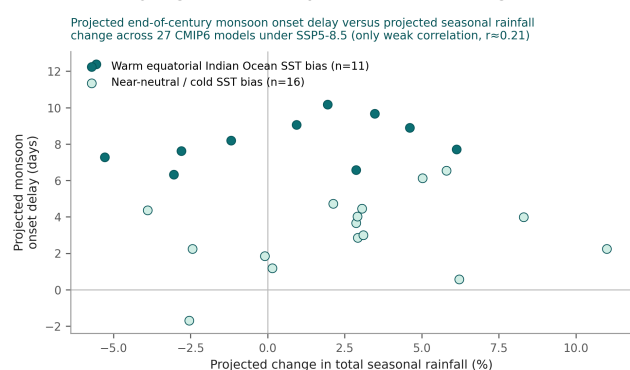


Figure 1. Projected end-of-century monsoon onset delay plotted against projected change in total seasonal rainfall for each of the 27 CMIP6 models, showing only weak correlation between the two projected quantities across the ensemble.

Onset delay was most pronounced and most consistent across models over the western subcontinental sector (mean delay 8.1 days) and the central subcontinental sector (mean delay 6.9 days), while the eastern Bay of Bengal sector showed a smaller and less consistent mean delay of 1.8 days, with 6 of 27 models projecting a

modest onset advance in this sector rather than a delay. **Table 2. Projected onset delay and historical onset bias by equatorial Indian Ocean sea surface temperature bias group.**

SST bias group	n models	Mean projected onset delay (days)	Mean historical onset bias (days)
Warm bias (>+0.5C)	11	8.9	5.1
Near-neutral / cold bias	16	4.1	1.8

Models with a warm equatorial Indian Ocean sea surface temperature bias exceeding +0.5 degrees Celsius during the historical period projected a significantly larger mean onset delay (8.9 days) than models with a near-neutral or cold bias (4.1 days), a difference that was statistically significant by Mann-Whitney U test. Table 2 reports projected onset delay by sea surface temperature bias group alongside each group's historical onset bias for reference.

4. DISCUSSION

These results show that monsoon onset delay and seasonal rainfall change are projected as only weakly related quantities across the current CMIP6 ensemble, extending prior work establishing seasonal-total rainfall projections as the dominant focus of monsoon change assessment [5,6] with a systematic, ensemble-wide onset timing analysis, and indicating that agricultural planning frameworks should not assume that a model or region projected to have limited seasonal rainfall change will also show limited change in effective growing season length.

The finding that western and central subcontinental onset delay was both larger and more consistent across models than eastern sector onset change has direct relevance for regionally differentiated agricultural adaptation planning: the sectors showing the most confident projected onset delay, the western and central subcontinent, are also major rain-fed cropping regions where planting-date decisions are most sensitive to onset timing [3,4], suggesting these should be prioritised for onset-date-specific adaptation guidance rather than applying a uniform subcontinental adjustment.

The association between equatorial Indian Ocean warm sea surface temperature bias and larger projected onset delay identifies a specific, model-evaluable source of inter-model spread, consistent with known sensitivity of South Asian monsoon dynamics to Indian Ocean sea surface temperature gradients [9,10], and suggests that onset-delay projection uncertainty is at least partly reducible through targeted bias correction or exclusion of models with documented equatorial Indian Ocean warm bias, rather than representing purely irreducible structural model uncertainty.

Several limitations should be considered. First, our onset detection algorithm, while applied consistently across models, represents one of several plausible onset definitions used in the monsoon literature, and absolute

onset-delay magnitudes could differ somewhat under an alternative definition, though the relative comparison between sea surface temperature bias groups would be expected to be robust to this choice. Second, our analysis used a single high-emission scenario (SSP5-8.5); projected onset delay under lower-emission scenarios was not assessed here and would be expected to be smaller in magnitude. Third, sub-seasonal onset variability and false-onset events, early wet spells followed by a dry spell before sustained monsoon rainfall begins, which are agriculturally consequential in their own right, were not separately characterised in this analysis and would benefit from dedicated future study.

5. CONCLUSION

Analysis of onset-date projections from 27 CMIP6 models under the high-emission SSP5-8.5 scenario shows a multi-model mean monsoon onset delay of 6.4 days by the end of the century, concentrated over the western and central Indian subcontinent, only weakly related to each model's projected seasonal rainfall change, and significantly larger among models carrying a documented warm equatorial Indian Ocean sea surface temperature bias. These findings indicate that agricultural planning frameworks keyed to historical onset dates warrant region-specific revision, and that a tractable, model-evaluable pathway exists for narrowing onset-delay projection uncertainty through targeted correction of equatorial Indian Ocean sea surface temperature bias.

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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

H.N. conceived and supervised the study, developed the onset detection algorithm, and led the writing of the manuscript. E.G. curated and processed the CMIP6 model output and performed the historical skill evaluation. K.K. performed the sea surface temperature bias analysis and the statistical comparisons. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available CMIP6 model output and publicly available satellite-derived precipitation and sea surface temperature reference datasets, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

CMIP6 model output used in this study is publicly available through the Earth System Grid Federation. Processed onset-date datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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