Climate Dynamics

The influence of cold SST anomalies surrounding the Maritime Continent on the El Niño-Indian monsoon teleconnection

--Manuscript Draft--

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Abstract:	The Indian summer monsoon (ISM) is strongly influenced by the El Niño-Southern Oscillation (ENSO), with Central Pacific (CP) El Niño events typically producing more severe droughts over India than Eastern Pacific (EP) events. Using idealized atmospheric model experiments, we show that this contrasting response is governed by sea surface temperature (SST) anomalies in the south-eastern Indian Ocean (SEIO). Under Pacific-only SST forcing, EP El Niño suppresses ISM rainfall more strongly than CP El Niño events. The addition of SEIO cooling reverses this hierarchy, with enhanced drying over India during CP events relative to EP events. The reversal arises because the zonal separation between the warm Pacific and the cold anomalies around the Maritime Continent (MC) is greater during EP events, forcing Walker descent over the MC, whereas the separation is less during CP events, allowing subsidence to spread over India. Diagnostics confirm that the combined response is strongly nonlinear. These results advance our mechanistic understanding of how the spatial configuration of SST anomalies across the Indo-Pacific governs the Indian summer monsoon response to El Niño, with implications for how ENSO-type diversity is represented in prediction systems.

Responses to Reviewers

We sincerely thank all three reviewers for their careful reading and constructive suggestions, which have substantially improved the manuscript. We have addressed each comment in full below. Responses to individual comments appear in *italics*, and text incorporated into the revised manuscript is shown in blue.

Reviewer 1

General Comment: The study quantifies the non-linear response of Indian Monsoon Summer Rainfall (IMSR) to ENSO and south-eastern Indian Ocean, depending on the location of SST anomalies over the Indo-Pacific, using an intermediate complex model with several idealized experiments. The presented results are novel and enhance the current understanding of the relation between IMSR–ENSO–Indian Ocean. The paper is well written and I find the work worthwhile for potential publication in Climate Dynamics. However, I would like the authors to address the following comments.

Comment #1: L45: Given the idealized nature of the study, the statement that SST anomalies surrounding the MC are relevant 'for seasonal prediction' seems overly strong. Drawing such a conclusion would typically require a more sophisticated model setup. I encourage the authors to reconsider this claim.

Response:

We fully agree with the reviewer and thank them for this important caution. The sentence has been removed and replaced in the revised abstract with appropriately measured language:

L44-47: These results advance our mechanistic understanding of how the spatial configuration of SST anomalies across the Indo-Pacific governs the Indian summer monsoon response to El Niño, with implications for how ENSO-type diversity is represented in prediction systems.

Comment #2: L102: Throughout the manuscript, it remains unclear why the authors emphasize the eastern Indian Ocean (EIO) but not the western Indian Ocean (WIO). The WIO warm pool may be equally important for nonlinear interactions. I would like the authors to address this concern.

Response:

We thank the reviewer for this important suggestion. To address the reviewer's request, we conducted additional experiments forcing IGCM4 with western Indian Ocean warming alone (I_W), the full Indian Ocean Dipole (I_B), and the complete observed Indian Ocean composite observed during EP and CP events (I), each combined with EP and CP Pacific basin forcing (Fig. S3). Across all six configurations, anomalous drying persists over central and northern India, with wet anomalies confined to the south-eastern Arabian Sea and the southern peninsular tip. In every pairing, EP forcing Fig. S3(a, c, e) produces stronger and more spatially organised Indian drying than the corresponding CP forcing Fig. S3(b, d, f), preserving the Pacific-only EP > CP suppression hierarchy.

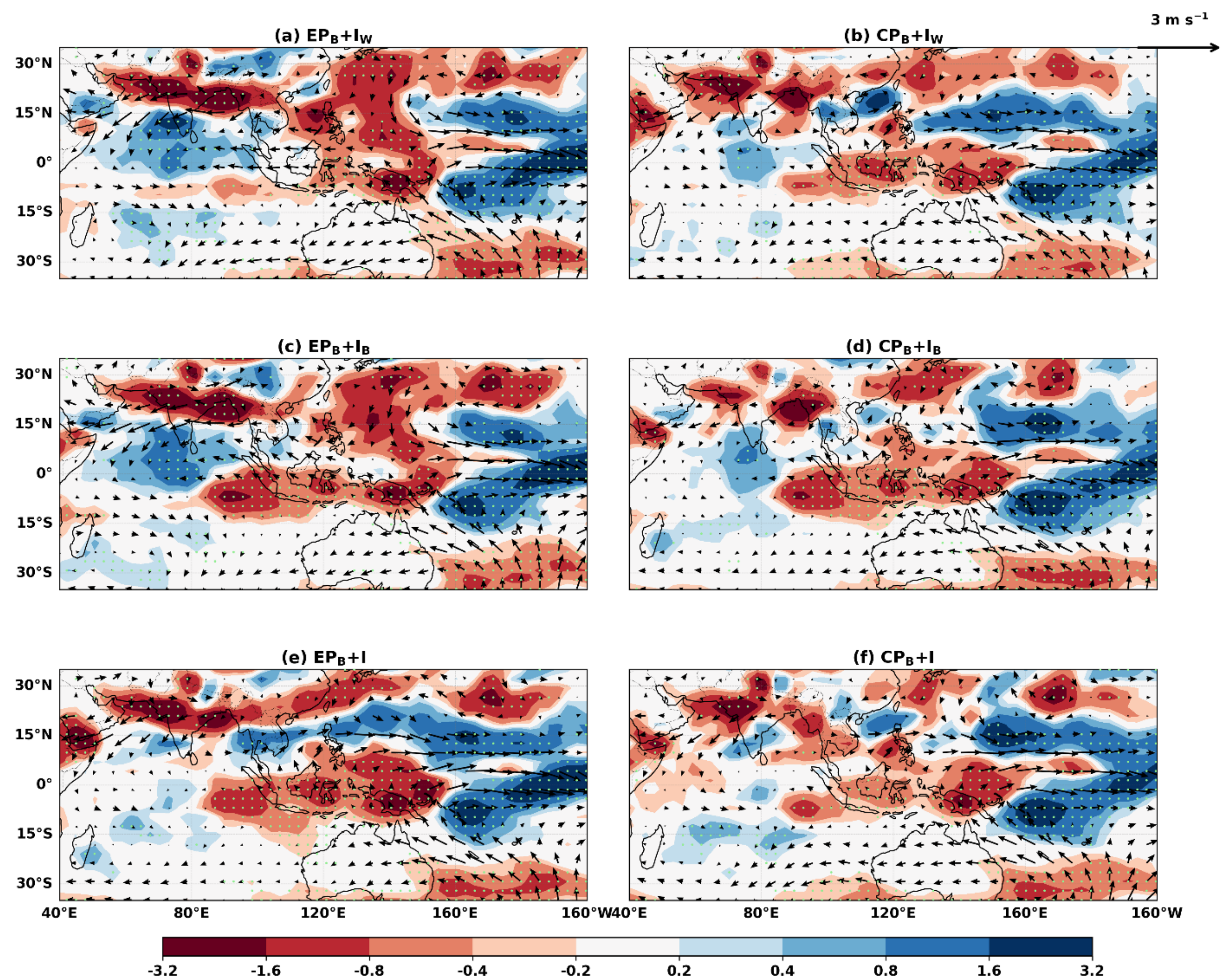

Figure S3. IGCM4 JJAS rainfall responses (mm d^{-1}, shaded) and 850 hPa wind anomalies (m s^{-1}, vectors) to combined Indo-Pacific SST forcing. (a, b) EP and CP Pacific basin combined with western Indian Ocean warming (EP_B+I_W, CP_B+I_W). (c, d) Combined with the full Indian Ocean Dipole (EP_B+I_B, CP_B+I_B). (e, f) Combined with the full observed Indian Ocean composite (EP_B+I, CP_B+I). Stippling indicates statistical significance at the 90% confidence level (Student's t-test).

*Critically, the addition of Western Indian Ocean warming (I_W) anomalies and the other Indian Ocean forcings (I_B, I) does not reproduce the EP–CP drought reversal observed in our primary experiments (*EP_B+I_C, CP_B+I_C) *with isolated SEIO cooling. This confirms that the reversal mechanism is uniquely tied to the SEIO cold pole. The figure is placed in the supplementary as Fig. S3, and the corresponding short discussion is updated in the main text. Also, the table for the model experiments is updated with the latest six experiments.*

L311-314: No such reversal in Pacific-only experiments after the addition of Western Indian Ocean warming anomalies (I_W) to EP_B and CP_B experiments. The same is not true even for the addition of the full Indian Ocean Dipole anomalies (I_B) and the complete observed Indian Ocean anomalies (I) for Pacific-only experiments (Fig. S3).

Comment #3: L116: The abbreviation 'MC' (Maritime Continent) has not been introduced earlier in this section.

Response:

We thank the reviewer, and ‘MC' is now defined at its first occurrence in the manuscript.

Comment #4: L140: What exactly is meant by 'seasonally varying SST climatology'? Does this refer to a monthly SST update?

Response:

The 'seasonally varying SST climatology' refers to the monthly SST climatology, and these 12 SST monthly climatology fields repeat identically every model year through the 35-year IGCM4 integration, so CTRL contains no prescribed interannual variability. The text has been revised to state this explicitly.

L140-144: IGCM4 is forced with a repeating monthly varying SST climatology derived from NOAA-CIRES 20th Century Reanalysis Version 3 (Compo et al. 2011) for the period 1971–2000. All simulations are run for 35 years, with the first 5 years being discarded for model spin-up and the final 30 used for analysis.

Comment #5: L157–172: The description in this section needs improvement. Specifically: (i) How are SST anomalies for ENSO and IOD created during their developing phase (November to October)? (ii) Are the ENSO/IOD SST anomalies added to the corresponding months of the 35-year integration or simply added to the climatology? (iii) The EP_C and CP_C anomalies have different magnitudes — what is the rationale for adding a constant cold SEIO anomaly to both? (iv) Could the authors indicate how frequently such an SST configuration occurs during the 35-year control integration?

Response:

We thank the reviewer for these detailed and important questions. We address each sub-question in turn.

i. *For each El Niño event, monthly SST anomalies are formed by removing the 1971–2000 monthly SST climatology, giving twelve monthly maps per event spanning the developing window from November of the preceding year to October of the El Niño event year; these are then composited across all El Niño events separately for each type. The window from November (Y-1) to October (Y), where 'Y' is the El Niño event year (for example, 1997-1998, Y refers to 1997), is chosen because it opens before the El Niño signature emerges and considers the developing phase of El Niño during the ISM. The window also covers the IOD's entire life cycle for any IOD event years.*

ii. *The composite SST anomalies created for each El Niño event type and IOD are added to the corresponding months of the SST climatology to build a new, repeating twelve-month forcing cycle that then drives the whole 35-year run.*

iii. *We deliberately apply the same I_C anomaly (from the positive IOD composite) to both EP_B and CP_B to ensure that any difference in the combined response can be unambiguously attributed to the Pacific forcing type alone, rather than to amplitude differences in the Indian Ocean forcing. The positive IOD SST pattern does not vary* *systematically between EP and CP El Niño backgrounds (Stuecker et al. 2017), making this experimental choice physically defensible. We acknowledge that the co-occurrence amplitude may vary slightly and have noted this as a limitation in the revised Discussion.*

iv. *CTRL has no interannual variability, so no such configuration occurs in it by construction; the relevant frequencies are those of the observed events from which the composites are built.*

L179-187: For each El Niño event, monthly SST anomalies are formed by removing the 1971–2000 monthly SST climatology, giving twelve monthly maps per event spanning the developing window from November of the preceding year to October of the El Niño event year; these are then composited across all El Niño events separately for each type. The window from November (Y-1) to October (Y), where 'Y' is the El Niño event year (for example, 1997-1998, Y refers to 1997), is chosen because it opens before the El Niño signature emerges and considers the developing phase of El Niño during the ISM. The window also covers the IOD's entire life cycle for any IOD event years

Comment #6: L180: Regarding the model biases, could the authors briefly comment on the sources of these biases?

Response:

We thank the reviewer for this comment. In general, all GCM whether coupled or Atmosphere only contain systematic biases resulting from inadequate physical parameterizations or poorly resolved processes ((Sperber et al. 2013; Bollasina and Ming 2013; Samanta et al. 2018). A primary reason for these biases is that IGCM4 uses simpler parameterizations of physical processes than state-of-the-art general circulation models (GCMs), and it has a relatively coarse resolution (T42; Joshi et al. 2015). This means simplified representations of moist processes, such as convective and boundary-layer mixing. Crucially, since all results are expressed as anomaly differences between SST-forced experiments and the CTRL simulation, we do not expect our main conclusions to be sensitive to this bias. We have updated the same in the revised manuscript.

L227-235: A primary reason for these biases is that IGCM4 uses simpler parameterizations of physical processes than state-of-the-art general circulation models (GCMs), and it has a coarse resolution (T42; Joshi et al. 2015). This means simplified representations of moist processes, such as convective and boundary-layer mixing. At upper levels (Fig. 3f), there are easterly biases over the MC and the subtropical Pacific. Despite these biases, the model reproduces large-scale monsoon features well and provides a suitable framework for idealised experiments. Since all results are expressed as anomaly differences between SST-forced experiments and the CTRL simulation, we do not expect our main conclusions to be sensitive to this bias.

Comment #7: Figure 3 appears to be of low resolution. I encourage the authors to provide a higher-quality version for the benefit of readers.

Response:

We thank the reviewer for this comment. Figure 3 (now Figure 4 after revision) has been revised.

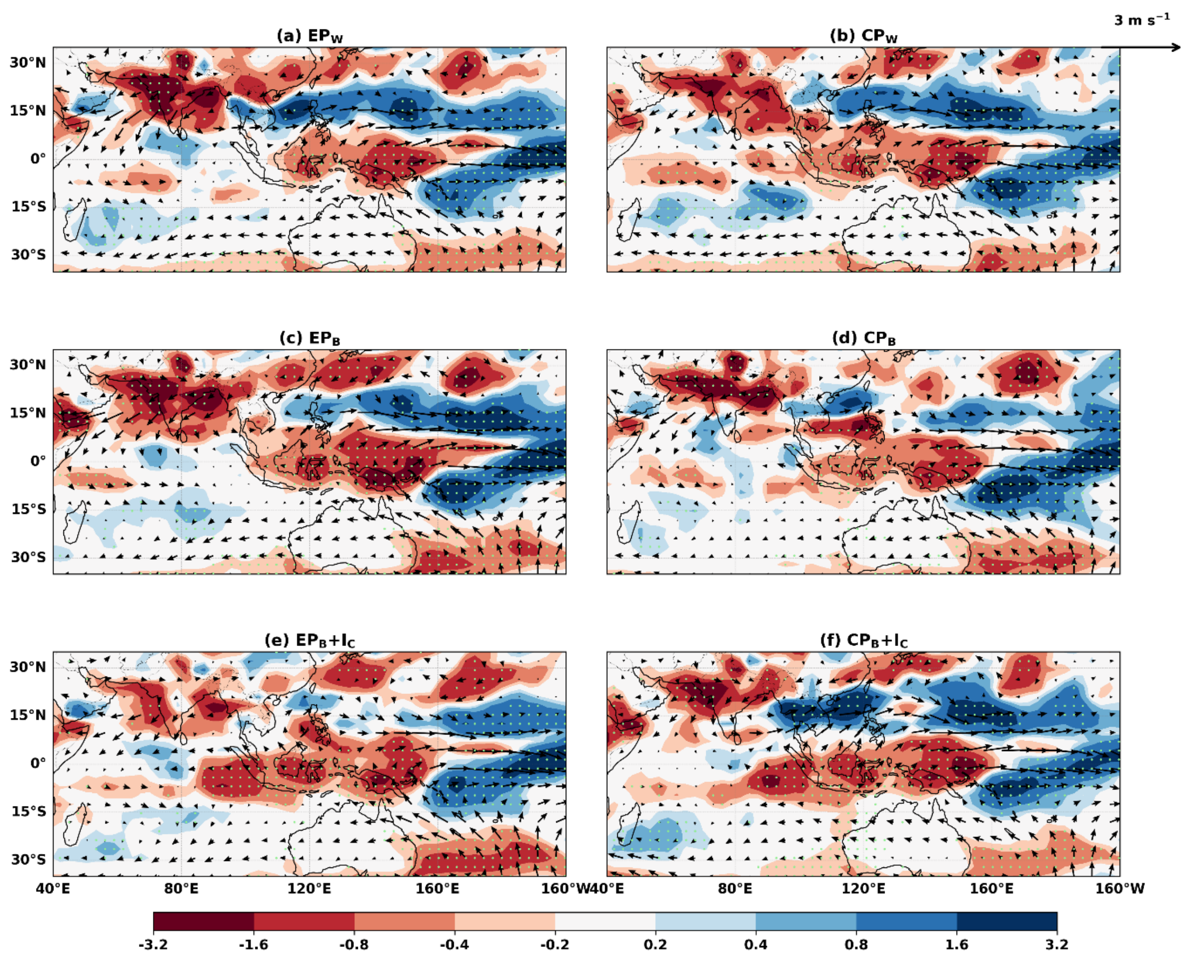

Figure 4. IGCM4 JJAS rainfall responses (mm d^{-1}, shaded) and 850 hPa circulation anomalies (m s^{-1}, vectors). (a, b) Pacific warm-only forcing (EP_W, CP_W). (c, d) Full

Pacific basin forcing (EP_B, CP_B). (e, f) Full Pacific basin combined with SEIO cold anomalies (EP_B+I_C, CP_B+I_C). Hatching and black vectors indicate statistical significance at the 90% confidence level (Student's t-test).

Comment #8: L279–L285: In the control experiment, do the authors observe a similar IMSR response to monthly SST forcing under conditions analogous to CP_B+I_C and EP_B+I_C? Addressing this would help readers relate the control experiment to the idealized experiments.

Response:

We thank the reviewer for this question. As mentioned in responses to Comments #4 and #5, we respectfully note that IGCM4 is forced with a monthly-varying SST climatology and does not contain El Niño or IOD-like anomalies.

Comment #9: L338: Could the authors identify or explain to readers the potential nonlinear pathways for EP and CP forcing in combination with SEIO anomalies?

Response:

We thank the reviewer for this valuable suggestion. Two distinct nonlinear pathways have been identified and are now discussed explicitly in the expanded Discussion.

Two distinct nonlinear pathways operate in our experiments. In EP_B+I_C, the ~160° zonal separation between the warm EP and cold SEIO forcing centres prevents their atmospheric responses from overlapping. Walker descent driven by the SEIO cold pole anchors to the Maritime Continent, while EP-driven descent remains in the central Pacific, producing near-complete drought relief over India (Fig. 5c). In CP_B+I_C, the smaller separation (~55°) allows the atmospheric responses of the two poles to overlap over the Maritime Continent, generating a more additive combined response whose descent signal extends westward into the Indian Ocean sector and maintains anomalous subsidence over India (Fig. 6d). We have updated this into section 3.3, while discussing about the non-linearity.

L387-396: The large zonal separation between the warm eastern Pacific anomaly centers and the cold anomaly over SEIO prevents their individual Gill-type atmospheric responses from overlapping. Walker descent driven by the SEIO cold pole anchors to the Maritime Continent, while EP-driven descent remains in the central Pacific, producing near-complete drought relief over India (Fig. 6c). In contrast, the CP_B+I_C residual (Fig. 6d) is weaker than the CP Pacific-only residual (Fig. 6b), indicating that the addition of SEIO cooling does not amplify the CP nonlinearity. In CP_B+I_C, the smaller separation (~55°) allows the atmospheric responses of the two poles to overlap over the Maritime Continent, generating a more additive combined response whose descent signal extends westward into the Indian Ocean sector and maintains anomalous subsidence over India (Fig. 6d).

Comment #10: L404–409: I would caution against emphasising or attributing the presented results to seasonal prediction, particularly regarding SSTs. While the study enhances our understanding of the large-scale ISMR response to SST forcing, the conclusions are drawn from a highly idealized setting.

Response:

We agree with the reviewer's comment. The relevant sentences in the Discussion (L404–409), which made claims about seasonal prediction beyond the scope of the IGCM4 framework, have been removed. The revised text reads:

L465-472: These results advance our mechanistic understanding of how the spatial configuration of Indo-Pacific SST anomalies governs the ISM response. The dynamical framework identified here is the zonal separation between Pacific warming and Maritime Continent cold anomalies as the governing factor, which may inform how SST-based diagnostics are constructed and interpreted in coupled prediction systems. However, translating these mechanistic insights into demonstrable improvements in forecast skill would require validation in fully coupled ocean–atmosphere models with realistic Indian Ocean variability, intraseasonal forcing, and air–sea feedbacks, which is beyond the scope of the present study.

Reviewer 2

The article primarily investigates the mechanisms underlying the more severe droughts associated with Central Pacific (CP) El Niño events compared to those associated with Eastern Pacific (EP) El Niño events, using sensitivity experiments with an atmospheric model. The authors argue that south-eastern Indian Ocean SST anomalies are the primary factor contributing to these severe drought conditions. While this study is compelling and may be appropriate for publication in Climate Dynamics, additional analyses are necessary before it can be considered for final acceptance.

Comment #1: Generate a panel plot depicting the rainfall, SST, and circulation anomalies of the CP and EP El Niño events (composite), from the observational/reanalysis dataset over the Indo-Pacific region and place it as the first figure in the manuscript. This will help readers understand the large-scale climate features associated with CP and EP El Niño events.

Response:

We thank the reviewer for this valuable suggestion. We have generated a panel plot of EP and CP composites from SST, rainfall & circulation anomalies, which appears as Figure 1 of the revised manuscript and is now described in the text quoted below.

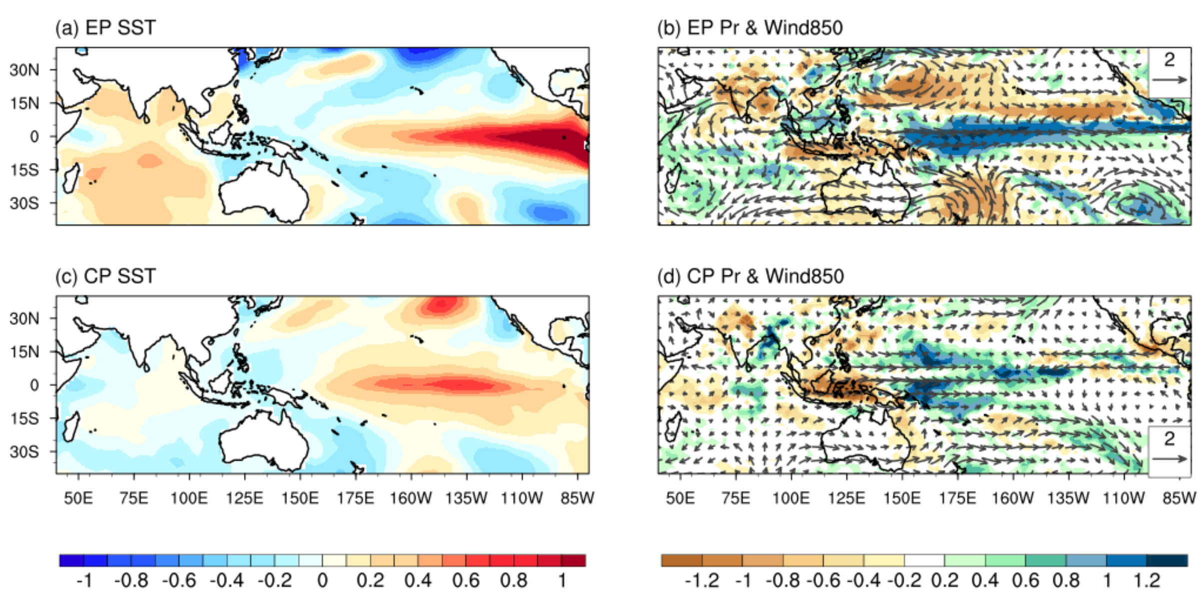

Figure 1. The composite maps of (a, c) SST and the (b, d) rainfall and circulation (850 hPa) anomalies for EP and CP El Niños events. The composites are based on the identified EP El and the CP El Niño years following Yu and Kim (2013)

L153-170: Figure 1 shows the observed composites of JJAS SST, rainfall, and 850 hPa circulation anomalies for EP and CP El Niño developing years. During EP El Niño Fig. 1(a, b), strong eastern Pacific warming drives a coherent Walker circulation response, with its descending branch extending continuously from the MC into the Indian subcontinent, evident as a spatially organised dry anomaly over India accompanied by anomalous low-level easterlies that suppress the cross-equatorial monsoon flow (Krishna Kumar et al. 2006). In contrast, during CP El Niño Fig. 1(c, d), the westward-displaced central Pacific warming generates a weaker double-cell Walker circulation (Ashok et al. 2007) whose western descending branch is largely confined to the Maritime Continent, leaving Indian rainfall comparatively less suppressed with disorganised 850 hPa wind anomalies. Yet observational and modeling studies consistently show that CP El Niño events produce more frequent and severe Indian monsoon droughts than EP events (Krishna Kumar et al. 2006; Dandi et al. 2020). This apparent contradiction is that EP suppresses India more strongly in the developing-phase composites, yet CP causes worse droughts in the observed record. This suggests that the Indian Ocean SST anomalies co-occurring with each ENSO type, clearly visible in panels (a) and (c), play a critical and differentially modulating role that the Pacific forcing alone cannot explain. Disentangling this requires controlled idealised experiments in which Pacific and Indian Ocean SST anomalies can be prescribed independently, motivating the IGCM4 experimental design of this study.

Comment #2: Evaluate the temporal variation of the correlation coefficient between Niño 3.4 SST and Indian summer monsoon land rainfall using both observational and model simulations. Also generate a spatial map of the correlation coefficient between Niño 3.4 SST and summer monsoon rainfall over the Indian region. This will help validate the IGCM4 model's ability to reproduce the observed ENSO-monsoon relationship.

Response:

We respectfully note that IGCM4 is forced with a repeating monthly climatological SST. The CTRL integration is designed to contain no interannual variability. Computing a Niño 3.4–ISM correlation from the CTRL is therefore not meaningful, as there are no interannual ENSO or *monsoon anomalies to correlate. This diagnostic is applicable to coupled models or runs with interannually varying SST forcing, neither of which is true for our framework.*

Comment #3: Pacific SST changes can induce SST anomalies over most parts of the Indian Ocean, and these changes can affect Indian summer monsoon rainfall. Since the present study uses an atmospheric model for the sensitivity experiments, such changes in the Indian Ocean will not appear in the simulations. The sensitivity experiments were limited only to the south-eastern Indian Ocean (SEIO) and Pacific Ocean SST forcings. Conduct additional sensitivity experiments by forcing the IGCM4 model with observed SST anomalies over the entire Indian Ocean during CP and EP events.

Response:

We thank the reviewer for this important suggestion. To address the reviewer's request, we conducted additional experiments forcing IGCM4 with western Indian Ocean warming alone (I_W), the full Indian Ocean Dipole (I_B), and the complete observed Indian Ocean composite observed during EP and CP events (I), each combined with EP and CP Pacific basin forcing (Fig. S3). Across all six configurations, anomalous drying persists over central and northern India, with wet anomalies confined to the south-eastern Arabian Sea and the southern peninsular tip. In every pairing, EP forcing Fig. S3(a, c, e) produces stronger and more spatially organised Indian drying than the corresponding CP forcing Fig. S3(b, d, f), preserving the Pacific-only EP > CP suppression hierarchy.

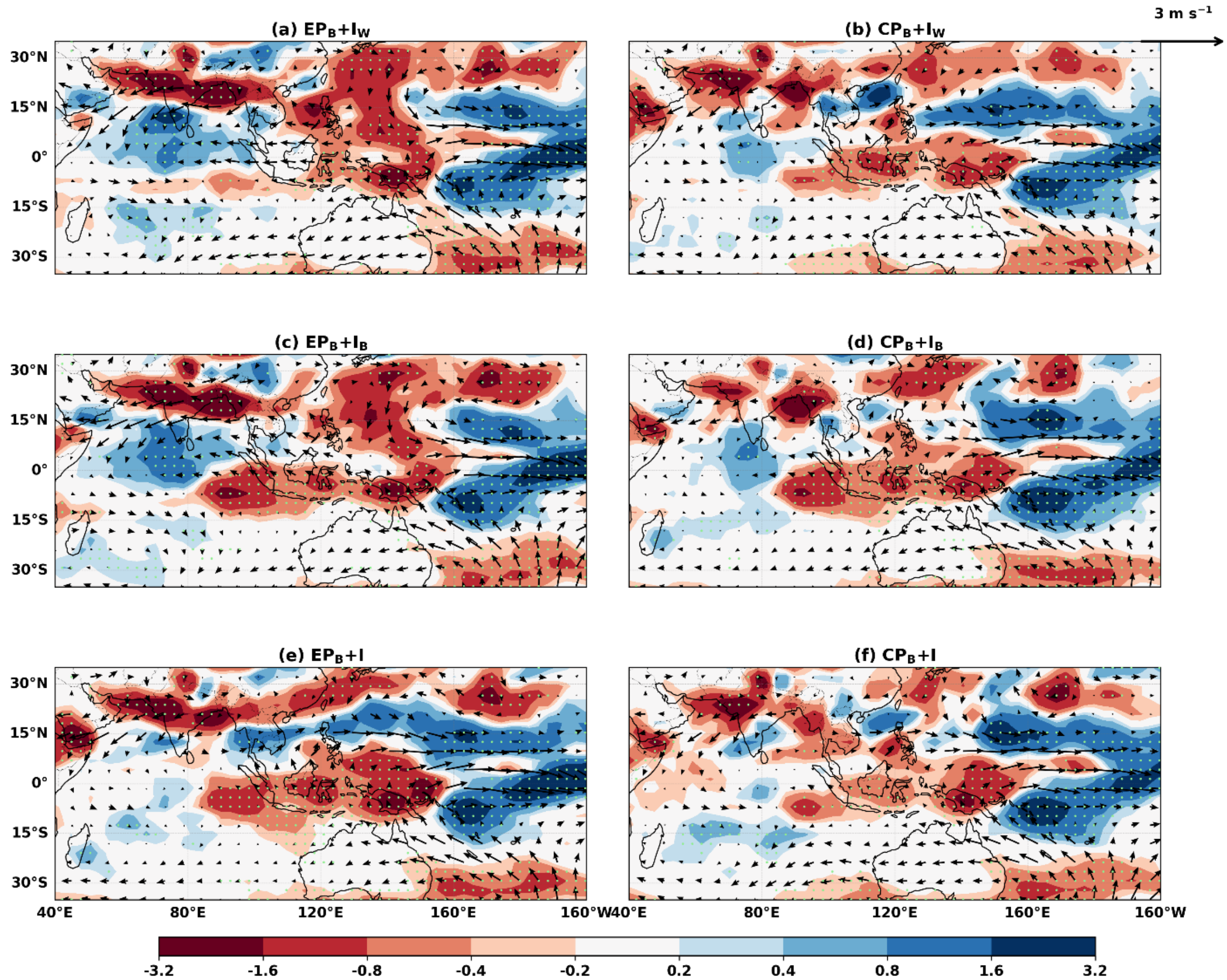

Figure S3. IGCM4 JJAS rainfall responses (mm d^{-1}, shaded) and 850 hPa wind anomalies (m s^{-1}, vectors) to combined Indo-Pacific SST forcing. (a, b) EP and CP Pacific basin combined with western Indian Ocean warming (EP_B+I_W, CP_B+I_W). (c, d) Combined with the full Indian Ocean Dipole (EP_B+I_B, CP_B+I_B). (e, f) Combined with the full observed Indian Ocean composite (EP_B+I, CP_B+I). Stippling indicates statistical significance at the 90% confidence level (Student's t-test).

*Critically, the addition of Western Indian Ocean warming (I_W) anomalies and the other Indian Ocean forcings (I_B, I) does not reproduce the EP–CP drought reversal observed in our primary experiments (*EP_B+I_C, CP_B+I_C) *with isolated SEIO cooling. This confirms that the reversal mechanism is uniquely tied to the SEIO cold pole. The figure is placed in the supplementary as Fig. S3, and the corresponding short discussion is updated in the main text. Also, the table for the model experiments is updated with the latest six experiments.*

L311-314: No such reversal in Pacific-only experiments after the addition of Western Indian Ocean warming anomalies (I_W) to EP_B and CP_B experiments. The same is not true even for the addition of the full Indian Ocean Dipole anomalies (I_B) and the complete observed Indian Ocean anomalies (I) for Pacific-only experiments (Fig. S3).

Reviewer 3:

The manuscript provides potentially valuable insights into how SEIO cold anomalies modulate the impact of different El Niño flavors on the Indian monsoon. The study also discusses the nonlinear responses that arise from the addition of SEIO cooling anomalies, triggering differential responses across India. While the study is promising and identifies the important role of SEIO anomalies, the following major/minor comments need to be addressed.

Major Comments:

Comment #1: Bay of Bengal wet bias could affect the EP vs CP response contrast. Describe substantial EP-CP differences in rainfall suppression, specifically in that region.

Response:

We thank the reviewer for pointing this out. The observed wet bias over the Bay of Bengal during JJAS is a persistent feature of atmospheric GCMs in general (Sperber et al. 2013; Bollasina and Ming 2013; Samanta et al. 2018). Since all results are expressed as anomaly differences between SST-forced experiments and the CTRL simulation, so we do not expect that our main conclusions to be sensitive to this bias.

Sperber, K.R., Annamalai, H., Kang, I.S., et al. (2013). The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Climate Dynamics, 41, 2711–2744. https://doi.org/10.1007/s00382-012-1607-6

Bollasina, M.A. and Ming, Y. (2013). The general circulation model precipitation bias over the southwestern equatorial Indian Ocean and its implications for simulating the South Asian monsoon. Climate Dynamics, 40, 823–838. https://doi.org/10.1007/s00382-012-1347-7

Samanta, D., Hameed, S.N., Jin, D., et al. (2018). Impact of a narrow coastal Bay of Bengal sea surface temperature front on an Indian summer monsoon simulation. Scientific Reports, 8, 17694. https://doi.org/10.1038/s41598-018-35735-3

Comment #2: Add quantitative numbers for suppression/enhancement comparison between EP and CP at places wherever it is required.

Response:

We thank the reviewer for this important suggestion. We have updated the results section with quantitative rainfall changes noted across the experiments.

Comment #3: In Section 4, the paper discusses how SEIO cooling reorganizes the Walker circulation differently under EP and CP forcing. The mechanism by which Pacific ENSO forcing communicates to the Indian Ocean via the oceanic Kelvin wave, along with other relevant references, is missing. [Klein et al. 1999; Xie et al. 2009]

Response:

We thank the reviewer for this suggestion; both references are now cited in Section 4. During the El Niño developing phase, anomalous Walker circulation changes communicate to the Indian Ocean primarily via the atmospheric bridge: enhanced subsidence over the eastern Indian Ocean reduces cloud cover and increases net surface heat flux, driving a basin-mean warming tendency (Klein et al. 1999). Concurrently, El Niño-induced equatorial easterlies within the Indian Ocean force upwelling oceanic Kelvin waves that propagate eastward and shoal the thermocline along the Sumatra–Java coast, generating the localised SEIO cold SST anomalies (Xie et al. 2009). The relevant reference have been added to the manuscript reference list:

Klein SA, Soden BJ, Lau N-C (1999) Remote sea surface temperature variations during ENSO: evidence for a tropical atmospheric bridge. J Clim 12:917–932

Minor Comments:

Comment #4: L145: Prescribe → prescribed

Response:

Corrected.

Comment #5: L157–158: Remove duplicate 'Yu and Kim'

Response:

Corrected

Comment #6: L242: Strengthening -> Strengthens

Response:

Corrected.

Comment #7: L283: 'reproducing the' → 'consistent with'

Response:

Corrected.

Comment #8: L294: 'directly adjacent to the MC' overstates the proximity of CP warming to the Maritime Continent

Response:

Corrected

Comment #9: L297–298: 'is reverse' → 'reversed'

Response:

Corrected.

Comment #10: L394: 'less separation' → 'smaller separation'

Response:

Corrected.

Comment #11: L397–398: Nonlinearity is stated to exist only 'in the case of EP' but CP also shows nonlinearity

Response:

The reviewer is correct. Nonlinearity exists in both EP and CP configurations and is corrected

Comment #12: In Fig. S2, panels (a,b) say 'EP_W, CP_W' (warm-only experiments) under 'Pacific cold-only forcing'; they should be EP_C, CP_C

Response:

Corrected.

Cover Letter

The Editor

Climate Dynamics

Springer

Dear Editor,

We are pleased to submit our manuscript entitled “The influence of cold SST anomalies surrounding the Maritime Continent on the El Niño-Indian monsoon teleconnection,” authored by Umakanth Uppara, Benjamin Webber, Manoj Joshi, and Andrew Turner, for consideration for publication in Climate Dynamics.

This study employs the Intermediate Global Climate Model (IGCM4), forced by anomalous SSTs over the Pacific and Indian Ocean corresponding to different flavors of El Niño and IOD. Using a suite of idealized experiments with IGCM4, we demonstrate that cold sea-surface temperature (SST) anomalies in the south-eastern Indian Ocean/Maritime Continent, typical of positive Indian Ocean Dipole events, completely reverse the relative impacts of EP and CP El Niño on Indian Summer Monsoon rainfall. This reversal arises from differences in the zonal separation between warm Pacific and cold Maritime Continent anomalies, which control the eastward extent of Walker-circulation descent and the resulting subsidence over India. Non-linear responses to SST forcings are analyzed. This work is highly relevant to the scope of climate dynamics, which emphasizes process-based understanding of tropical climate variability and teleconnections.

An earlier version of this manuscript's preprint is still available at the ESS Open Archive https://essopenarchive.org/doi/full/10.1002/essoar.10512660.1. Please keep this in mind when checking for plagiarism. We confirm that the manuscript is original, not under consideration elsewhere, and that all authors have approved the submission. There are no conflicts of interest to declare. We believe this manuscript will be of broad interest to the journal and look forward to your consideration.

Sincerely,

Dr. Umakanth Uppara, Scientist

University of East Anglia (work carried out),

Indian Institute of Tropical Meteorology, Pune, India (current working)

The influence of cold SST anomalies surrounding the Maritime Continent on the El Niño-Indian monsoon teleconnection

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Abstract

The Indian summer monsoon (ISM) is strongly influenced by the El Niño-Southern Oscillation (ENSO), with Central Pacific (CP) El Niño events typically producing more severe droughts over India than Eastern Pacific (EP) events. Using idealized atmospheric model experiments, we show that this contrasting response is governed by sea surface temperature (SST) anomalies in the south-eastern Indian Ocean (SEIO). Under Pacific-only SST forcing, EP El Niño suppresses ISM rainfall more strongly than CP El Niño events. The addition of SEIO cooling reverses this hierarchy, with enhanced drying over India during CP events relative to EP events. The reversal arises because the zonal separation between the warm Pacific and the cold anomalies around the Maritime Continent (MC) is greater during EP events, forcing Walker descent over the MC, whereas the separation is less during CP events, allowing subsidence to spread over India. Diagnostics confirm that the combined response is strongly nonlinear. These results advance our mechanistic understanding of how the spatial configuration of SST anomalies across the Indo-Pacific governs the Indian summer monsoon response to El Niño, with implications for how ENSO-type diversity is represented in prediction systems.

Keywords Indian summer monsoon; ENSO diversity; Indian Ocean Dipole; Maritime Continent; Walker circulation; IGCM4

1.0 Introduction

The El Niño–Southern Oscillation (ENSO), originating in the tropical Pacific Ocean, exerts a dominant remote influence on the Indian summer monsoon (ISM), often leading to droughts during El Niño events (Rasmusson and Carpenter 1983). These impacts are particularly pronounced during the developing phase of ENSO, when SST anomalies intensify and dynamically interact with the evolving monsoon circulation (Webster et al. 1998; Krishna Kumar et al. 1999). During this phase, the eastward shift of the Walker circulation induces anomalous descent over the western Pacific and Indian subcontinent, suppressing convective activity and monsoon rainfall (Goswami 1998; Lau and Wang 2006). Observational and modelling studies have consistently demonstrated such responses, but they also reveal substantial decadal variability in the ENSO–ISM teleconnection, attributed to shifts in the background mean state and the diversity of individual ENSO events (Roy et al. 2019; Goswami and An 2023).

A major contributor to this variability is the diversity of ENSO types. While canonical EP El Niño events feature SST warming concentrated in the Niño3 region, CP El Niños exhibit anomalous warming in the Niño4 region, with convection anomalies displaced westward (Ashok et al. 2007; Yeh et al. 2009). These distinctions produce different atmospheric responses: CP events induce focused upper-level convergence over South Asia, leading to intense suppression of the ISM, whereas EP events generate weaker, more zonally extended responses (Krishna Kumar et al. 2006). Several studies have shown that CP events trigger more frequent or severe monsoon droughts through distinct atmospheric teleconnection pathways (Krishna Kumar et al. 2006; Kao and Yu 2009), though the relative importance of different mechanisms remains under investigation.

In addition to Pacific SST anomalies, the ISM is sensitive to regional forcings in the Indian Ocean. The Indian Ocean plays an important role in modulating the ENSO-ISM teleconnection. The Indian Ocean Dipole (IOD), characterised by anomalous SST cooling in the eastern Indian Ocean and warming in the western Indian Ocean, can modify the Walker circulation and alter the monsoon's response to concurrent El Niño forcing (Saji et al. 1999; Ashok et al. 2001). During positive IOD events that coincide with El Niño, the Indian Ocean forcing has been shown to partially offset El Niño-induced subsidence over India, mitigating monsoon drying in some years (Cherchi and Navarra 2013). Sensitivity experiments using prescribed diabatic heating have shown that Indian Ocean heating anomalies weaken the anomalous anticyclone over India that is induced by Pacific El Niño forcing, indicating that the Indian Ocean partially counteracts the Pacific's monsoon-suppressing influence (Jang and Straus 2012). However, these studies treated ENSO as a single phenomenon and did not examine whether Indian Ocean anomalies, specifically those in the eastern Indian Ocean (EIO), modulate the ISM response differently under EP versus CP Pacific forcing.

Recent work further suggests that monsoon responses are governed not only by the magnitude of SST anomalies, but also by their horizontal gradients, particularly across the Indo-Pacific warm pool (Hoell and Funk 2013; Ashok et al. 2004; Roxy et al. 2015). The combined atmospheric response does not follow a simple linear superposition of individual basin effects; instead, nonlinear interactions can enhance or offset individual responses, depending on the spatial alignment of SST anomalies and the strength of inter-basin SST anomaly gradients (Krishnaswamy et al. 2015; Goswami and An 2023). Such nonlinearities are difficult to disentangle in coupled climate models, which also suffer from persistent biases in their simulation of the SST mean state and gradients therein (Sperber et al. 2013; Yang et al. 2019).

Despite the established importance of both ENSO diversity and Indian Ocean SST anomalies for the ISM, it is unclear how south-eastern Indian Ocean (SEIO) cooling typical of positive Indian Ocean Dipole (pIOD) events across the Maritime Continent (MC) differentially modulates EP versus CP El Niño teleconnections to the ISM. Previous work has shown that SEIO SST anomalies are a significant precursor of both ISM and IOD variability, with cold SEIO SSTs weakening the monsoon circulation through modulation of the local Hadley cell and triggering positive IOD events through wind-evaporation-SST and wind-thermocline-SST feedbacks (Terray et al. 2005; Terray et al. 2007). However, these studies treated ENSO as a single phenomenon and did not examine whether the SEIO's modulating effect on the ISM depends on the spatial flavour of concurrent Pacific forcing. Here we address this using a suite of idealised experiments with the Intermediate General Circulation Model version 4 (IGCM4). This model's computational efficiency and transparency make it well-suited for mechanistic diagnosis of large-scale teleconnections (Joshi et al. 2015; Ratna et al. 2021). Our objectives are to: (1) examine the ISM response to Pacific SST forcing in EP versus CP El Niños; (2) evaluate how SEIO cooling modulates this response; and (3) quantify the nonlinearity of the atmospheric response to combined Indo-Pacific SST forcings.

2. Data and Methods

2.1 Model configuration

This study uses the Intermediate General Circulation Model version 4 (IGCM4), a global spectral primitive-equation atmospheric model with simplified physical parameterisations, designed for idealised experiments (Joshi et al. 2015; Ratna et al. 2021; van der Wiel et al. 2016). The model is run at a T42 spectral resolution (~2.8° × 2.8° grid) with 20 vertical levels. Physical processes, including convection and boundary-layer mixing, are parameterised in simplified form. Land surface temperature and soil moisture evolve interactively using a two-layer soil model (Forster et al. 2000). IGCM4 is forced with a repeating monthly varying SST climatology derived from NOAA-CIRES 20th Century Reanalysis Version 3 (Compo et al. 2011) for the period 1971–2000. All simulations are run for 35 years, with the first 5 years being discarded for model spin-up and the final 30 used for analysis. IGCM4 has been widely used in studies of large-scale climate dynamics (Joshi et al. 2015; Ratna et al. 2021). Its structure enables the isolation of large-scale dynamical responses to prescribe SST forcing.

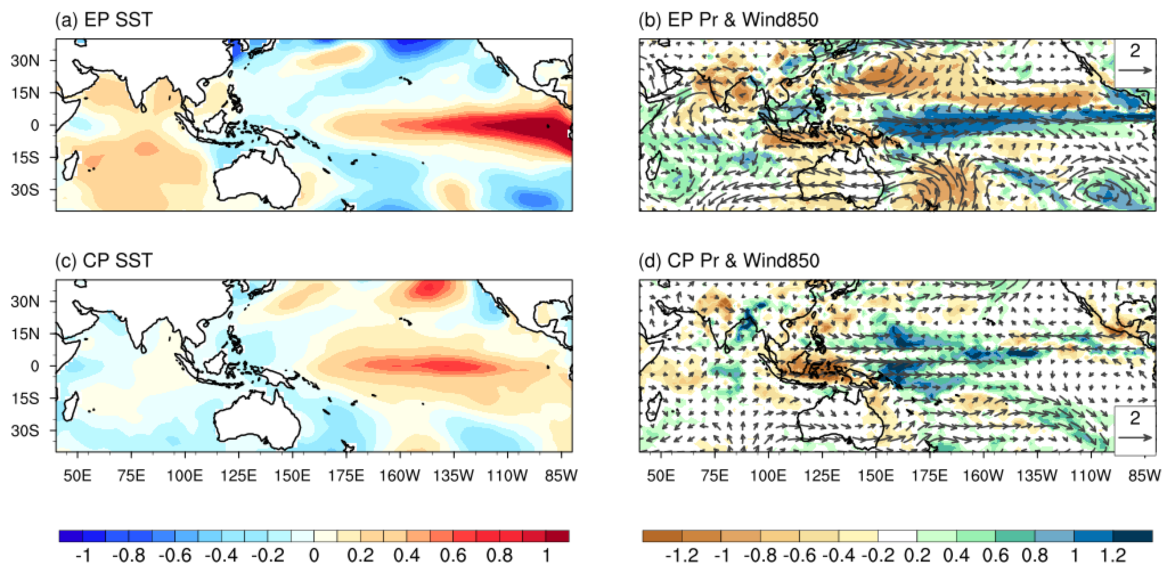

Figure 1. The composite maps of (a, c) SST and the (b, d) rainfall and circulation (850 hPa) anomalies for EP and CP El Niños events. The composites are based on the identified EP El and the CP El Niño years following Yu and Kim (2013)

Figure 1 shows the observed composites of JJAS SST, rainfall, and 850 hPa circulation anomalies for EP and CP El Niño developing years. During EP El Niño Fig. 1(a, b), strong eastern Pacific warming drives a coherent Walker circulation response, with its descending branch extending continuously from the MC into the Indian subcontinent, evident as a spatially organised dry anomaly over India accompanied by anomalous low-level easterlies that suppress the cross-equatorial monsoon flow (Krishna Kumar et al. 2006). In contrast, during CP El Niño Fig. 1(c, d), the westward-displaced central Pacific warming generates a weaker double-cell Walker circulation (Ashok et al. 2007) whose western descending branch is largely confined to the Maritime Continent, leaving Indian rainfall comparatively less suppressed with disorganised 850 hPa wind anomalies. Yet observational and modeling studies consistently show that CP El Niño events produce more frequent and severe Indian monsoon droughts than EP events (Krishna Kumar et al. 2006; Dandi et al. 2020). This apparent contradiction is that EP suppresses India more strongly in the developing-phase composites, yet CP causes worse droughts in the observed record. This suggests that the Indian Ocean SST anomalies co-occurring with each ENSO type (Fig. 1a, c), play a critical and differentially modulating role that the Pacific forcing alone cannot explain. Disentangling this requires controlled idealised experiments in which Pacific and Indian Ocean SST anomalies can be prescribed independently, motivating the IGCM4 experimental design of this study.

2.2 Experimental design and SST forcing

SST anomalies are constructed from observed composites of developing years of El Niño events following Yu and Kim (2013). The identified EP El Niño years are 1951, 1969, 1972, 1976, 1982, 1987, 1997, 2006, 2015, and the CP El Niño years are 1953, 1957, 1963, 1965, 1968, 1977, 1991, 1994, 2002, 2004, 2009. The positive IOD events in the years 1961, 1963, 1972, 1982, 1983, 1994, 1997, 2006, 2012, and 2015 are obtained from the Bureau of Meteorology (http://www.bom.gov.au/climate/iod). For each El Niño event, monthly SST anomalies are formed by removing the 1971–2000 monthly SST climatology, giving twelve monthly maps per event spanning the developing window from November of the preceding year to October of the El Niño event year; these are then composited across all El Niño events separately for each type. The window from November (Y-1) to October (Y), where 'Y' is the El Niño event year (for example, 1997-1998, Y refers to 1997), is chosen because it opens before the El Niño signature emerges and considers the developing phase of El Niño during the ISM. The window also covers the IOD's entire life cycle for any IOD event years. This period captures the seasonal evolution of SST anomalies before ENSO peaks, minimizing feedback contamination during the monsoon season (June - September).

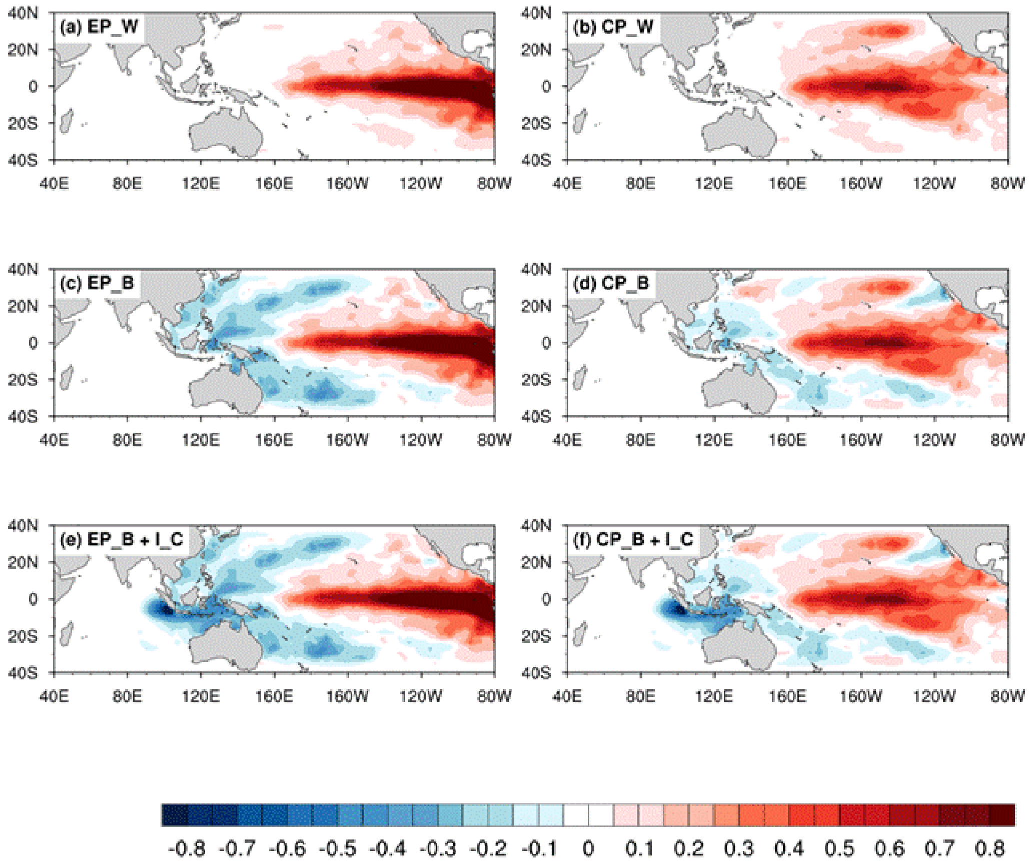

Figure 2. JJAS mean composites of SST anomalies (°C), used as surface forcing in IGCM4 experiments. (a) EP_W, (b) CP_W, (c) EP_B, (d) CP_B, (e) EP_B+I_C, (f) CP_B+I_C. In the naming convention, EP and CP denote Eastern and Central Pacific composites; W and C subscripts indicate warm-only and cold-only SST anomalies; B denotes full Pacific basin; I_C denotes SEIO cold anomalies from positive IOD composites.

To isolate the effects of SST polarity, each composite is split into warm (EP_W, CP_W), cold (EP_C, CP_C), and basin-wide (EP_B, CP_B) anomaly fields (Table 1). Additionally, a composite of cold SST anomalies in the SEIO and warm SST anomalies over WIO is generated from positive IOD years and referred to as the I_C and I_W anomalies, respectively. The SST composites over the Indian Ocean are also generated for the full positive IOD (referred to as 'I') and co-occurred Indian Ocean anomalies (referred as "I_B"). These anomaly fields are added to the monthly SST climatology to construct the SST forcing for each experiment. The experimental setup (Table 1) consists of 16 model experiments designed to isolate the atmospheric response to Pacific and Indian Ocean SST anomalies. Figure 2 shows the spatial distribution of SST anomalies used in six experiments (EP_W, CP_W, EP_B, CP_B, EP_B+I_C, and CP_B+I_C), whereas the remaining ten experiments

(EP_B+I_W, CP_B+I_W, EP_B+I, CP_B+I, EP_B+I_B, CP_B+I_B, EP_C, CP_C, EP_C+I_C, and CP_C+I_C) are shown in supplementary material (Fig. S1-S5). Of these ten supplementary experiments, the first six are designed to examine the role of SEIO on ISM relative to WIO, IOD, and the observed Indian Ocean anomalies, while the remaining four experiments are designed to diagnose the nonlinear response to SST forcing, as discussed in the results section.

2.3 Model climatology and biases

The IGCM4 control simulation captures key features of the ISM climatology, including rainfall maxima over the Western Ghats, central India, and the Bay of Bengal (Fig. 3c). Low-level (850 hPa) monsoon winds form a cross-equatorial flow over the western Indian Ocean and southwesterlies over the subcontinent, broadly consistent with reanalysis data (Fig. 3a). At 200 hPa, the model simulates the tropical easterly jet and upper-level divergence patterns typical of the monsoon (Fig. 3d). However, the model displays wet biases over part of India, the northern Bay of Bengal and the western Pacific (Fig. 3e), with corresponding circulation errors including enhanced southerlies over the Indian Ocean and stronger westerlies over the western Pacific. In general, all GCMs, whether coupled or Atmosphere-only, contain systematic biases resulting from inadequate physical parameterizations or poorly resolved processes (Sperber et al. 2013; Bollasina and Ming 2013; Samanta et al. 2018). A primary reason for these biases is that IGCM4 uses simpler parameterizations of physical processes than state-of-the-art general circulation models (GCMs), and it has a coarse resolution (T42; Joshi et al. 2015). This means simplified representations of moist processes, such as convective and boundary-layer mixing. At upper levels (Fig. 3f), there are easterly biases over the MC and the subtropical Pacific. Despite these biases, the model reproduces large-scale monsoon features well and provides a suitable framework for idealised experiments. Since all results are expressed as anomaly differences between SST-forced experiments and the CTRL simulation, we do not expect our main conclusions to be sensitive to this bias.

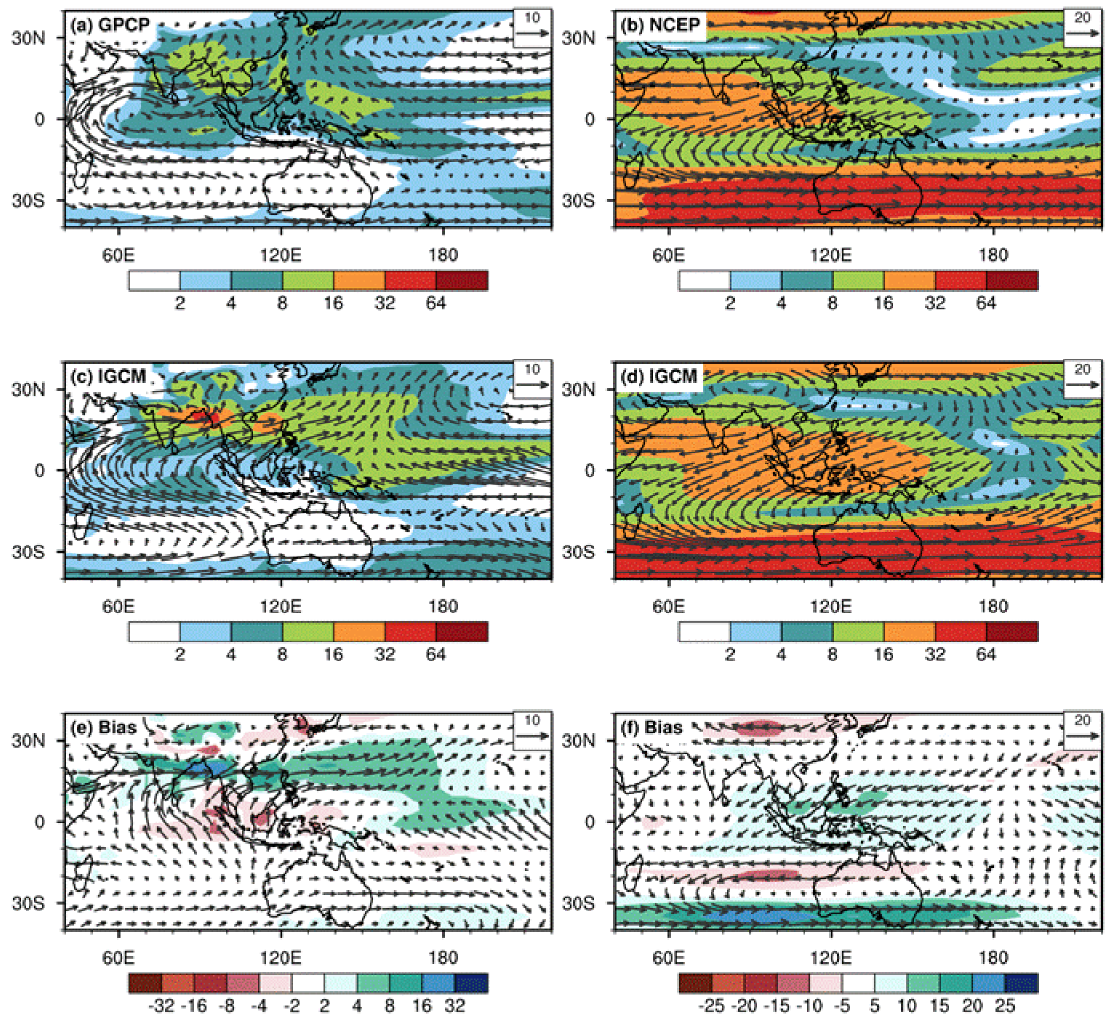

Figure 3. Observed (reanalysis) and IGCM4-simulated JJAS climatology. (a) GPCP rainfall (mm d^{-1}, shaded) overlaid with 850 hPa winds (m s^{-1}, vectors) from NCEP reanalysis. (b) 200 hPa windspeed (m s^{-1}, shaded) overlaid with wind vectors. (c, d) IGCM4-simulated rainfall and circulation. (e, f) Model biases.

Experiment	**SST Forcing**
CTRL – Control	Global monthly SST climatology
EP_W – Eastern Pacific Warm	CTRL + Pacific warm SST anomalies (EP composite)
CP_W – Central Pacific Warm	CTRL + Pacific warm SST anomalies (CP composite)
EP_C – Eastern Pacific Cold	CTRL + Pacific cold SST anomalies (EP composite)
CP_C – Central Pacific Cold	CTRL + Pacific cold SST anomalies (CP composite)
EP_B – Eastern Pacific Basin	CTRL + full Pacific basin SST anomalies (EP composite)

CP_B – Central Pacific Basin	CTRL + full Pacific basin SST anomalies (CP composite)
EP_B+I_C	CTRL + EP Pacific basin + SEIO cold SST anomalies
CP_B+I_C	CTRL + CP Pacific basin + SEIO cold SST anomalies
EP_B+I_W	CTRL + EP Pacific basin + WIO warm SST anomalies
CP_B+I_W	CTRL + CP Pacific basin + WIO warm SST anomalies
EP_B+I_B	CTRL + EP Pacific basin + full IOD SST anomalies
CP_B+I_B	CTRL + CP Pacific basin + full IOD SST anomalies
EP_B+I	CTRL + EP Pacific basin + Indian Basin SST anomalies
CP_B+I	CTRL + CP Pacific basin + Indian Basin SST anomalies
EP_C+I_C	CTRL + EP Pacific cold + SEIO cold SST anomalies
CP_C+I_C	CTRL + CP Pacific cold + SEIO cold SST anomalies

Table 1. Summary of model experiments. W and C subscripts denote warm-only and cold-only Pacific SST anomalies, respectively. B denotes full Pacific basin (warm + cold). I_C denotes SEIO cold anomalies from positive IOD composites. I_B refers to full IOD (warm + cold), and ‘I’ refers to observed Indian Basin SST anomalies during EP and CP.

3.0 Results

3.1 Monsoon response to Pacific SST anomalies

Under Pacific warm-only forcing (EP_W), JJAS rainfall is significantly suppressed over northwest India, the eastern Arabian Sea, and the head Bay of Bengal, with peak deficits exceeding 1.6 mm d^{-1} (Fig. 4a). Anomalous low-level easterlies reduce moisture transport into the Indian subcontinent, indicating a weakened monsoon flow. At 200 hPa, the velocity potential field reveals anomalous convergence centred over the Indian subcontinent and the MC, flanked by anomalous divergence over the eastern equatorial Pacific (Fig. 5a), consistent with an eastward-shifted Walker circulation. At 850 hPa, the velocity potential field exhibits a mirror-image pattern (Fig. S4). These features are consistent with the Matsuno–Gill framework (Gill 1980; Sardeshmukh and Hoskins 1988)with far-eastern Pacific heating driving a broad Walker circulation adjustment whose anomalous subsidence branch extends westward across the Indo-Pacific basin (Cai et al. 2019; Yeh et al. 2018).

The CP_W experiment produces a qualitatively similar but weaker response (Figs. 4b, 5b). Rainfall deficits are weaker over India, and extend across the northern Bay of Bengal, with little suppression over the eastern Arabian Sea. Upper-level convergence over South Asia is less intense and more spatially dispersed than in EP_W. The more westward location of heating in CP_W produces a Walker circulation adjustment that is more zonally compact, with subsidence positioned directly over the Philippine Sea, generating a strong local circulation anomaly. The broader subsidence signal does not extend as efficiently into the Indian Ocean sector as it does under EP_W forcing (Weng et al. 2007; Stuecker et al. 2017; Pothapakula et al. 2020). Consequently, large-scale descent over the Indian subcontinent is weaker, and the monsoon suppression is more spatially confined.

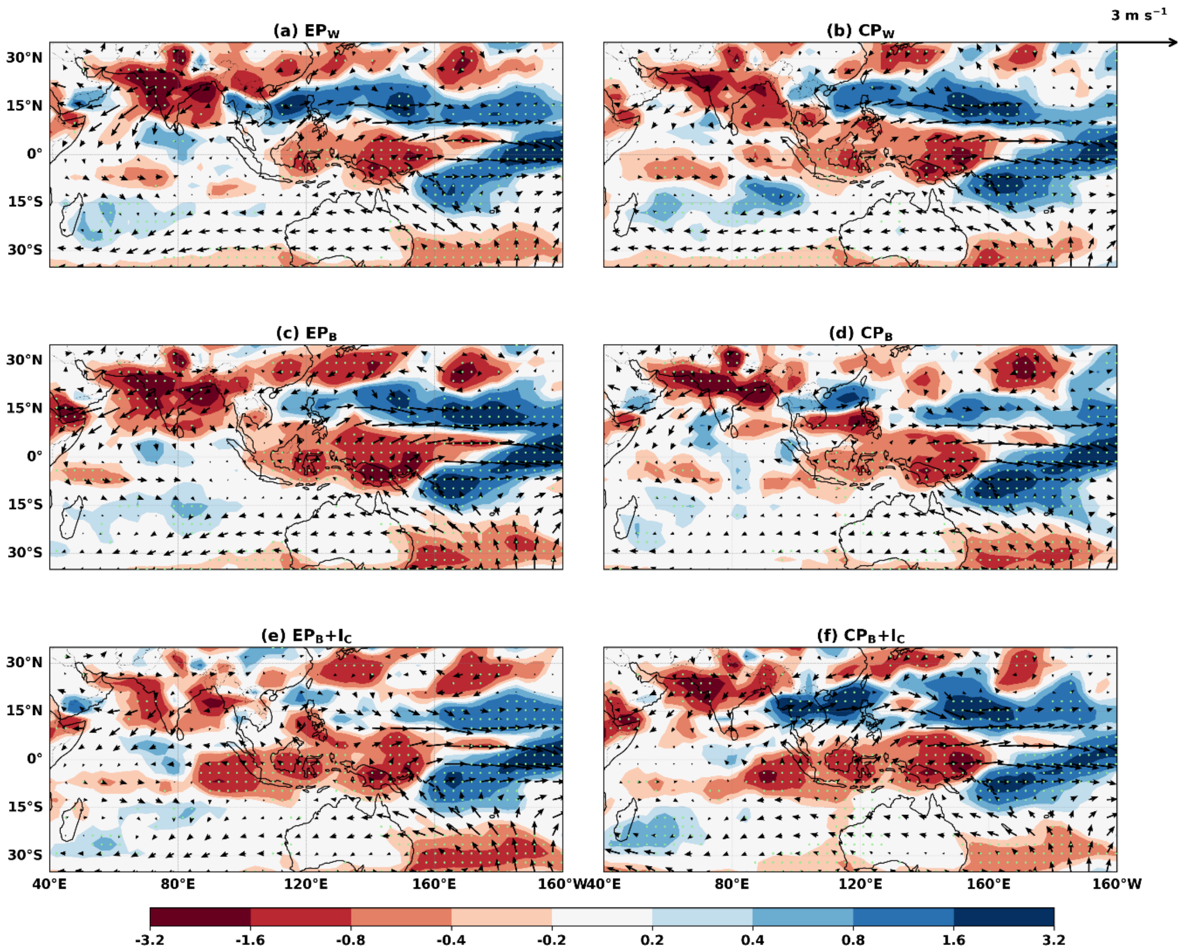

Figure 4. IGCM4 JJAS rainfall responses (mm d^{-1}, shaded) and 850 hPa circulation anomalies (m s^{-1}, vectors). (a, b) Pacific warm-only forcing (EP_W, CP_W). (c, d) Full Pacific basin forcing (EP_B, CP_B). (e, f) Full Pacific basin combined with SEIO cold anomalies (EP_B+I_C, CP_B+I_C). Hatching and black vectors indicate statistical

significance at the 90% confidence level (Student's t-test).

When both warm and cold Pacific SST anomalies are combined (EP_B, CP_B), the responses diverge further (Figs. 4c–d, 5c–d). In EP_B, monsoon suppression intensifies and extends across the entire Indian subcontinent, from the Arabian Sea to the Bay of Bengal, accompanied by strengthened low-level easterly anomalies and intensified upper-level convergence over India, East Africa, and the MC (Fig. 5c). This enhancement relative to EP_W indicates that the addition of western Pacific cold SST anomalies increases the zonal contrast in the anomaly field across the Pacific basin i.e., the warming in the east and cooling in the west amplifies the perturbation to the Walker circulation and strengthens the anomalous subsidence over South Asia. In contrast, the CP_B response shows only a modest enhancement relative to CP_W (Figs. 4d, 5d), with rainfall deficits remaining confined to the monsoon trough and northern Bay of Bengal. The addition of western Pacific cold anomalies does not substantially sharpen the zonal SST anomaly in the CP configuration, and the ISM response remains approximately linear.

Experiments forced only with cold Pacific anomalies (EP_C, CP_C; Fig. S2a-d) confirm this asymmetry. The EP_C response over the western Pacific is considerably stronger than the CP_C response, indicating that western Pacific cold anomalies interact more efficiently with far-eastern Pacific warming than with central Pacific warming. These Pacific-only results establish that EP El Niño produces stronger ISM suppression than CP El Niño when the Pacific is considered in isolation. This finding appears to contradict the observational record, which consistently shows that CP El Niño events are associated with more frequent and severe ISM droughts than EP events (Krishna Kumar et al. 2006). This apparent discrepancy arises because the Pacific-only experiments omit the Indian Ocean SST anomalies that co-occur with El Niño in nature (Krishnaswamy et al. 2015).

3.2 Impact of south-eastern Indian Ocean cooling

Superimposing identical SEIO cold anomalies (I_C) onto the EP_B and CP_B forcings yields strikingly different ISM outcomes, reversing the suppression in the Pacific-only experiments. No such reversal in pacific only experiments after the addition of western Indian Ocean warming anomalies (I_W) to EP_B and CP_B experiments. The same is not true even for the addition of the full Indian Ocean Dipole anomalies (I_B), and the complete observed Indian

Ocean anomalies for Pacific only experiments (Fig. S3). This confirms that the reversal mechanism is uniquely tied to the SEIO cold pole. In EP_B+I_C (Fig. 4e), rainfall deficits over the Indian subcontinent are nearly eliminated. Only residual drying persists over parts of the eastern Arabian Sea and Bay of Bengal, while rainfall suppression is displaced southward onto the SEIO and MC. Low-level easterly anomalies over India weaken substantially, indicating a partial recovery of monsoon moisture transport. At 200 hPa (Fig. 5e), anomalous upper-level convergence is entirely absent over the Indian subcontinent; weak convergence centres are confined to the MC and East Africa. This pattern is fundamentally different from EP_B (Fig. 5c), where convergence peaks directly over India, and indicates that SEIO cooling has reorganised the Walker circulation such that anomalous descent concentrates over the MC rather than the Indian subcontinent.

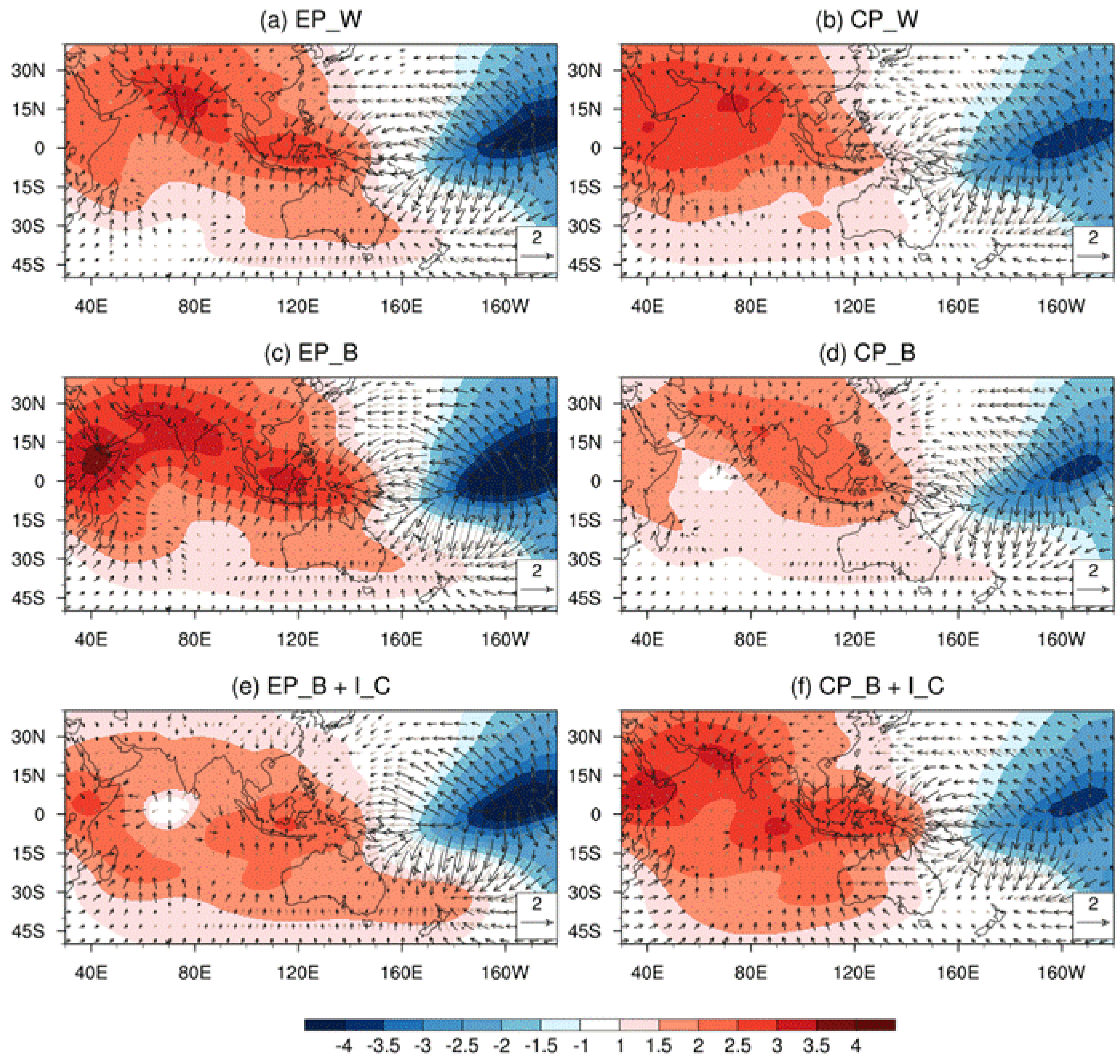

Figure 5. As Fig. 4, but for 200 hPa velocity potential (10^{-6} m^2 s^{-1}, shaded) and divergent wind anomalies (vectors). Only velocity potential signals significant at the 90% level are shaded; divergent winds are grey (black) below (above) this significance level.

The CP_B+I_C response is dramatically different (Figs. 4f, 5f). Rainfall deficits persist across the Indian subcontinent with only modest reduction relative to CP_B, while enhanced suppression develops over the SEIO. The upper-level velocity potential pattern (Fig. 5f) closely resembles EP_B (Fig. 5c) rather than CP_B: convergence peaks over the Indian subcontinent, East Africa, and the MC, indicating sustained anomalous subsidence over India. The overall rainfall deficit over India is substantially larger in CP_B+I_C than in EP_B+I_C, consistent with the observational finding that CP El Niño events coincident with positive IOD conditions tend to produce more severe ISM droughts than corresponding EP events (Krishna Kumar et al. 2006).

This contrasting response arises from differences in the longitudinal position of the warming center between EP and CP events in the Pacific and the cold anomalies around MC (Fig. 2e–f). In EP_B+I_C, the western Pacific cold anomalies are extensive and merge with the SEIO cold anomalies to form a broad continuous zone of suppressed convection spanning the MC. Because the EP warming centre lies in the far-eastern Pacific (~120–80°W), and there is no competing heat source near the MC to counteract the cold-SST-forced descent, anomalous subsidence is concentrated entirely within the MC region, sparing the Indian subcontinent. In CP_B+I_C, the warm CP anomalies lie close to the dateline (~170°E–150°W), significantly closer to the MC. Therefore, the CP-forced anomalous ascent generates compensating descent that extends westward into the Indian Ocean sector, and the Indian subcontinent experiences sustained anomalous descent. Despite the SEIO cooling being identical in both configurations, its effect on the ISM is reversed. It alleviates drying during EP events but sustains or amplifies drying during CP events. Therefore, the zonal positioning of the warming center in the Pacific, along with cooling anomalies around the MC, controls the location of subsidence and is the central dynamical mechanism of the study.

3.3 Evidence of nonlinear atmospheric response

The atmospheric response to combined SST forcings is substantially nonlinear, and the character of the nonlinearity differs fundamentally between EP and CP configurations. To quantify this, we define a nonlinear residual as the difference between the full-basin response and the linear sum of the individual warm-only and cold-only components. For the Pacific-only case, the EP residual is EP_B – (EP_W + EP_C); the CP residual is defined analogously.

For the combined Indo-Pacific case, the residual is EP_B+I_C – (EP_W + EP_C+I_C), and correspondingly for CP (Fig. 6).

In Pacific-only configurations (Figs. 6a–b), opposite-signed residuals emerge over the Indian subcontinent. The EP residual shows positive rainfall anomalies over northwest India and the head Bay of Bengal (exceeding +1 mm d^{-1}; Fig. 6a), indicating that the full EP_B response is wetter over India than the linear sum of EP_W and EP_C. This constructive nonlinearity partially mitigates monsoon suppression. The CP residual, by contrast, shows negative rainfall anomalies over Indian land (≤ -1 mm d^{-1}; Fig. 6b), reflecting synergistic nonlinear amplification of drought. This El Niño type-dependent asymmetry arises because the Pacific cold anomalies sharpen the zonal contrast in the anomaly field across the Pacific basin in the EP configuration than in the CP configuration, generating different patterns of nonlinear convective reorganisation. The upper-level velocity potential residuals (Figs. S5a–b) confirm these opposing dynamical signatures.

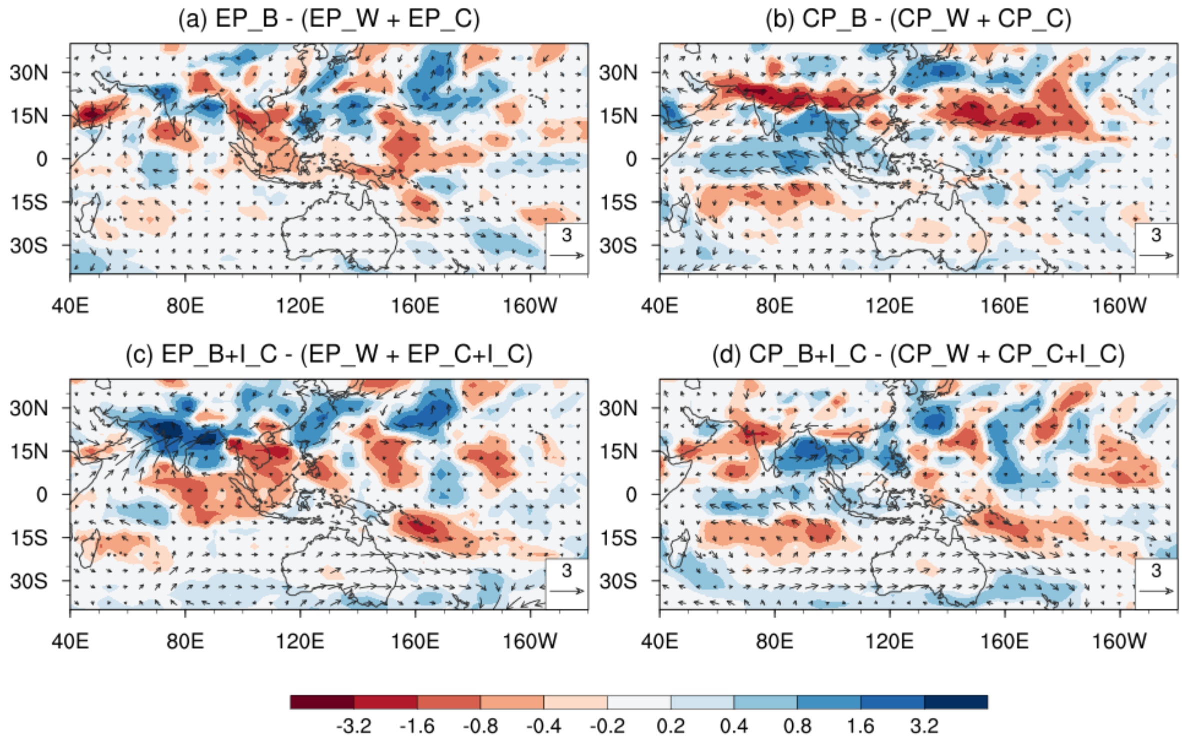

Figure 6. Nonlinear residuals in IGCM4 JJAS rainfall (mm d^{-1}, shaded) and 850 hPa circulation (m s^{-1}, vectors). (a) EP_B – (EP_W + EP_C). (b) CP_B – (CP_W + CP_C). (c) EP_B+I_C – (EP_W + EP_C+I_C). (d) CP_B+I_C – (CP_W + CP_C+I_C).

Superimposing SEIO cooling has a markedly asymmetric effect on these pre-existing nonlinearities (Figs. 6c–d) and the corresponding circulation anomalies (Figs. S5c-d). In EP_B+I_C, positive rainfall residuals exceeding +3 mm d^{-1} blanket the entire Indian subcontinent, the Bay of Bengal, and the eastern Arabian Sea (Fig. 6c), demonstrating that the near-complete relief from drought over India is overwhelmingly nonlinear in origin. The large zonal separation between the warm eastern Pacific anomaly centers and the cold anomaly over SEIO prevents their individual Gill-type atmospheric responses from overlapping. Walker descent driven by the SEIO cold pole anchors to the Maritime Continent, while EP-driven descent remains in the central Pacific, producing near-complete drought relief over India (Fig. 6c). In contrast, the CP_B+I_C residual (Fig. 6d) is weaker than the CP Pacific-only residual (Fig. 6b), indicating that the addition of SEIO cooling does not amplify the CP nonlinearity. In CP_B+I_C, the smaller separation (~55°) allows the atmospheric responses of the two poles to overlap over the Maritime Continent, generating a more additive combined response whose descent signal extends westward into the Indian Ocean sector and maintains anomalous subsidence over India (Fig. 6d). This indicates that SEIO cooling interacts strongly and nonlinearly with EP forcing, but has a comparatively linear, additive effect when combined with CP forcing (Krishnaswamy et al. 2015).

4. Discussion

The idealised IGCM4 experiments reveal a clear dynamical mechanism governing how SEIO cold SST anomalies reshape the El Niño–ISM teleconnection differently for EP and CP events. The mechanism operates through the zonal separation between the warm Pacific and the cold anomalies around MC (Klein et al. 1999). A large separation in EP_B+I_C anchors Walker descent over the cold pole, shielding India from anomalous subsidence. This explains why Pacific-only forcing produces an EP > CP monsoon suppression hierarchy, while the inclusion of Indian Ocean anomalies reverses this to CP > EP, consistent with the observational finding that CP El Niño events tend to produce worse ISM droughts than EP events, particularly during concurrent positive IOD conditions (Krishna Kumar et al. 2006).

Krishna Kumar et al. (2006) demonstrated that moderate CP El Niño events have historically produced more severe ISM droughts than even strong EP events, attributing this to the location of Pacific warming relative to the Indian subcontinent. Our experiments extend this interpretation by showing that Pacific forcing alone (EP_B and CP_B) cannot reproduce the observed differences. The SEIO cooling that naturally accompanies positive IOD events, which frequently co-occur with El Niño, is essential. The nonlinearity analysis (Fig. 6) further demonstrates that this reversal is not a simple additive effect of SEIO cooling in the case of EP but arises from a reorganisation of the Walker circulation. These findings have implications for seasonal monsoon prediction.

Our results demonstrate that the combined response of Indian and Pacific Ocean SST anomalies is strongly non-additive and depends on the relative spatial configuration of warming and cooling centres across the Indo-Pacific. Incorporating the indices that capture the spatial configuration of warming and cooling centres across the Indo-Pacific Oceans rather than treating basin-level indices independently may improve predictive skill, particularly for distinguishing between El Niño events that produce drought and those that do not. These findings are also relevant under future warming. Goswami and An (2023) showed that increased co-occurrence of El Niño and positive IOD events under CO_2 forcing weakens the ENSO–ISM teleconnection, while extreme positive IOD events are projected to become substantially more frequent under greenhouse warming (Cai et al. 2014). If SEIO cooling becomes more concurrent with El Niño, the mechanism identified here suggests that the relative drought impact of CP versus EP events will be further amplified.

Several limitations should be acknowledged. IGCM4 is an intermediate-complexity atmospheric model that lacks ocean–atmosphere coupling, intraseasonal variability, and mesoscale land–atmosphere feedbacks, all of which contribute to real-world monsoon dynamics. The model's wet bias over the northern Bay of Bengal (Fig. 3e) and upper-level easterly bias over the MC (Fig. 3f) may affect the spatial detail of the simulated responses, though these biases fall within the CMIP5 model spread (Terray et al. 2005). Despite these limitations, the model's structure enables unambiguous attribution of large-scale circulation adjustments to specific SST forcing patterns and reveals nonlinearities in ENSO–ISM teleconnections that are obscured in coupled models.

5.0 Conclusions

This study uses AGCM experiments to isolate the atmospheric mechanisms through which SEIO cold SST anomalies modulate the El Niño–ISM teleconnection differently for EP and CP El Niño events. Three principal findings emerge. First, under Pacific-only forcing, EP El Niño produces stronger and more widespread ISM rainfall suppression than CP El Niño. Second, the inclusion of SEIO cooling reverses these responses. In EP_B+I_C, the large zonal separation between the warm eastern Pacific and the cold anomaly around MC anchors anomalous Walker descent onto the MC, nearly eliminating Indian drying (Figs. 4e, 5e). In CP_B+I_C, the smaller separation allows subsidence to spread across the Indian subcontinent, producing drought conditions consistent with observational evidence that CP events lead to more severe ISM failures during concurrent positive IOD conditions (Figs. 4f, 5f). Third, the combined atmospheric response to Pacific and Indian Ocean SST anomalies is strongly nonlinear in both EP and CP configurations, but with drought relief during EP than CP (Fig. 6). The drought relief in EP_B+I_C is also nonlinear, arising from reorganisation of the Walker circulation rather than from linear superposition of individual basin effects.

These results establish that the zonal separation between the warm Pacific and the colder anomaly around MC governs the position and intensity of anomalous subsidence over South Asia, providing a unifying framework for understanding why the ENSO–ISM relationship varies so markedly across individual El Niño events. These results advance our mechanistic understanding of how the spatial configuration of Indo-Pacific SST anomalies governs the ISM response. The dynamical framework identified here is the zonal separation between Pacific warming and Maritime Continent cold anomalies as the governing factor, which may inform how SST-based diagnostics are constructed and interpreted in coupled prediction systems. However, translating these mechanistic insights into demonstrable improvements in forecast skill would require validation in fully coupled ocean–atmosphere models with realistic Indian Ocean variability, intraseasonal forcing, and air–sea feedbacks, which is beyond the scope of the present study.

Statements & Declarations

Data availability

The IGCM4 model output generated during this study is available from the corresponding author upon reasonable request. The NOAA-CIRES 20th Century Reanalysis data are available from https://psl.noaa.gov/data/20thC_Rean/. GPCP precipitation data are available from https://www.ncei.noaa.gov/products/global-precipitation-climatology-project. NCEP reanalysis data are available from https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

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Author contributions

U.U. designed and performed the experiments, analyzed the results, and wrote the manuscript. B.W., M.J., and A.T. supervised the research, provided critical revisions, and contributed to interpretation and manuscript revision

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References

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T (2007) El Niño Modoki and its possible teleconnection. J Geophys Res Oceans 112:C11007

Ashok K, Guan Z, Saji NH, Yamagata T (2004) Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian summer monsoon. J Clim 17:3141–3155

Ashok K, Guan Z, Yamagata T (2001) Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophys Res Lett 28:4499–4502

Bollasina MA, Ming Y (2013) The general circulation model precipitation bias over the southwestern equatorial Indian Ocean and its implications for simulating the South Asian monsoon. Clim Dyn 40:823–838. https://doi.org/10.1007/s00382-012-1347-7

Cai W, Borlace S, Lengaigne M, van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L, England MH, Wang G, Guilyardi E, Jin F-F (2014) Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. Nature 510:254–258

Cai W, Wu L, Lengaigne M, Li T, McGregor S, Kug J-S, Yu J-Y, Stuecker MF, Santoso A, Li X, Ham Y-G, Chikamoto Y, Ng B, McPhaden MJ, Du Y, Dommenget D, Jia F, Kajtar JB, Keenlyside N, Lin X, Luo J-J, Martín-Rey M, Ruprich-Robert Y, Wang G, Xie S-P, Yang Y, Kang SM, Choi J-Y, Gan B, Kim G-I, Kim C-E, Kim S, Kim J-H, Chang P (2019) Pantropical climate interactions. Science 363:eaav4236

Cherchi A, Navarra A (2013) Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. Clim Dyn 41:81–103

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ (2011) The Twentieth Century Reanalysis Project. Q J R Meteorol Soc 137:1–28

Forster PMdF, Blackburn M, Glover R, Shine KP (2000) An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. Clim Dyn 16:833–849

Gill AE (1980) Some simple solutions for heat-induced tropical circulation. Q J R Meteorol Soc 106:447–462

Goswami BB, An S-I (2023) An assessment of the ENSO–monsoon teleconnection in a warming climate. npj Clim Atmos Sci 6:82

Goswami BN (1998) Interannual variations of the Indian summer monsoon in a GCM: external conditions versus internal feedbacks. J Clim 11:501–522

Hoell A, Funk C (2013) The ENSO-related West Pacific sea surface temperature gradient. J Clim 26:9545–9561

Jang Y, Straus DM (2012) The Indian monsoon circulation response to El Niño diabatic heating. J Clim 25:7487–7508

Joshi M, Stringer M, van der Wiel K, O’Callaghan A, Fueglistaler S (2015) IGCM4: a fast, parallel and flexible intermediate climate model. Geosci Model Dev 8:1157–1167

Kao H-Y, Yu J-Y (2009) Contrasting Eastern-Pacific and Central-Pacific types of ENSO. J Clim 22:615–632

Klein SA, Soden BJ, Lau N-C (1999) Remote sea surface temperature variations during ENSO: evidence for a tropical atmospheric bridge. J Clim 12:917–932

Krishna Kumar K, Rajagopalan B, Cane MA (1999) On the weakening relationship between the Indian monsoon and ENSO. Science 284:2156–2159

Krishna Kumar K, Rajagopalan B, Hoerling M, Bates G, Cane MA (2006) Unraveling the mystery of Indian monsoon failure during El Niño. Science 314:115–119

Krishnaswamy J, Vaidyanathan S, Rajagopalan B, Bonell M, Sankaran M, Bhalla RS, Badiger S (2015) Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. Clim Dyn 45:175–184

Lau N-C, Wang B (2006) Interactions between the Asian monsoon and the El Niño/Southern Oscillation. In: Wang B (ed) The Asian Monsoon. Springer, pp 479–512

Pothapakula PK, Primo C, Sørland S, Ahrens B (2020) The synergistic impact of ENSO and IOD on Indian summer monsoon rainfall in observations and climate simulations – an information theory perspective. Earth Syst Dynam 11:903–923

Rasmusson EM, Carpenter TH (1983) The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. Mon Weather Rev 111:517–528

Ratna SB, Cherchi A, Osborn TJ, Joshi M, Uppara U (2021) The extreme positive Indian Ocean Dipole of 2019 and associated Indian summer monsoon rainfall response. Geophys Res Lett 48:e2020GL091497

Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K, Goswami BN (2015) Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. Nat Commun 6:7423

Roy I, Tedeschi RG, Collins M (2019) ENSO teleconnections to the Indian summer monsoon under changing climate. Int J Climatol 39:3031–3042

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363

Samanta D, Hameed SN, Jin D et al (2018) Impact of a narrow coastal Bay of Bengal sea surface temperature front on an Indian summer monsoon simulation. Sci Rep 8:17694. https://doi.org/10.1038/s41598-018-35735-3

Sardeshmukh PD, Hoskins BJ (1988) The generation of global rotational flow by steady idealized tropical divergence. J Atmos Sci 45:1228–1251

Sperber KR, Annamalai H, Kang IS et al (2013) The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Clim Dyn 41:2711–2744. https://doi.org/10.1007/s00382-012-1607-6

Sperber KR, Annamalai H, Kang I-S, Kitoh A, Moise A, Turner AG, Wang B, Zhou T (2013) The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Clim Dyn 41:2711–2744

Stuecker MF, Timmermann A, Jin F-F, Chikamoto Y, Zhang W, Wittenberg AT, Widiasih E, Zhao S (2017) Revisiting ENSO/Indian Ocean Dipole phase relationships. Geophys Res Lett 44:2481–2492

Terray P, Chauvin F, Douville H (2007) Impact of southeast Indian Ocean sea surface temperature anomalies on monsoon-ENSO-dipole variability in a coupled ocean–atmosphere model. Clim Dyn 28:553–580

Terray P, Dominiak S, Delecluse P (2005) Role of the southern Indian Ocean in the transitions of the monsoon-ENSO system during recent decades. Clim Dyn 24:169–195

van der Wiel K, Matthews AJ, Joshi MM, Stevens DP (2016) The influence of diabatic heating in the South Pacific Convergence Zone on Rossby wave propagation and the mean flow. Q J R Meteorol Soc 142:703–713

Webster PJ, Magaña VO, Palmer TN, Shukla J, Tomas RA, Yanai M, Yasunari T (1998) Monsoons: processes, predictability, and the prospects for prediction. J Geophys Res Oceans 103:14451–14510

Weng H, Ashok K, Behera SK, Rao SA, Yamagata T (2007) Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. Clim Dyn 29:113–129

Yang B, Zhang Y, Qian Y, Wu T, Huang A, Fang Y (2019) Better monsoon precipitation in coupled climate models due to bias compensation. npj Clim Atmos Sci 2:14

Yeh S-W, Cai W, Min S-K, McPhaden MJ, Dommenget D, Dewitte B, Collins M, Ashok K, An S-I, Yim B-Y, Kug J-S (2018) ENSO atmospheric teleconnections and their response to greenhouse gas forcing. Rev Geophys 56:185–206

Yeh S-W, Kug J-S, Dewitte B, Kwon M-H, Kirtman BP, Jin F-F (2009) El Niño in a changing climate. Nature 461:511–514

Yu J-Y, Kim ST (2013) Identifying the types of major El Niño events since 1870. Int J Climatol 33:2105–2111