Anonymous Referee#1:

General comment:

The paper examines an interesting phenomenon of warming in the north Bay of Bengal region about 10-15 days prior to Indian summer monsoon rainfall onset and the authors have discussed the possible atmospheric forcing and response to the warming and its impact on monsoon onset. The manuscript is well written and the idea is interesting. I recommend that the manuscript be accepted pending some minor changes and improvements.

=> Dear Referee, thank you for taking the time to review our manuscript and for appreciating our study. We would also like to thank you for your comments, which have helped us revise the manuscript into a better version. We understand that you have minor comments regarding improving the flow of narration (especially in the introduction section) and clarifying some arguments including the use of modeling experiments.

In our point-by-point reply to the referee's comments below, text quoted from the manuscript in our responses is highlighted in green. All line numbers refer to the manuscript in track-changes form.

Detailed comments:

1. The introduction section needs to focus only on the literature review without mixing it with the explanation of the hypothesis and the methodology used for conducting this study. There can be a separate paragraph for explaining the rationale of the study.

   => We have revised the introduction section following the referee's suggestion. The introduction is now organized as a literature review, followed by an explanation of the hypothesis, and finally an outline of the methodology towards the end. We believe the flow of the narration has improved considerably after this revision. Thank you.

2. Line 30: How does preparation of composites suppress interannual variability? The authors need to explain this.

   => In composite analysis, since all onset dates are aligned, interannual variations are suppressed, yielding a common picture of onset evolution across different years.

   We have included this sentence in the revised manuscript (L53-54) to improve the clarity of our narration. Thank you.

3. In figure 2: Were the onset dates cross verified with IMD onset dates? Is there any discrepancy?

=> We did not cross-verify the dates with IMD onset dates. Nonetheless, Li et al. (2024) provide a detailed overview of how strongly different onset indices correlate with IMD onset dates. The TT index exhibits a significant correlation with IMD onset dates, which is typically true for most monsoon onset indices (Bombardi et al. 2020). We have mentioned this in the revised manuscript (L90-94).

4. Line 34: Can the authors point to any specific index that seems to have arbitrary thresholds?

   => An example of an index that uses an arbitrary threshold is the Onset Circulation Index (OCI), defined as the 850 hPa zonal wind averaged over the southern Arabian Sea (5°N–15°N, 40°E–80°E). The monsoon onset date is identified as the first day when the OCI exceeds a threshold value of 6.2 m s−1 for six consecutive days.

   In the interest of maintaining the flow of the narration, we did not include this specific example in the manuscript. Nonetheless, we have mentioned that (L57-58), "a detailed list of different monsoon indices – large-scale, regional, and local – can be found in Bombardi et al. (2020) and Li et al. (2024)." We hope the referee will agree.

5. Lines 173-175: How can a cold atmospheric column carry higher relative humidity? Or is that a typo. It needs to be corrected.

   =>Yes, it is true that cooler air holds less moisture. However, if the actual amount of water vapor in the air remains the same, a colder atmosphere will exhibit a relatively higher relative humidity. We have revised the statement in the manuscript as follows (L178-181):

   "During early-onset years, the atmospheric column over BoB, 10–15 days before onset, is expectedly colder than that for the late-onset years. We also found the total moisture content (specific humidity) is not substantially different. However, since the atmosphere is colder for early-onset years, it has a relatively higher relative humidity considering the total moisture content is comparable."

   Thank you.

6. The experiments using CAM model seems to add very little to the explanation of the dynamics of the phenomenon discussed in the paper. Is the idea of the paper to understand the dynamics of early and late onset features or to test the fidelity of the model? This needs clarification.

   => Thank you for this insightful comment. The primary aim is to understand the dynamics and to test the associated hypothesis in a model framework, rather than to evaluate model fidelity. As the referee correctly points out, the model has biases—for example, CAM does not simulate an earlier onset in response to a warm SST anomaly in the northern BoB when measured with the TT index. We hypothesize that this could be due to overly strong homogenization of upper-level temperatures in the model compared to observations and/or biases in simulating the SST-convection relationship. Another possibility is that, since onset in CAM is already relatively early, the large-scale background conditions (e.g., land temperatures) may not support an even earlier onset despite the prescribed SST anomalies. Nonetheless, the circulation response to the imposed SST forcing is captured in the model, which provides proof of concept for our hypothesis.

Relevant revisions can be found in L229-244 of the revised manuscript.

References mentioned in the responses:

Li, X., Wang, L., Zhong, S., and Liu, L.: Comparative analysis of indices in capturing the onset and withdrawal of the South Asian Summer Monsoon, Environmental Research Communications, 6, 031 007, https://doi.org/10.1088/2515-7620/ad352b, 2024.

Bombardi, R. J., Moron, V., and Goodnight, J. S.: Detection, variability, and predictability of monsoon onset and withdrawal dates: A review, International Journal of Climatology, 40, 641–667, https://doi.org/10.1002/joc.6264, 2020.

Anonymous Referee#2:

General comment:

The paper discusses the influence of sea surface temperature (SST) in the Bay of Bengal on the timing of the Indian monsoon onset. While I agree that SST in the Bay of Bengal is an important factor in determining onset timing, I recommend that the paper, in its present form, be rejected.

=> Dear Referee, thank you for your time reviewing our manuscript. We appreciate your critical comments, which have helped us revise the manuscript into a more complete and balanced version.

In comments 1 and 2, you raise important points regarding additional factors that can influence monsoon onset, such as the MJO and the seasonal cycle. We fully agree. In the revised manuscript, we now discuss these aspects explicitly and cite the key references you kindly highlighted. We have also expanded the discussion to include other relevant large-scale modes such as PDO, ENSO, and IOD, which have been reported in earlier studies as influencing monsoon onset. Furthermore, we have included a preliminary analysis of MJO phases and early-versus-late onset SST composites with the seasonal cycle removed in the Supplementary Information.

Regarding comment 3 on the model experiments, we have streamlined and clarified our arguments in the revision. While we acknowledge the limitations of the model setup, we emphasize how the experiments still provide useful insight into circulation responses to SST forcing. We hope the referee will find this revised presentation more convincing.

In our point-by-point reply below, text quoted from the manuscript in our responses is highlighted in green. All line numbers refer to the manuscript in track-changes form.

Detailed comments:

1. The authors completely neglect the role of atmospheric dynamics, such as intraseasonal oscillations, equatorial waves, and atmosphere–ocean coupling. The influence of the Madden-Julian Oscillation (MJO) phase on monsoon variability and onset has been discussed in many papers (see references below). MJO convection arriving over the Indian Ocean in late May can propagate northward, triggering the onset. On the other hand, dry intraseasonal conditions in late May can delay the onset. While SST anomalies in the Bay of Bengal can influence the northward propagation of convection, these SST anomalies are not independent of atmospheric circulation; rather, they are

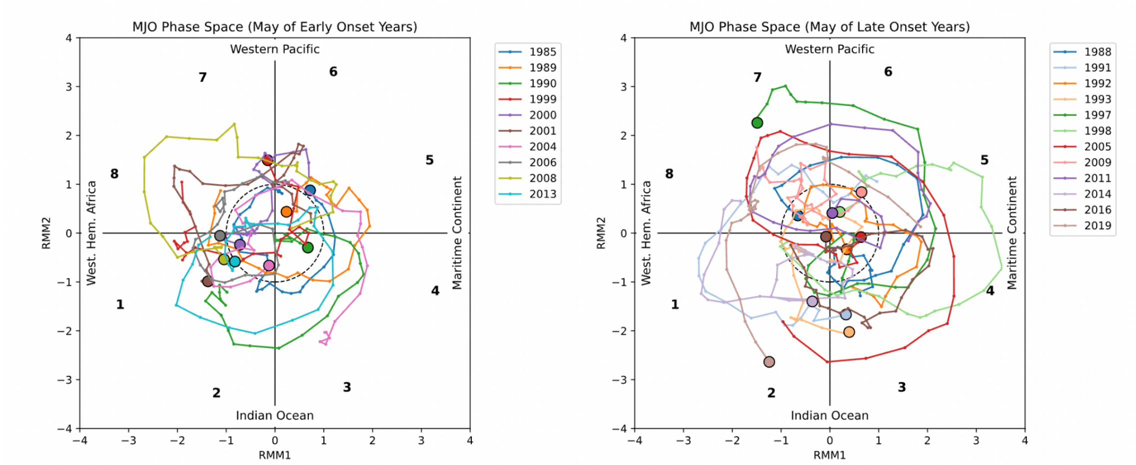
often responses to intraseasonal oscillations or tropical cyclones developing in early May. While I understand that the authors focus on the impact of SST, the role of atmospheric dynamics must be discussed. At a minimum, the MJO phase should be included in the analysis.

=>Thank you for this insightful comment. We have added a paragraph referring to a set of previous works that addressed the role of intraseasonal and low-frequency modes in monsoon onset. We have also included an MJO phase diagram for early and late onset years in the Supplementary Information (Supplementary Fig. S8) and briefly discussed it in the text. We suspect that the warm SST anomaly in the northern BoB is a manifestation of these different factors, and we have mentioned this explicitly in the revised manuscript.

For the referee's record, the revised paragraph is provided below (L191-210):

"Our hypothesis arguably indicates a mechanism that can be impacted by intraseasonal activities. For example, many studies report that monsoon onset is favored during the wet phase of the intraseasonal monsoon modes (Wang et al., 2009; Shroyer et al., 2021; Qian et al., 2019; Kikuchi, 2021; Lenka et al., 2024, etc.). In addition to these monsoon modes, which are part of the monsoon dynamics itself, an important driver of monsoon onset is the Madden-Julian Oscillation (MJO). MJO convection arriving over the Indian Ocean in May can propagate northward, triggering the onset (Bhatla et al., 2017; Taraphdar et al., 2018; Lenka et al., 2023). These multiple intraseasonal drivers, apart from advancing and delaying monsoon onset, sometimes result in bogus and double onsets (Flatau et al., 2001; Tyagi et al., 2025). A preliminary analysis of MJO phase during May for early and late onset years is provided in Supplementary Fig. S8 (MJO phase is plotted using the real-time multivariate MJO index (RMM) data (Gottschalck et al., 2010) obtained from the Australian Bureau of Meteorology). MJO activity over the Indian Ocean appears to be slightly more active for late onset years, consistent with the findings of Taraphdar et al. (2018). Nonetheless, there is considerable year-to-year variability. It should be noted that, in addition to intraseasonal modes, slowly varying boundary conditions – for example the Pacific Decadal Oscillation (PDO) (Watanabe and Yamazaki, 2014; Hu et al., 2023), the El Niño Southern Oscillation (ENSO) (Li et al., 2018; Choudhury et al., 2021), and the Indian Ocean Dipole (IOD) (Sankar et al., 2011; Cherchi et al., 2021) – also affect the monsoon onset. Recently, the North Pacific Victoria Mode has also been reported to affect the monsoon onset (Zhang et al., 2024). We did not pursue a detailed analysis of intraseasonal modes and slowly varying boundary conditions contrasting early and late onset cases, since our interest is the manifestation of these various factors, which arguably is a warm SST in the northern BoB 10-15 days before monsoon onset, and our motivation is investigating the atmospheric response to it. Alternatively, the warm anomalies in the northern BoB might be a feature of the background conditions that interact with the intraseasonal variabilities – for example, the MJO as argued by Taraphdar et al. (2018) – affecting monsoon onset."

For the referee's record, the MJO phase diagrams for early (left panel) and late (right panel) onset years are provided below.

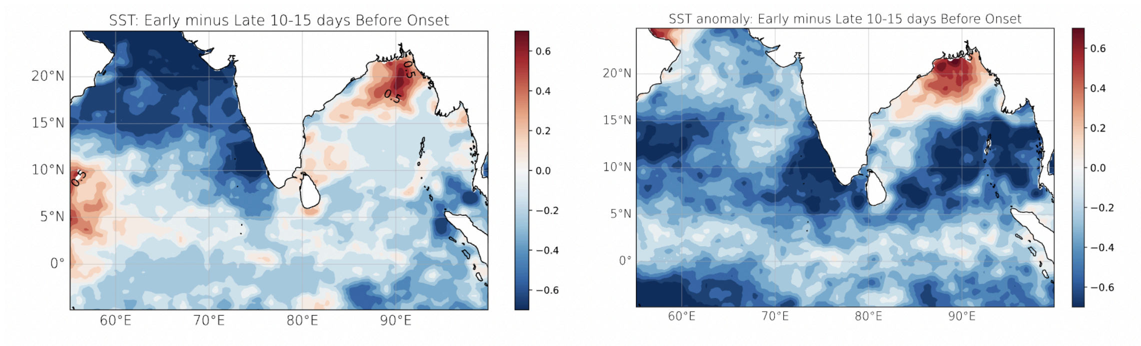


2. In the SST, precipitation, and circulation differences between early and late onset cases shown in the paper, it is difficult to separate the effect of the seasonal cycle from the proposed influence of the SST anomaly. I suggest that, before calculating these differences, the authors first compute anomalies relative to the seasonal cycle.

=> Thank you for this insightful comment. We have included a plot of SST anomalies after removing the seasonal cycle. The warm anomalies remain noticeable even when the seasonal cycle is removed (Fig. S1 in the Supplementary Information). Furthermore, our hypothesis emphasizes that it is the absolute SST that is critical for driving an atmospheric dynamical response. The same magnitude of anomaly over a colder ocean may not trigger a comparable response. Thus, we argue that warm anomalies riding on already warm waters of the Bay of Bengal in May - that is, the absolute SST - are what force the atmosphere.

Since the SST anomalies did not change substantially after seasonal cycle removal (Fig. S1 in the Supplementary Information), we retained Figure 3 in the main manuscript in its original form.

For the referee's record, the difference plots with (left panel) and without (right panel) removal of the annual cycle are provided below.



3. Because the observational cases used to formulate the hypothesis on SST influence included various intraseasonal dynamic states, while the model experiments were initialized with the same atmospheric conditions, the model experiments do not truly test the proposed hypothesis. In fact, the model results do not support the mechanisms of onset variability proposed by the authors. The inclusion of the SST warm patch does not lead to an earlier onset, even though precipitation is enhanced in the 5–10°N region of the Bay of Bengal. The authors suggest that this is because the monsoon index they use reflects a broader large-scale pattern. However, since they initially claim that this index provides a good characterization of the onset, this explanation is not sufficient to account for the negative result of the experiment. It is possible that, since the onset in CAM is already early, the model's large-scale conditions (e.g., land temperatures) may not support an even earlier monsoon onset related to local SST conditions in the Bay of Bengal. However, I suspect that the inclusion of a cold patch, rather than a warm one, in the Bay of Bengal could delay the onset -such a result could to some extent confirm the authors hypothesis on SST influence on onset timing.

   => We agree with the referee that the model does not exhibit an early onset in response to a warm SST anomaly in the northern BoB, and we have noted this in the manuscript. However, this does not necessarily invalidate our hypothesis. As the referee pointed out, the model has its own biases. Following the referee's comment, we included the discussion below clarifying our argument (L244-250):

   "We suspect that the unaltered large-scale tropospheric temperature (depicted by the ∇TT index) in response to warm SST anomalies in the northern BoB reflects biases in simulating convection and/or the SST–convection relationship in the model. Observations indicate a lagged convection response to SST increase (Roxy, 2014). In climate models, convection is sometimes over-sensitive to SST changes (Goswami et al., 2014). This compelled us to examine model responses using circulation-based onset indices. This does not necessarily indicate any superiority of circulation-based indices over the ∇TT index (Bombardi et al. 2020). Rather, we adopted this approach to investigate whether the model exhibits any response that is consistent with our hypothesis."

We especially thank the referee for suggesting the exciting and clever experiment of prescribing cold SST anomalies over the Bay of Bengal. However, since our hypothesis emphasizes the critical role of the absolute SST, prescribing cold SST anomalies is not consistent with our hypothesis. Following this suggestion, we added the discussion below in the revised manuscript (L235-244):

"Another possibility is that, since the onset in CAM is already early, the model's large-scale conditions (for example, land temperatures) may not support an even earlier monsoon onset in response to the prescribed warm SST anomalies in the Bay of Bengal. Arguably, an alternative can be to test the hypothesis by prescribing cold anomalies in the Bay of Bengal and checking if the model produces a delayed onset. However, since our hypothesis is based on the atmospheric dynamic response to warming of already warm mean SSTs (Goswami et al., 2021), prescribing cold SST anomalies is not consistent with our hypothesis. Since it is the absolute SST that is critical (Shroyer et al., 2021), the model cannot be expected to yield dynamically mirror-opposite results for cold and warm anomalies. Although we do not see an early onset in terms of an altered large-scale state of the model, we shall see below that the circulation response is consistent with our hypothesis when the warm SST anomaly is imposed."

Thank you