Supplement of Weather Clim. Dynam., 7, 583–596, 2026
https://doi.org/10.5194/wcd-7-583-2026-supplement
© Author(s) 2026. CC BY 4.0 License.

Supplement of

What advances monsoon onset over India?

Bidyut Bikash Goswami and Caroline Jane Muller

Correspondence to: Bidyut Bikash Goswami (bgoswami@ista.ac.at)

The copyright of individual parts of the supplement might differ from the article licence.

Contains

- Table S1
- Figures S1-S13

NOTE: References mentioned here can be found in the bibliography of the main paper.

Table S1: List of early and late monsoon onset years. The early and late-onset years are defined based on the onset criteria described in the Method section of the main manuscript. The years marked in blue are used for TRMM data.

Monsoon onset	Years
Early	1985 1989 1990 1999 2000 2001 2004 2006 2008 2013
Late	1988 1991 1992 1993 1997 1998 2005 2009 2011 2014 2016 2019

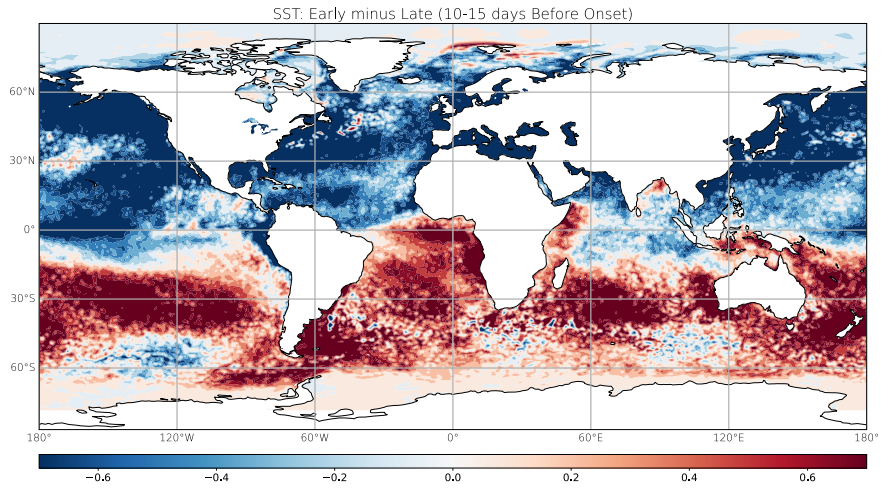

Figure S1: Global ocean SST anomalies for early monsoon onset. BoB is the only oceanic region with an isolated patch of wide-spread warm anomalies in the northern hemisphere tropics, 10-15 days before monsoon onset. Data input: OISST data for the early and late onset years are mentioned in Table S1.

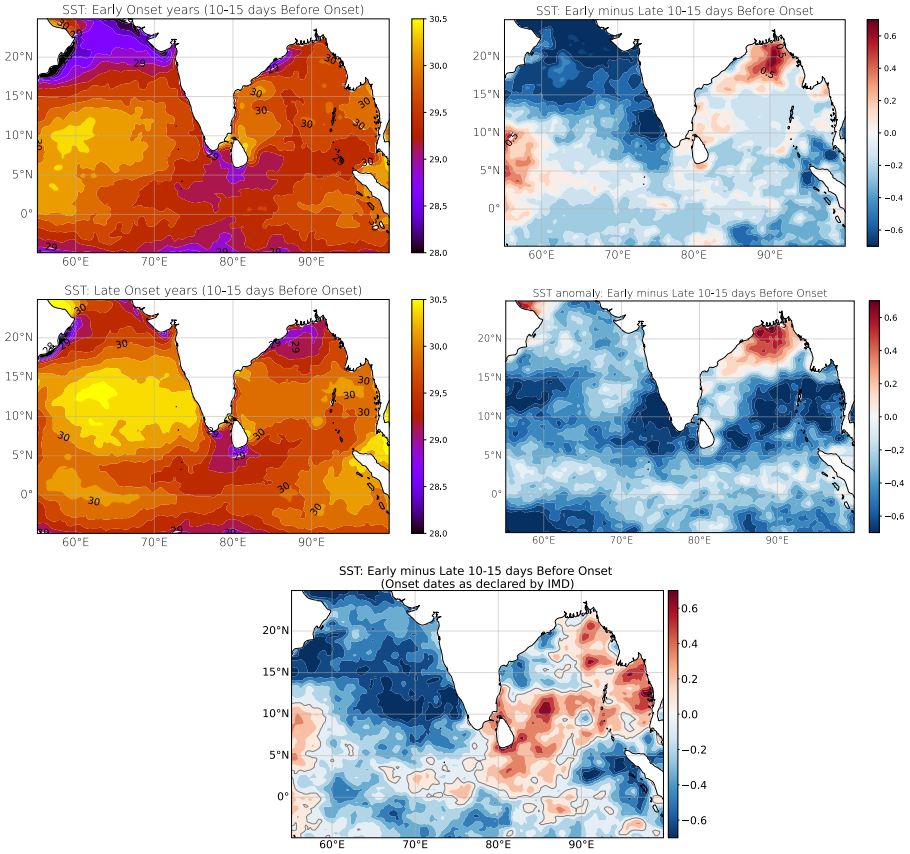

Figure S2: Indian Ocean composite SST for early and late onset and their difference. This figure depicts the presence of widespread warm anomalies in BoB in early-onset years. The difference plot is shown in the right hand side top panel which is a repetition of Figure 3a of the main manuscript. The middle-right panel is same as the bottom-left panel except the seasonal cycle (daily climatology) is removed from the SST data. Data input: OISST data for the early and late onset years are mentioned in Table S1. The bottom-center panel shows the SST difference computed using IMD-declared monsoon onset dates (Table 1 of Satish and Suneetha, 2022) for the period 1985–2019.

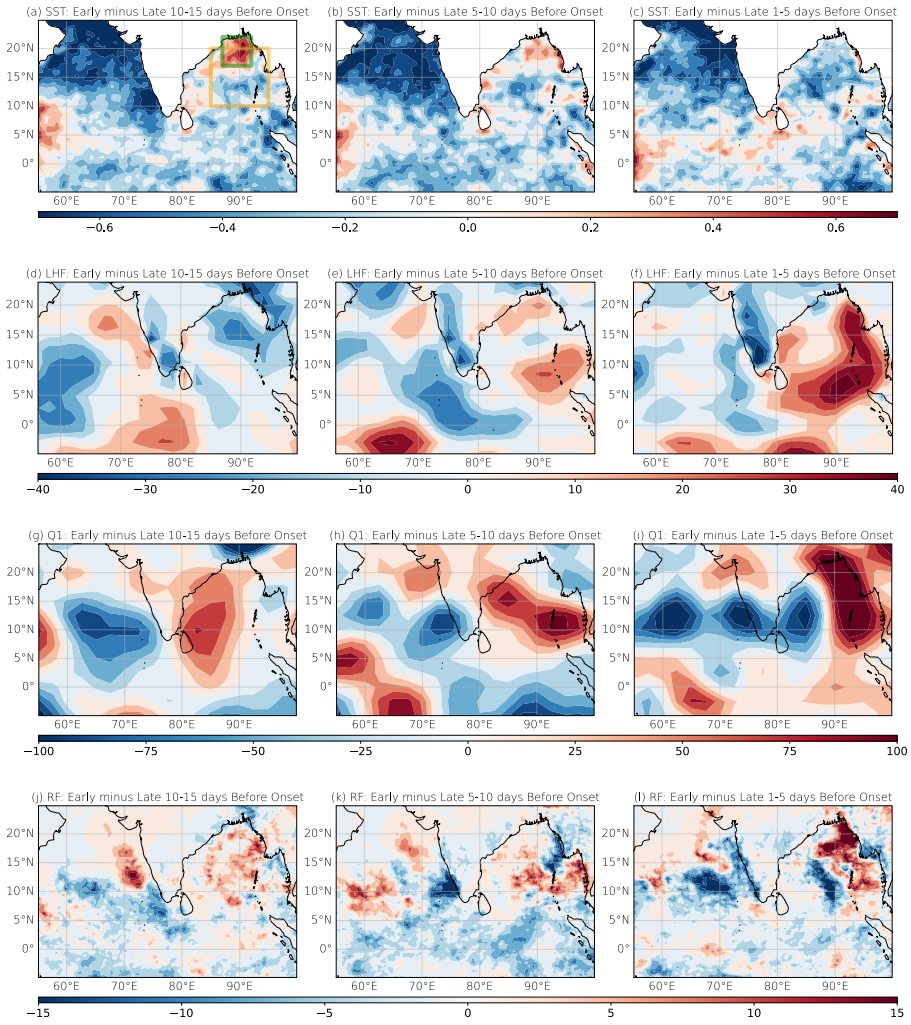

Figure S3: Early monsoon onset anomalies. Observed SST (from OISST data in °C) (top panels), latent heat flux (from NCEP reanalysis in W m^{-2}) (2^{nd} row panels), diabatic heating (in W m^{-2}, computed from NCEP reanalysis using the NCL script available in `https://www.ncl.ucar.edu/Applications/Scripts/Q1Q2_yanai_1.ncl`) (3^{rd} row panels), and rainfall (mm day^{-1}) (bottom panels); anomalous composite fields for early minus late onset years: 10-15 days in 1^{st} column, 5-10 days in 2^{nd} column, and 1-5 days in 3^{rd} column, before monsoon onset date, respectively. SST and rainfall fields are reproduced from Figure 3 of the main manuscript for the sake of completeness of this figure. Data input: All data for the early and late onset years are mentioned in Table S1.

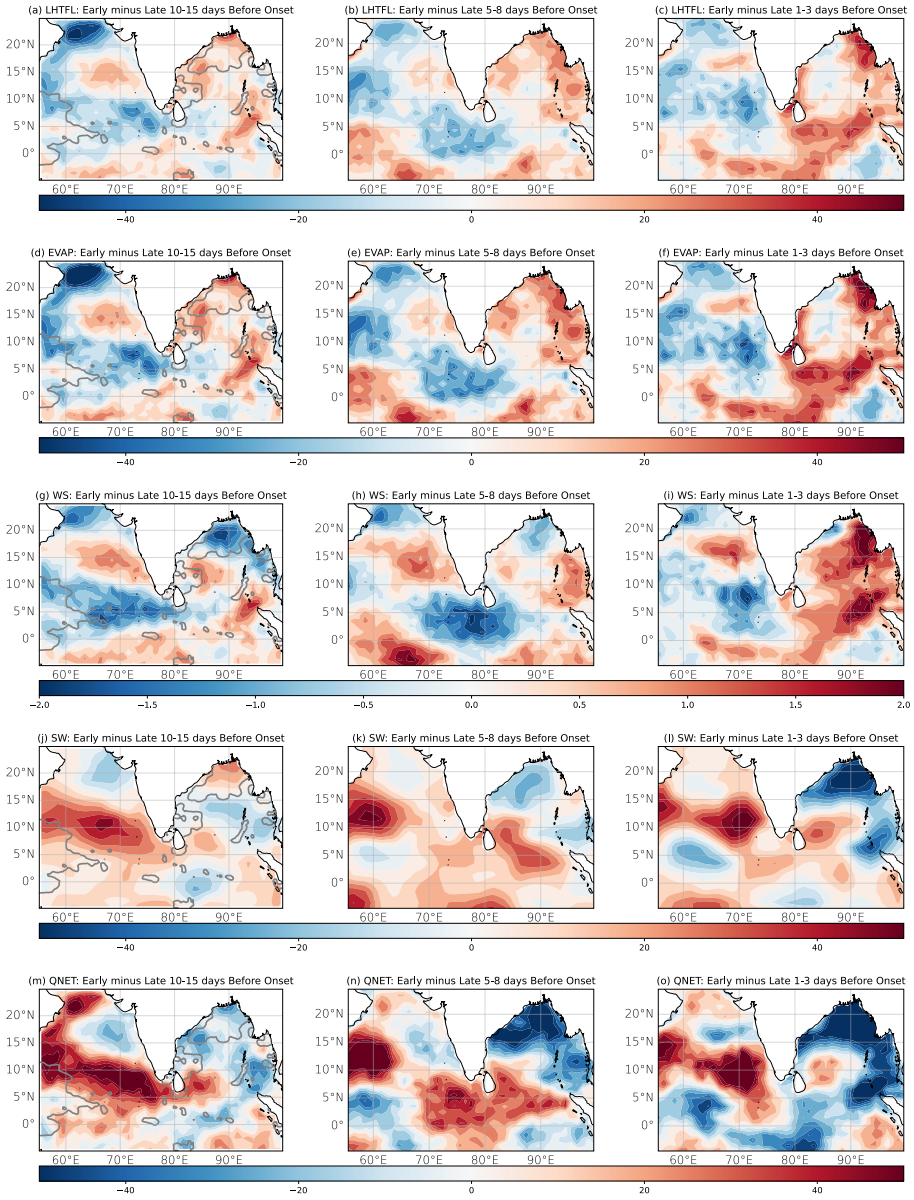

Figure S4: Early monsoon onset anomalies. Same as Figure S3 except for observed latent heat flux, positive upward (LHTFL; 1st row panels, W m^{-2}), evaporation rate (EVAP; 2nd row panels, cm yr^{-1}), surface (10m) wind speed (WS; 3rd row panels, m s^{-1}), incoming solar radiation (short wave) at the surface, positive downward (SW; 4th row panels, W m^{-2}), and daily mean net surface heat flux, positive downward (QNET; 5th row panels, W m^{-2}). Data input: All data from OAFLUX data (1985-2009: `https://climatedataguide.ucar.edu/climate-data/oaflux-objectively-analyzed-air-sea-fluxes-global-oceans`).

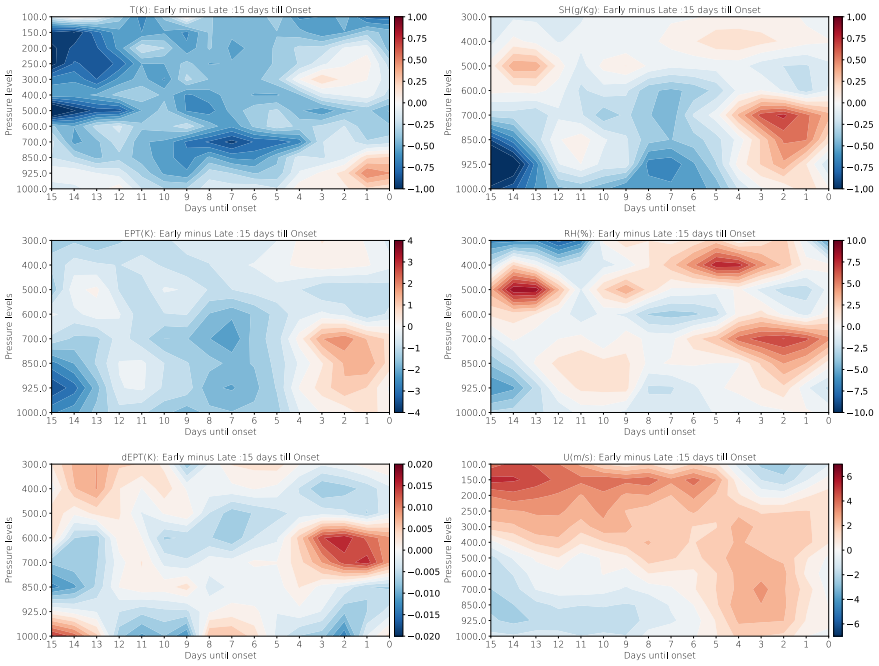

Figure S5: Time-height cross-sections. Early onset minus late onset composite for the vertical profiles of different meteorological fields from 15 days until monsoon onset. Air temperature (T), specific humidity (SH), equivalent potential temperature (EPT), relative humidity (RH), vertical gradient of EPT, and zonal wind (U), averaged over the region marked by the Orange Box in Figure S3a. Data input: NCEP reanalysis data for the early and late onset years are mentioned in Table S1.

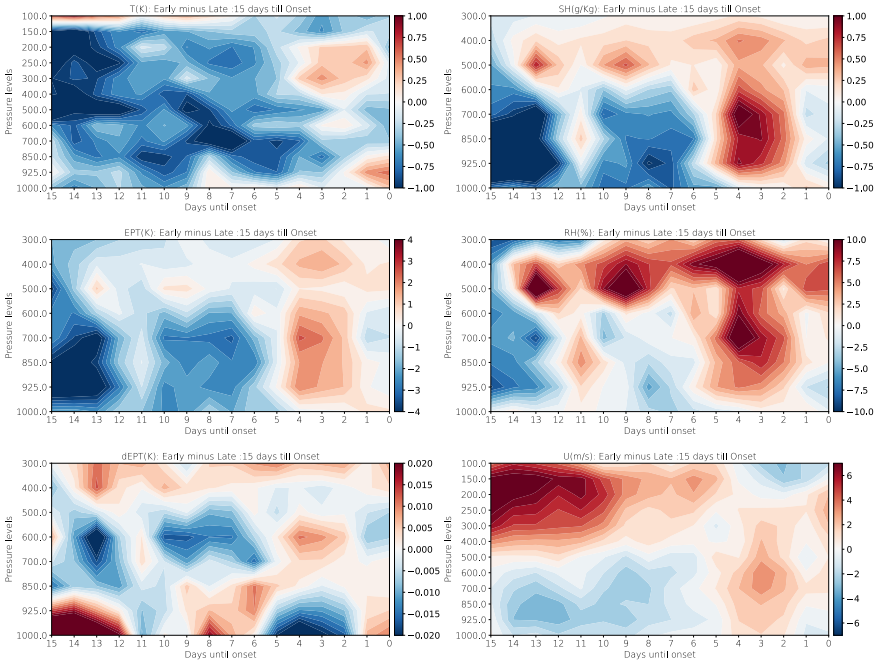

Figure S6: Time-height cross-sections. Same as Figure S5, except over the region marked by the Green Box in Figure S3a.

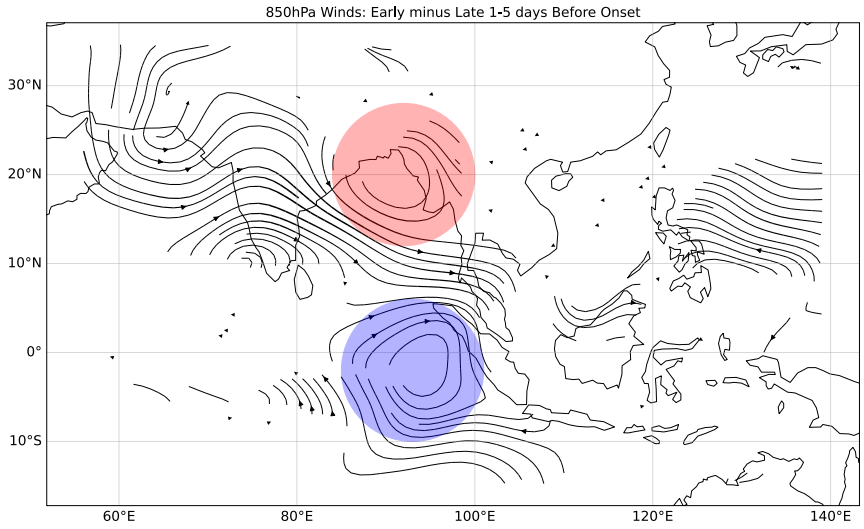

Figure S7: Repeat of Figure 3i. A streamline visualization of Figure 3i of the paper, to emphasize a pair of cyclonic Rossby responses indicated by the red circle (north) and blue circle (south).

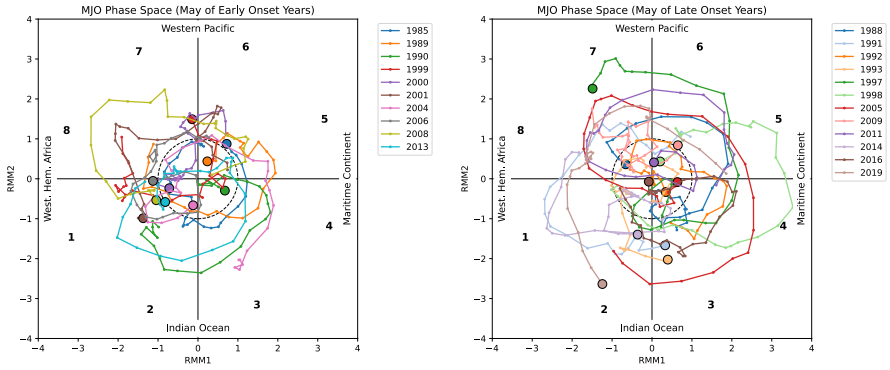

Figure S8: MJO activity during May MJO phase is plotted for early (left hand panel) and late (right hand panel) onset years using the real-time multivariate MJO index (RMM) data obtained from the Australian Bureau of Meteorology).

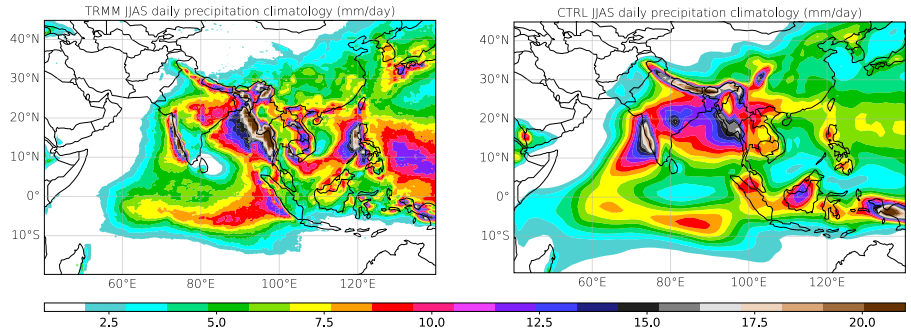

Figure S9: Model fidelity. JJAS mean daily rainfall from TRMM (left) and in the CTRL simulation (right).

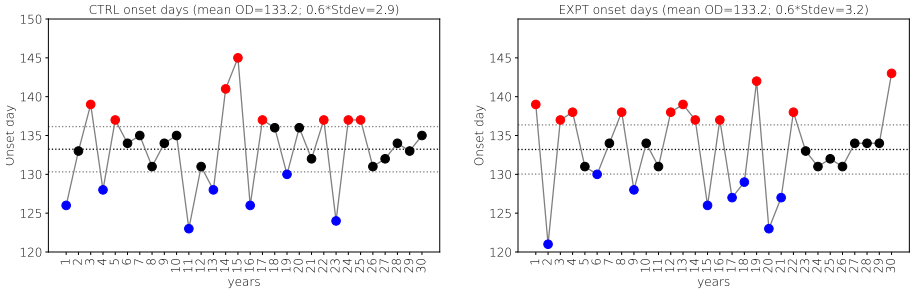

Figure S10: Model-simulated monsoon onset dates. Onset dates for the 30 years, that are analyzed in this study, each of the CTRL (left) and EXPT (right) simulations calculated based on the tropospheric temperature gradient index of Xavier et al. (2007). The bracketed numbers in the title of each panel indicate the standard deviation of the onset dates. In harmony with Figure 2 of the paper, the early, late, and normal onset years are marked by red, blue, and black circular markers, although these model years classified under these categories are not used in any analysis presented in this study.

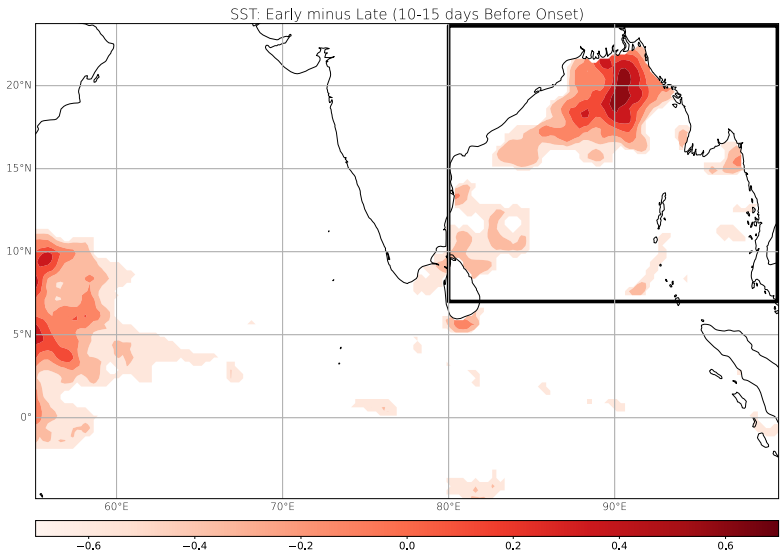

Figure S11: SST (°C) forcing for EXPT simulation. Only the SST anomalies confined within the black box are imposed in EXPT simulation, for 5 days, from 117$^{\text{th}}$-122$^{\text{nd}}$ day, of each year. These anomalies are computed from the composite of SST for early onset years minus that for late-onset years, 10-15 days before monsoon onset. SST data is from OISST and the years considered are as mentioned in Table S1. This Figure is the same as Figure 3a or Figure S2 (bottom panel), except this figure depicts only the positive anomalies.

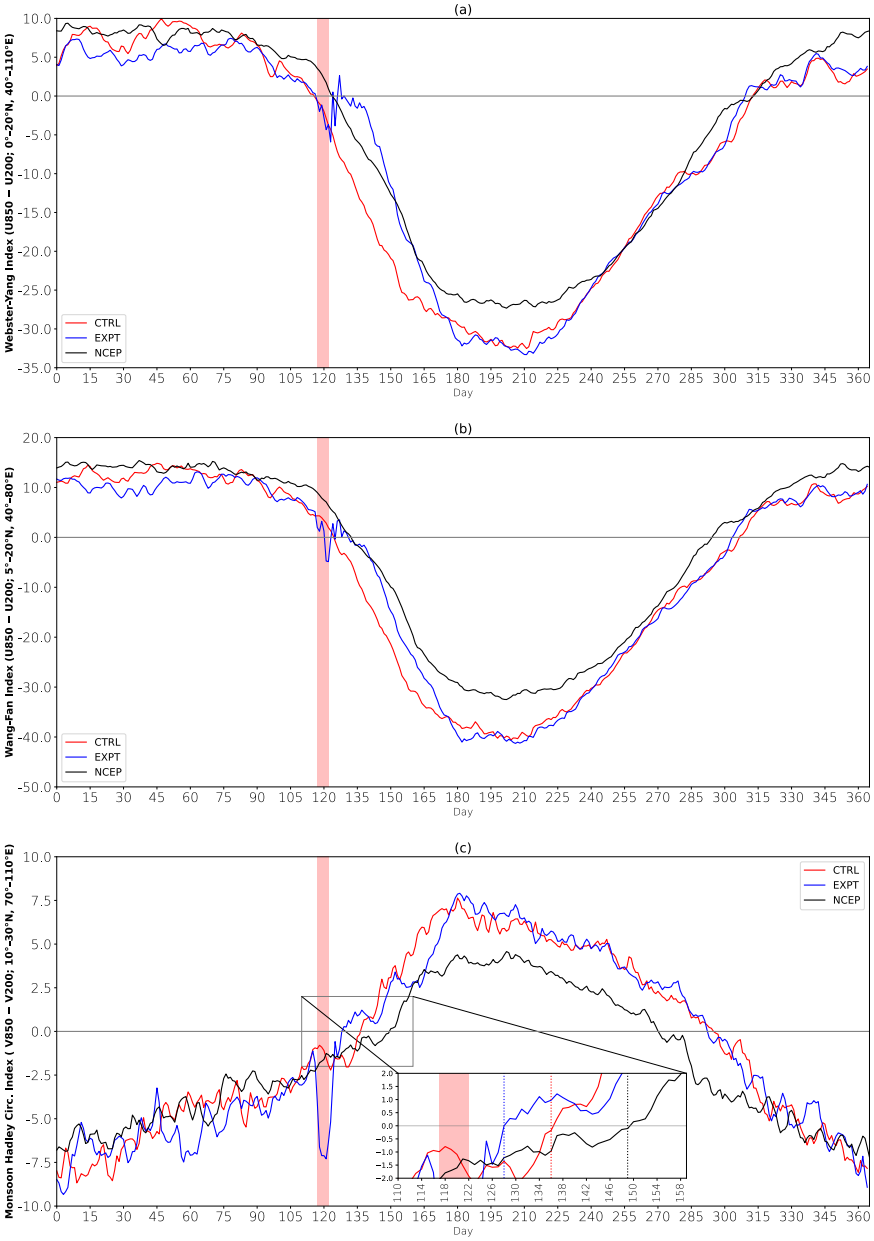

Figure S12: Circulation based monsoon onset indices. (a) Webster and Yang index, (b) Wang and Fan index, and (c) Hadley circulation index. A zoomed view emphasizing the onset timings, marked by dotted vertical lines, is depicted in inset in (c). The red patch in each panel marks the timing of the anomalous SST forcing in the EXPT simulation.

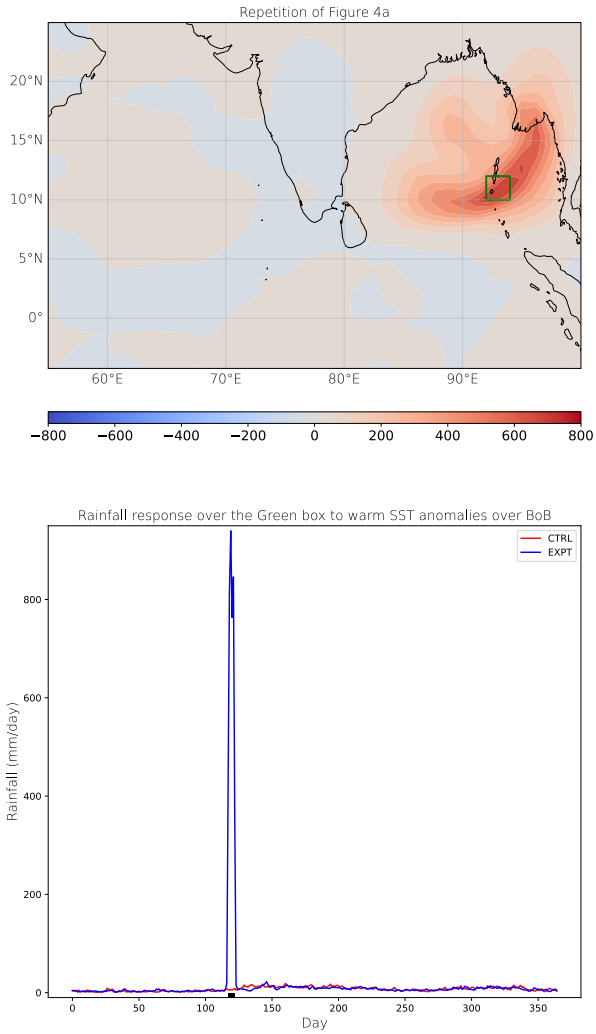

Figure S13: Abrupt model response to imposed SST in EXPT simulation. The top panel is a repetition of Figure 4a of the paper, which is rainfall anomaly (EXPT-CTRL) 10-15 days before monsoon onset in the models. The bottom panel depicts the daily rainfall time series over the green box as marked in the top panel. The location of the green box is chosen to represent the maximum amplitude in the model response. The timing of the anomalous SST forcing in the EXPT simulation is marked by the black block in the bottom panel plot. Arguably model response is abrupt. Nonetheless, it is intriguing to note the model response in the backdrop of the findings of Wu et al. (2012) who show an enhanced rainfall in the central-eastern Bay of Bengal (BoB) following a warm northern BoB via the formation of a monsoon onset vortex (MOV) (Figure 7 of Wu et al. (2012).