A statistically predictive model for future monsoon failure in India

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Supplementary Information

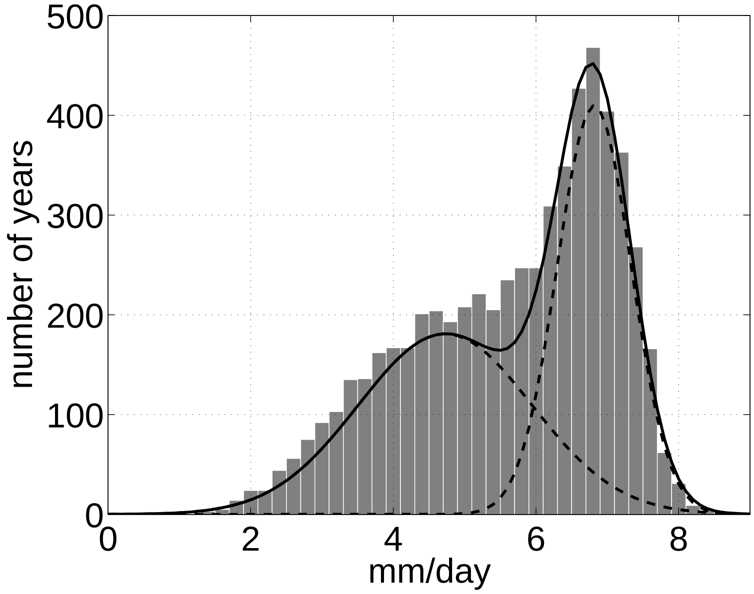

Figure S1. Gray bars as in Fig. 1A in the main paper. Black dashed lines show the characteristics of the two modes obtained from latent–classes analysis, and the solid line shows their superposition.

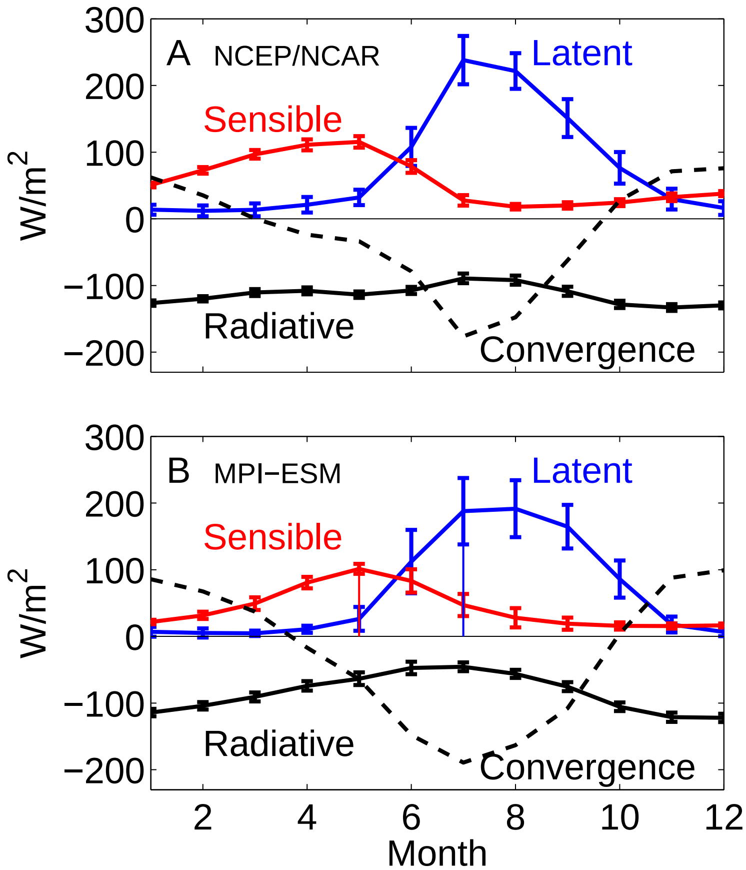

Figure S2. Net contributions to the monthly moist static energy budget of the atmospheric column over India (land area within 5-30°N, 70-90°E), **(A)** in NCEP/NCAR reanalysis data [1, averaged over 1948-2007], and **(B)** in the MPI-ESM climate model (averaged over the 1206 years of the first ensemble simulation; cf. Appendix A.1 in the main paper): Radiative fluxes (black solid line), sensible heat flux from the ground (red), latent heat flux due to precipitation (blue), and convergence of heat due to advection by the large-scale time-mean circulation and eddies (black dashed line). Errorbars denote one standard deviation. Sensible heat flux is strongest just before the monsoon onset, but during the rainy season, latent heat release dominates the energy budget, balanced by advective processes that transport the excess heat out of the region.

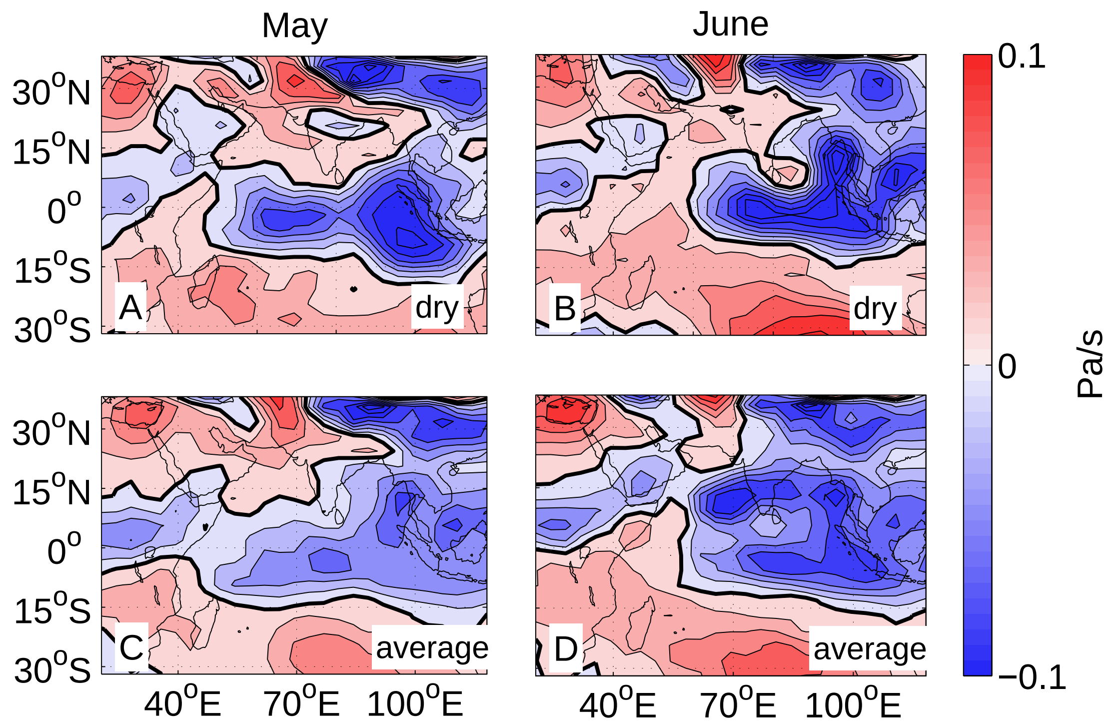

Figure S3. Monthly mean vertical velocity ω (in Pa/s) at 500hPa in the MPI-ESM climate model, in May (**A, C**) and June (**B, D**) of the dry year (upper panels), and averaged over the 17 previous years (lower panels). Positive ω (red shading) indicates subsidence of air. Contour spacing is 0.02 Pa/s. In the dry year, central India and the Arabian Sea are characterized by subsidence instead of upwelling.

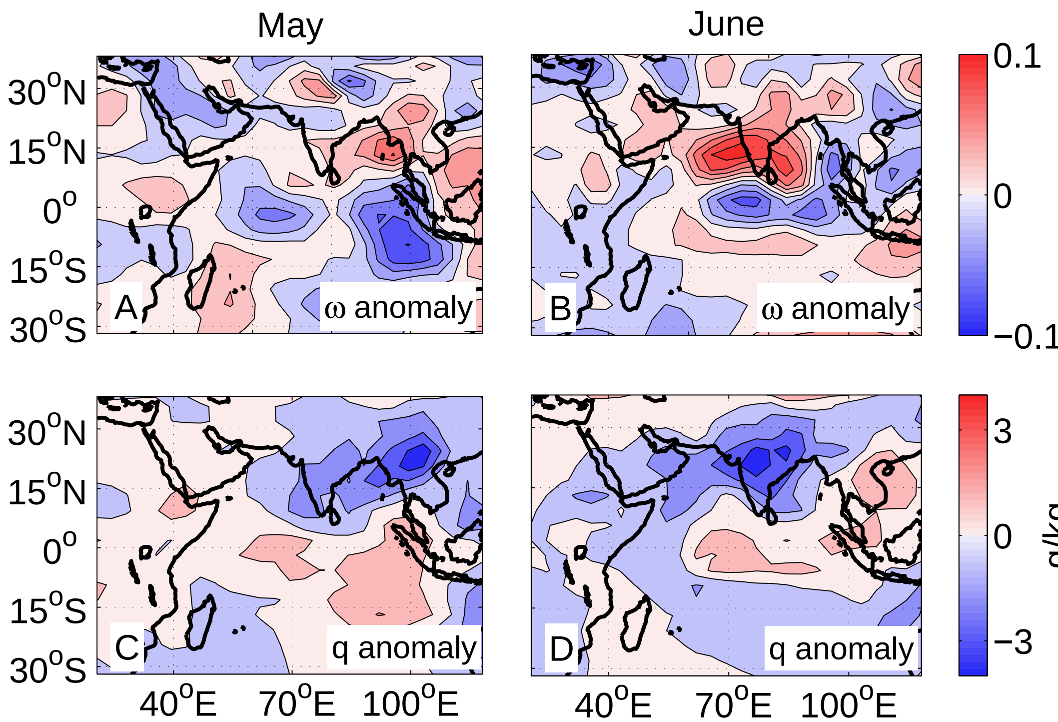

Figure S4. (**A**) Anomaly of MPI-ESM monthly mean vertical velocity ω (in Pa/s, contour spacing 0.02) at 500hPa in May of the dry year, with respect to the average over the 17 previous years; (**B**) same for June; (**C**) anomaly of monthly mean lower troposphere (500-1000hPa) specific humidity (g/kg, contour spacing 1 g/kg) in May of the dry year, with respect to the average over the 17 previous years; (**D**) same for June. Anomalous subsidence of dry air over India and the Northern Indian Ocean leads to moisture depletion in the monsoon region.

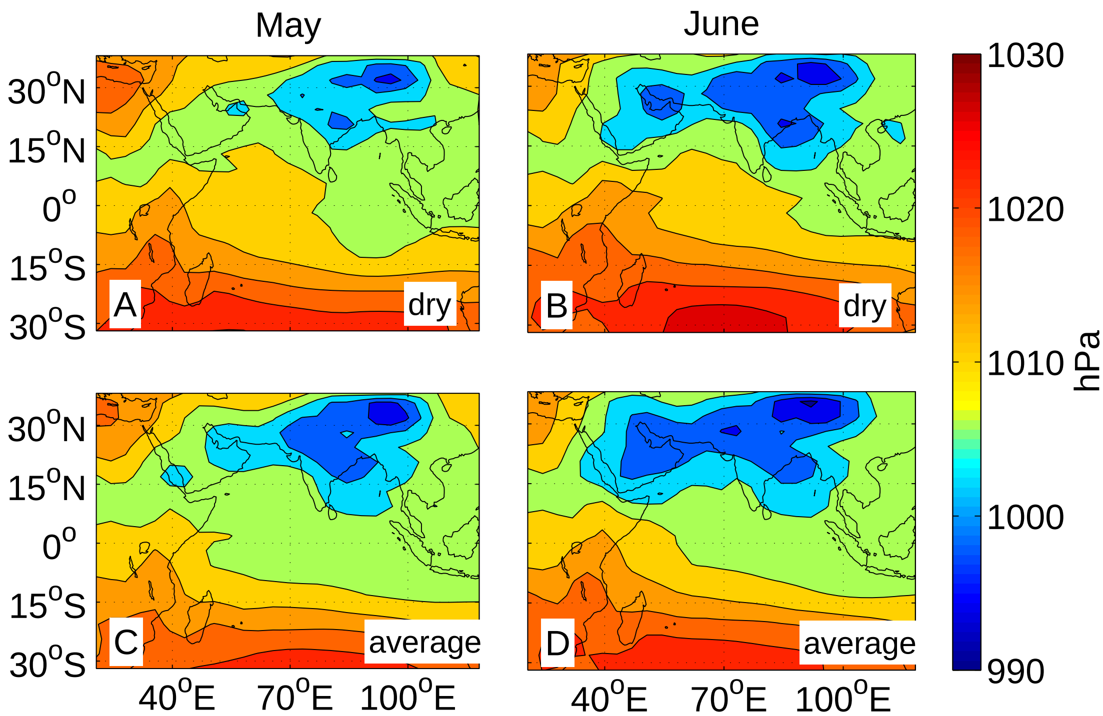

Figure S5. (**A**) MPI-ESM monthly mean sea level pressure (in hPa) in May (**A, C**) and June (**B, D**) of the dry year (upper panels), and averaged over the 17 previous years (lower panels). Contour spacing is 4 hPa. The Eurasian surface Low is diminished over India and the Arabian Sea in the dry year, consistent with anomalous subsidence and suppressed precipiation over the region (cf. Fig. S3).

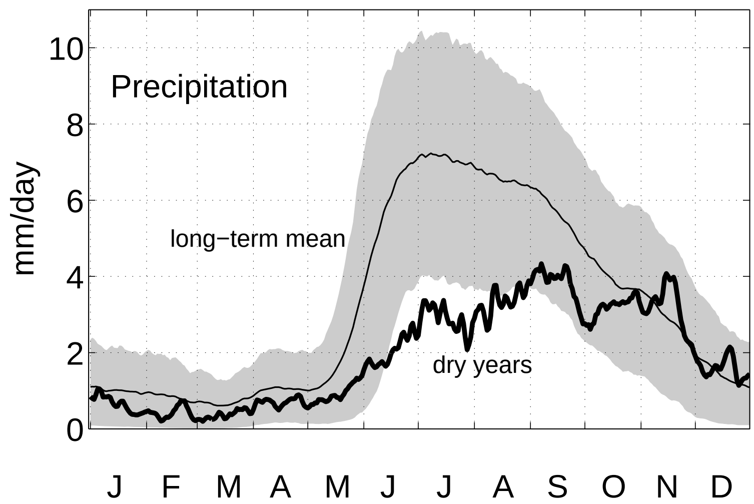

Figure S6. Annual cycle of daily precipitation over India as a long-term mean over the first 1206-year climate model simulation (thin line; shading denotes the 16% and 84% quantiles), and averaged over all dry years within this simulation (JJA mean precipitation lower than 2.5 mm/day, thick line).

Table S1. Parameters of the day-to-day model.

Parameter	Symbol	Value used for...		
		Fig. 1A (historical)	Fig. 1B (future)	Fig. 5 (transient)
length of season	l		135 time steps	
length of memory period	τ		17 time steps	
precipitation in wet state	P_+	9 mm/day	10.9 mm/day	varying linearly with global temperature*
precipitation in dry state	P_-	0 mm/day	1.9 mm/day	varying linearly with global temperature*
initial probability	p_{init}	0.75	0.2	varying linearly with May Nino3.4 MSLP*
maximum probability	p_m	0.8	0.82	0.82

*see Appendix A.3, main article

References

[1] Kistler R, *et al.* (2001) The NCEP/NCAR 50-year reanalysis. *Bull Amer Meteor Soc* 82:247 – 267.