



## Impact of the modulated annual cycle and intraseasonal oscillation on daily-to-interannual rainfall variability across monsoonal India

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Variability of the Indian summer monsoon is decomposed into an interannually modulated annual cycle (MAC) and a northward-propagating, intraseasonal (30–60-day) oscillation (ISO). Multichannel Singular Spectrum Analysis (M-SSA) is applied to daily fields of observed outgoing long-wave radiation (OLR) and 925-hPa reanalysis winds over the Indian region from 1975 to 2008 to achieve this decomposition. The MAC is essentially given by the year-to-year changes in the annual and semi-annual components; it displays a slow northward migration of OLR anomalies coupled with an alternation between the northeast winter and southwest summer monsoons. The impact of these oscillatory modes on rainfall is then analyzed using a 1-degree gridded daily dataset, focusing on monsoonal India (MI, here defined as north of 17°N and west of 90°E) during the months of June to September. Daily rainfall variability is partitioned into three states using a Hidden Markov Model. Two of these states are shown to agree well with previous classifications of “active” and “break” phases of the monsoon, while the third state exhibits a dipolar east-west pattern with abundant rainfall east of about 77°E and low rainfall to the west. Occurrence of the rainfall states is an asymmetric function of both the MAC and ISO components. On average, monsoon breaks are favored by large negative anomalies of MAC, and vice versa, while ISO impact is found to be decisive when the MAC is near neutral during the onset and withdrawal phases of the monsoon. Active monsoon spells are found to require a synergy between the MAC and ISO, while the east-west rainfall dipole is less sensitive to interactions between them. The driest years, defined from spatially averaged June–September rainfall anomalies, are found to be mostly a result of breaks occurring during the onset and withdrawal stages of the monsoon (i.e. mid-June to mid-July, and during September). These breaks are in turn associated with anomalously late MAC onset or early MAC withdrawal, often together with a large-amplitude negative ISO event. The occurrence of breaks during the core of the monsoon (i.e. from late July to late August) is restricted to a few years when MAC was exceptionally weak (e.g., 1987 or 2002). Wet years are shown to be mostly associated with more frequent active spells and a stronger MAC than usual, especially at the end of the monsoon season.