

Abstract

The Indian Summer Monsoon (ISM) has long been viewed as a self-regulated coupled ocean–atmosphere system, wherein floods and droughts alternate in successive years due to feedbacks mediated by cross-equatorial ocean heat transport (OHT). This thesis critically examines that paradigm by evaluating the relative contributions of OHT, large-scale teleconnections, and synoptic-scale systems to ISM interannual variability, and by assessing how extreme floods and droughts may evolve under future climate scenarios. Analyses using reanalysis data reveal that the persistence of cross-equatorial OHT is too short-lived to explain year-to-year reversals in ISM rainfall. While rainfall differences between flood and drought years exceed 20%, associated OHT differences remain below 2%, and the response of the local Hadley circulation is negligible. These findings suggest that OHT plays only a minor role in governing interannual ISM variability. By contrast, the El Niño–Southern Oscillation (ENSO) exerts strong control on sea surface temperature (SST) anomalies in the northern Indian Ocean, which in turn influence subsequent monsoon behavior. However, the correlation between winter Niño3.4 anomalies and following-summer ISM rainfall is weak, underscoring the indirect and non-linear nature of ENSO–ISM linkages. Synoptic variability, especially low-pressure systems (LPS), emerges as a critical driver of ISM rainfall extremes. Drought years are associated with two fewer LPS per summer and disrupted west-northwestward propagation compared to flood years. LPS activity thus substantially shapes interannual rainfall variability and governs the spatial coherence of extreme events. Future projections from CMIP6 multimodel ensembles indicate marked changes in ISM extremes. While biases exist at the model level, the ensemble reproduces historical excess and deficit statistics reasonably well. Under high-emission scenarios, extreme excess years are projected to become more frequent, with shorter return periods, signaling a transition to more intense wet seasons. Extreme deficit years display weaker and more uncertain trends. LPS remain central to excess–deficit contrasts, with more frequent and coherent tracks during wet years, though their overall frequency shows only marginal declines in a warmer climate. ENSO’s role also evolves: the historical association of La Niña with excess rainfall and El Niño with deficit years weakens, and extreme excess events increasingly occur during El Niño years under SSP585, suggesting a fundamental reorganization of ENSO–ISM interactions in a warming

world. Taken together, this thesis demonstrates that ISM interannual variability arises from a combination of remote and regional processes rather than from OHT alone. The findings highlight the growing importance of synoptic-scale variability and shifting ENSO dynamics in shaping extreme rainfall, with direct implications for monsoon prediction, climate adaptation, and disaster risk reduction across South Asia.