Arabian Sea Mini Warm Pool: Formation, Variability, and Its Role in Indian Summer Monsoon Onset

The southeastern Arabian Sea hosts one of the warmest pre-monsoon oceanic features in the tropics—the Arabian Sea Mini Warm Pool (MWP)—a region where sea surface temperatures (SSTs) exceed 30 °C during April–May. Despite its relatively small spatial scale, the MWP plays a significant role in shaping regional air–sea interactions by influencing the onset of the Indian Summer Monsoon (ISM). The formation of the MWP results from a delicate interplay between seasonal solar heating, weak winds, and salinity-driven stratification, which together trap heat in the upper ocean, allowing for rapid warming of the sea surface. However, the formation mechanism of the MWP and its climatic consequences remain a topic of debate. Given its influence on convection and low-level circulation near the Kerala coast, understanding the MWP formation and its impact on the ISM onset is crucial for enhancing predictions of monsoon onset, a phenomenon of profound socioeconomic significance for the Indian subcontinent.

A coupled atmosphere–ocean numerical model is used to examine the relative contributions of atmospheric and oceanic processes in the development of the MWP. The numerical model is configured for three independent years (2013, 2016, 2018) to understand the influence of the atmosphere and ocean during the mature phase (i.e., April-June) of the MWP. During the past decade, the MWP reached its maximum spatial extent in 2016 and was effectively missing in 2013. In contrast, the 2018 MWP closely resembled its climatological extent. The simulated model output from April to June shows good agreement with observations, with SST and sea surface salinity (SSS) biases of less than 1.75 °C and one psu, respectively, and minimal bias within the MWP region. The mixed-layer heat budget further indicates that during April and May, the net surface heat flux is the primary driver of MWP warming, reaching approximately 0.1 °C per day. Once the MWP becomes fully developed, vertical processes dominate, exerting a continuous cooling effect of nearly –0.08 °C/day. The dissipation of the MWP is primarily linked to the decline in net surface heat flux. Sensitivity experiments demonstrate that favorable oceanic preconditioning can enhance the MWP by up to 136% in strong MWP years. In contrast, unfavorable atmospheric conditions can suppress its intensity by 82%, highlighting the coupled control of both systems. Weak winds—forming a wind-shadow zone in moderate to strong MWP years—modulate its spatial extent by reducing turbulent mixing.

The role of prevailing atmospheric conditions and ocean preconditioning before April has a significant influence on modulating the MWP's spatial extent and intensity. Thus, it becomes very interesting to understand how the ocean preconditioning can influence the MWP's formation. For that, we first showed that an intense MWP develops after a strong El Niño event, with the El Niño accounting for 64% of MWP's interannual variability. We further show that next to a strong El Niño events, the southeastern Arabian Sea undergoes a sequence of oceanic adjustments that favor the development of an anomalously intense MWP in the subsequent spring. During El Niño years, weakened ISM winds reduce cloud cover and significantly suppress Ekman transport and coastal upwelling, allowing enhanced shortwave radiation to warm the upper ocean from June to October. In the subsequent winter, a weakened East India Coastal Current (EICC) reduces freshwater transport and increases surface salinity, leading to mixed-layer deepening, which diminishes climatological cooling and promotes more efficient heat storage. Additional horizontal and vertical oceanic processes reinforce this warming. By the next March–May (subsequent to an El Niño year), anomalous easterlies reduce latent heat loss and cloud cover, creating ideal conditions for an intense MWP. This multi-season evolution demonstrates why strong MWPs frequently follow major El Niño events and provides a potential early predictor of ISM onset timing.

After El Niño events, an anomalous anticyclone emerges over the northern Arabian Sea during April–June of next year, generating easterly wind anomalies that weaken the climatological southwesterly monsoon wind. This weak wind simultaneously favors MWP expansion in May. It delays the monsoon onset in Kerala (MoK), establishing a clear positive relationship: stronger MWPs are statistically associated with later onset dates. Conversely, after La Niña events, the strong southwesterly monsoon winds maintain vigorous turbulent mixing, preventing the formation of MWP and resulting in early onset tendencies. To quantify the direct influence of the MWP on MoK, we performed regional coupled atmosphere–ocean numerical model (RCM) experiments, including "noMWP" sensitivity runs. These experiments show that subsequent to El Niño events, the MWP strengthens convection and enhances low-level wind convergence over the Kerala coast, effectively advancing the MoK and offsetting part of the El Niño-induced delay. Thus, the MWP does not merely respond to large-scale climate drivers—it actively feeds back on the monsoon system, modifying onset timing and improving predictability.

Finally, we evaluate how Coupled Model Intercomparison Project Phase 6 (CMIP6) models represent the MWP and its associated impacts on ISM. Although CMIP6 models adequately capture El Niño–Southern Oscillation (ENSO)-driven basin-wide warming patterns, they consistently fail to simulate the MWP, placing the warmest SSTs over the equatorial Arabian Sea instead of the southeastern basin. This deficiency stems from a persistent cold SST bias in the northern Arabian Sea, which prevents MWP development. Regional modeling experiments demonstrate that this cold bias weakens low-level circulation, reduces convection, delays the monsoon onset by 7–16 days across models, and even disrupts the northward progression of the monsoon. Improving the representation of northern Arabian Sea SSTs and air–sea coupling is therefore critical for enhancing monsoon modeling and prediction in CMIP6 frameworks.

Overall, this thesis establishes the Mini Warm Pool as a key oceanic precursor of monsoon onset, shaped by oceanic preconditioning, atmospheric forcing, and ENSO-related teleconnections. The results underscore the need for improved observational coverage and model fidelity in the southeastern Arabian Sea to advance monsoon onset prediction and enhance our understanding of Indian Ocean climate variability.