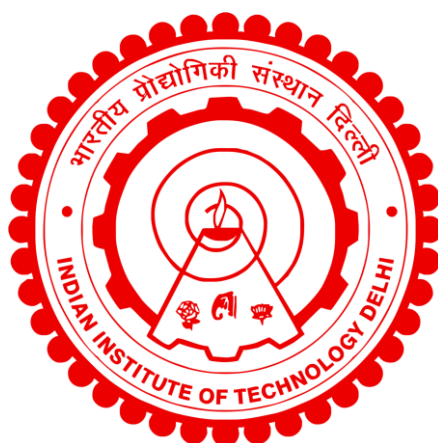


ARABIAN SEA MINI WARM POOL: FORMATION, VARIABILITY, AND ITS ROLE IN INDIAN SUMMER MONSOON ONSET

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by

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Submitted

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DEDICATION

*Dedicated to my Ma, Dadu, and
Didi, and to all those whose
wishes, blessings, and hopes for
my well-being and success have
guided me throughout this
journey.*

CERTIFICATE

This is to certify that the thesis entitled “**Arabian Sea Mini Warm Pool: Formation, Variability, and Its Role in Indian Summer Monsoon Onset**”, submitted by **Mr. SANKAR PRASAD LAHIRI**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Place: New Delhi
Date: 8 April, 2026

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Place: New Delhi

Date: 8 April, 2026

Sankar Prasad Lahiri

ABSTRACT

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.

सारांश

दक्षिणपूर्वी अरब सागर उष्णकटिबंधीय में सबसे गर्म मानसून पूर्व समुद्री विशेषताओं में से एक है-अरब सागर मिनी वार्म पूल (एमडब्ल्यूपी)-एक ऐसा क्षेत्र जहां अप्रैल-मई के दौरान समुद्र की सतह का तापमान (एसएसटी) 30 डिग्री सेल्सियस से अधिक हो जाता है। अपने अपेक्षाकृत छोटे स्थानिक पैमाने के बावजूद, एमडब्ल्यूपी भारतीय ग्रीष्मकालीन मानसून (आईएसएम) की शुरुआत को प्रभावित करके क्षेत्रीय हवाई-समुद्री बातचीत को आकार देने में महत्वपूर्ण भूमिका निभाता है। एम. डब्ल्यू. पी. का गठन मौसमी सौर ताप, कमजोर हवाओं और लवणता-संचालित स्तरीकरण के बीच एक नाजुक परस्पर क्रिया के परिणामस्वरूप होता है, जो एक साथ ऊपरी महासागर में गर्मी को रोकते हैं, जिससे समुद्र की सतह तेजी से गर्म होती है। हालाँकि, एम. डब्ल्यू. पी. के गठन तंत्र और इसके जलवायु संबंधी परिणाम बहस का विषय बने हुए हैं। केरल तट के पास संवहन और निम्न-स्तरीय परिसंचरण पर इसके प्रभाव को देखते हुए, एमडब्ल्यूपी के गठन और आईएसएम की शुरुआत पर इसके प्रभाव को समझना मानसून की शुरुआत की भविष्यवाणियों को बढ़ाने के लिए महत्वपूर्ण है, जो भारतीय उपमहाद्वीप के लिए गहन सामाजिक-आर्थिक महत्व की घटना है।

एम. डब्ल्यू. पी. के विकास में वायुमंडलीय और महासागरीय प्रक्रियाओं के सापेक्ष योगदान की जांच करने के लिए एक युग्मित वातावरण-महासागर संख्यात्मक मॉडल का उपयोग किया जाता है। MWP के परिपक्व चरण (i.e., अप्रैल-जून) के दौरान वायुमंडल और महासागर के प्रभाव को समझने के लिए संख्यात्मक मॉडल को तीन स्वतंत्र वर्षों (2013,2016,2018) के लिए कॉन्फिगर किया गया है। पिछले दशक के दौरान, एमडब्ल्यूपी 2016 में अपनी अधिकतम स्थानिक सीमा तक पहुंच गया और 2013 में प्रभावी रूप से गायब था। इसके विपरीत, 2018 एमडब्ल्यूपी इसकी जलवायु संबंधी सीमा से निकटता से मिलता-जुलता था। अप्रैल से जून तक सिमुलेटेड मॉडल आउटपुट क्रमशः 1.75 डिग्री सेल्सियस और एक पीएसयू से कम के एसएसटी और एसएसएस पूर्वाग्रहों और एमडब्ल्यूपी क्षेत्र के भीतर न्यूनतम पूर्वाग्रह के साथ टिप्पणियों के साथ अच्छा समझौता दिखाता है। मिश्रित-परत गर्मी बजट आगे इंगित करता है कि अप्रैल और मई के दौरान, शुद्ध सतह गर्मी प्रवाह MWP वार्मिंग का प्राथमिक चालक है, जो प्रति दिन लगभग 0.1 डिग्री सेल्सियस तक पहुंचता है। एक बार जब एमडब्ल्यूपी पूरी तरह से विकसित हो जाता है, तो ऊर्ध्वाधर प्रक्रियाएं हावी होती हैं, लगभग-0.08 डिग्री सेल्सियस/दिन का निरंतर शीतलन प्रभाव डालती हैं। एम. डब्ल्यू. पी. का अपव्यय मुख्य रूप से शुद्ध सतह ताप प्रवाह में गिरावट से जुड़ा हुआ है। संवेदनशीलता प्रयोगों से पता चलता है कि अनुकूल महासागरीय पूर्व शर्त मजबूत MWP वर्षों में MWP को 136% तक बढ़ा सकती है। इसके विपरीत, प्रतिकूल वायुमंडलीय स्थितियां इसकी तीव्रता को 82% तक दबा सकती हैं, जो दोनों प्रणालियों के युग्मित नियंत्रण को उजागर करती हैं। कमजोर हवाएँ-मध्यम से मजबूत एमडब्ल्यूपी वर्षों में एक पवन-छाया क्षेत्र बनाती हैं-अशांत मिश्रण को कम करके इसकी स्थानिक सीमा को संशोधित करती हैं।

अप्रैल से पहले प्रचलित वायुमंडलीय स्थितियों और महासागर पूर्व-कंडीशनिंग की भूमिका का एमडब्ल्यूपी की स्थानिक सीमा और तीव्रता को संशोधित करने पर महत्वपूर्ण प्रभाव पड़ता है। इस प्रकार, यह समझना बहुत दिलचस्प हो जाता है कि महासागर की पूर्व शर्त एमडब्ल्यूपी के गठन को कैसे प्रभावित कर सकती है। उसके लिए, हमने पहली बार दिखाया कि एक तीव्र MWP एक मजबूत अल नीनो घटना के बाद विकसित होता है, जिसमें अल नीनो MWP की अंतरवार्षिक परिवर्तनशीलता का 64% हिस्सा है। हम आगे दिखाते हैं कि मजबूत अल नीनो घटनाओं के बाद, दक्षिणपूर्वी अरब सागर में समुद्री समायोजन का एक क्रम होता है जो बाद के वसंत में एक विसंगत रूप से तीव्र एमडब्ल्यूपी के विकास का समर्थन करता है। अल नीनो वर्षों के दौरान, कमजोर आईएसएम हवाएं बादल के आवरण को कम करती हैं और एकमान परिवहन और तटीय उत्थान को काफी दबा देती हैं, जिससे जून से अक्टूबर तक ऊपरी महासागर को गर्म करने के लिए शॉर्टवेव विकिरण में वृद्धि होती है। बाद की सर्दियों में, कमजोर ई. आई. सी. सी. परिवहन और सतह की लवणता में वृद्धि मिश्रित परत को गहरा करती है, जिससे जलवायु संबंधी शीतलन कम होता है और अधिक कुशल गर्मी भंडारण को सक्षम बनाता है। अतिरिक्त क्षैतिज और ऊर्ध्वाधर महासागरीय प्रक्रियाएँ इस वार्मिंग को मजबूत करती हैं। अगले मार्च-मई के मौसम तक (एक अल नीनो वर्ष के बाद) विसंगत पूर्वी हवाएँ अव्यक्त गर्मी के नुकसान और बादल के आवरण को कम कर देती हैं, जिससे एक तीव्र एमडब्ल्यूपी के लिए आदर्श परिस्थितियाँ पैदा होती हैं। यह बहु-मौसम विकास दर्शाता है कि क्यों मजबूत एमडब्ल्यूपी अक्सर प्रमुख एल नीनो घटनाओं का पालन करते हैं और आईएसएम की शुरुआत के समय का एक संभावित प्रारंभिक भविष्यवक्ता प्रदान करते हैं।

अल नीनो की घटनाओं के बाद, अप्रैल-जून के दौरान उत्तरी अरब सागर के ऊपर एक विसंगत एंटीसाइक्लोन उभरता है, जिससे पूर्वी हवा की विसंगतियाँ पैदा होती हैं जो जलवायु संबंधी दक्षिण-पश्चिमी मानसून के प्रवाह को कमजोर करती हैं। यह कमजोर दक्षिण-पश्चिमी हवा एक साथ मई में एमडब्ल्यूपी के विस्तार का समर्थन करती है। यह केरल (एम. ओ. के.) में मानसून की शुरुआत में देरी करता है और एक स्पष्ट सकारात्मक संबंध स्थापित करता है: मजबूत एम. डब्ल्यू. पी. सांख्यिकीय रूप से बाद की शुरुआत की तारीखों से जुड़े होते हैं। इसके विपरीत, ला नीना की घटनाओं के बाद, दक्षिण-पश्चिमी मानसून की तेज हवाएं जोरदार अशांत मिश्रण बनाए रखती हैं, जो एमडब्ल्यूपी के गठन को रोकती हैं और जिसके परिणामस्वरूप जल्दी शुरू होने की प्रवृत्ति होती है। एमओके पर एमडब्ल्यूपी के प्रत्यक्ष प्रभाव की मात्रा निर्धारित करने के लिए, हमने क्षेत्रीय युग्मित वातावरण-महासागर संख्यात्मक मॉडल (आरसीएम) प्रयोग किए, जिसमें "नोएमडब्ल्यूपी" संवेदनशीलता रन शामिल हैं। इन प्रयोगों से पता चलता है कि अल नीनो के दौरान, बाद के वर्षों में, एमडब्ल्यूपी संवहन को मजबूत करता है और केरल तट पर निम्न-स्तरीय पवन अभिसरण को बढ़ाता है, प्रभावी रूप से एमओके को आगे बढ़ाता है और ईएनएसओ-प्रेरित देरी के हिस्से को ऑफसेट करता है। इस प्रकार, एमडब्ल्यूपी केवल बड़े पैमाने पर जलवायु चालकों का जवाब नहीं देता है-यह सक्रिय रूप से मानसून प्रणाली पर वापस फीड करता

है, शुरुआत के समय को संशोधित करता है और पूर्वानुमान में सुधार करता है।

अंत में, हम मूल्यांकन करते हैं कि सीएमआईपी6 मॉडल एमडब्ल्यूपी और आईएसएम पर इसके संबंधित प्रभावों का प्रतिनिधित्व कैसे करते हैं। हालांकि सीएमआईपी6 मॉडल ईएनएसओ-संचालित बेसिन-वाइड वार्मिंग पैटर्न को पर्याप्त रूप से पकड़ते हैं, वे लगातार एमडब्ल्यूपी का अनुकरण करने में विफल रहते हैं, जिससे सबसे गर्म एसएसटी दक्षिणपूर्वी बेसिन के बजाय भूमध्यरेखीय अरब सागर के ऊपर रहते हैं। यह कमी उत्तरी अरब सागर में लगातार ठंडे एसएसटी पूर्वाग्रह से उपजी है, जो लवणता-प्रेरित स्तरीकरण को रोकता है और एमडब्ल्यूपी के विकास को रोकता है। क्षेत्रीय मॉडलिंग प्रयोगों से पता चलता है कि यह शीत पूर्वाग्रह निम्न-स्तर के परिसंचरण को कमजोर करता है, संवहन को कम करता है, मॉडल में मानसून की शुरुआत में 7-16 दिनों की देरी करता है, और यहां तक कि मानसून की उत्तर की ओर प्रगति को बाधित करता है। इसलिए सी. एम. आई. पी. 6 ढांचे में मानसून मॉडलिंग और भविष्यवाणी को बढ़ाने के लिए उत्तरी अरब सागर एस. एस. टी. और वायु-समुद्र युग्मन के प्रतिनिधित्व में सुधार करना महत्वपूर्ण है।

कुल मिलाकर, यह शोध प्रबंध मिनी वार्म पूल को मानसून की शुरुआत के एक प्रमुख महासागरीय अग्रदूत के रूप में स्थापित करता है, जो महासागरीय पूर्व शर्त, वायुमंडलीय बल और ई. एन. एस. ओ. से संबंधित टेलीकनेक्शन द्वारा आकार देता है। परिणाम मानसून की शुरुआत की भविष्यवाणी को आगे बढ़ाने और हिंद महासागर जलवायु परिवर्तनशीलता की हमारी समझ को बढ़ाने के लिए दक्षिणपूर्वी अरब सागर में बेहतर अवलोकन कवरेज और मॉडल निष्ठा की आवश्यकता को रेखांकित करते हैं।

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ABBREVIATIONS

ACC	Antarctic Circumpolar Current
AdS	Andaman Sea
AE	Anticyclonic Eddy
AEs	Anticyclonic Eddies
AI	Andaman Island
AMJ	April-May-June
AS	Arabian Sea
AVHRR	Advanced Very High Resolution Radiometer
BL	Barrier Layer
BLT	Barrier Layer Thickness
BoB	Bay of Bengal
CC	Correlation Coefficient
CMIP6	Coupled Model Intercomparison Project Phase 6
COAWST	Coupled Ocean-Atmosphere Wave Sediment Transport Model
DJF	December-January-February
ECMWF	European Centre for Medium-Range Weather Forecasts
EICC	East India Coastal Current
ENSO	El Niño Southern Oscillation
ERA5	ECMWF Reanalysis Phase 5
ESA	European Space Agency
GPH	Geo-potential Height
IMD	India Meteorological Department
IO	Indian Ocean
IOB	Indian Ocean Basin Mode
IOD	Indian Ocean Dipole
IPOC	Indo-Pacific Ocean Capacitor Effect
IPWP	Indo-Pacific Warm Pool

ISM	Indian Summer Monsoon
ISMR	Indian Summer Monsoon Rainfall
ISO	Intra-seasonal Oscillation
ITF	Indonesian Throughflow
ITCZ	Intertropical Convergence Zone
JJA	June-July-August
KPP	K-Profile Parameterization
KW	Kelvin Wave
LH	Lakshadweep High
LL	Lakshadweep Low
LSM	Land Surface Model
LHF	latent Heat Flux
MAM	March-April-May
MCT	Model Coupling Toolkit
MJO	Madden Jullian Oscillation
MLD	Mixed Layer Depth
MMM	Multi-Model Mean
MoK	Monsoon Onset in Kerala
MOV	Monsoon Onset Vortex
MSE	Moist Static Energy
MWP	Mini Warm Pool
NAS	Northern Arabian Sea
NHF	Net Surface Heat Flux
NOAA	National Oceanic and Atmospheric Administration
OND	October-November-December
ORAS5	ECMWF Ocean Reanalysis System 5
PBL	Planetary Boundary Layer
PCC	Pearson Correlation Coefficient
PW	Precipitable Water
RAMA	Research Moored Array for African-Asian-Australian
RCM	Regional Coupled Model
RH	Relative Humidity

RV	Relative Vorticity
RMSE	Root Mean Square Error
ROMS	Regional Ocean Modeling System
RSST	Relative Sea Surface Temperature
RW	Rossby Waves
SBoB	Southern Bay of Bengal
SCRIP	Spherical Coordinate Remapping Interpolation Package
SEAS	Southeastern Arabian Sea
SHF	Sensible Heat Flux
SKE	Surface Kinetic Energy
SLP	Sea Level Pressure
SMC	Summer Monsoon Current
SON	September-October-November
SSH	Sea Surface Height
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
STD	Standard Deviation
SWTIO	Southwestern Tropical Indian Ocean
TCHP	Tropical Cyclone Heat Potential
THF	Turbulent Heat Flux
TKE	Turbulent Kinetic Energy
WMC	Winter Monsoon Current
WRF	Weather Research and Forecast
WBC	Western Boundary Current

NOTATION

English Symbols

T_{cline}	Surface or bottom boundary layer thickness
$V_{stretching}$	Vertical Stretching Function
$V_{transform}$	Vertical transformation Function
P_{DIFF}	Percentage Difference
W_{MR}	Water Vapor Mixing Ratio
K_M	Vertical turbulent eddy viscosity coefficient
K_C	Vertical turbulent eddy diffusivity coefficient
R_d	gas Constant
S_s	Shear component of Strain
S_n	Normal Component of Strain
$X_{e1,e2}$	Euclidean Distance
R^2	Coefficient of determination
KE_g	Geostrophic Kinetic Energy

Greek Symbols

θ_s	Sigma Coordinate surface stretching parameter
θ_b	Sigma Coordinate bottom stretching parameter
θ	Potential Temperature
θ_m	Moist Potential Temperature
θ_e	Equivalent Potential Temperature
ω	Vertical Velocity
γ	heat capacity ratio of dry air
ϕ	Geopotential Height
ξ	Vertical component of relative vorticity
η	Sea Surface Height
μ	Median
σ	Standard Deviation