

STUDY OF OCEANIC MESOSCALE EDDIES IN THE BAY OF BENGAL USING A NUMERICAL MODEL

NAVIN CHANDRA



**CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2025**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2025

Study of Oceanic Mesoscale Eddies in the Bay of Bengal using a Numerical Model

by

NAVIN CHANDRA

Centre for Atmospheric Sciences

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

May 2025

QUOTATIONS

*What we know is a drop,
what we don't know is an ocean.*

- Sir Isaac Newton -

DEDICATION

*Dedicated to my beloved wife, my
parents, and the person who
always inspires me, my elder
brother.*

CERTIFICATE

This is to certify that the thesis entitled "**Study of Oceanic Mesoscale Eddies in the Bay of Bengal using a Numerical Model**", submitted by **Mr. NAVIN CHANDRA**, 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: 16 May, 2025

Prof. Vimlesh Pant
Research Guide
Professor
Centre for Atmospheric Sciences
Indian Institute of Technology Delhi
New Delhi-110016, India

ACKNOWLEDGEMENTS

First and Foremost, I owe an enormous debt of appreciation to Prof. Vimlesh Pant, my supervisor, for having faith in me. He remained there for me each phase of the way as I've worked to finish my thesis, giving encouragement, support, and direction. I was able to improve my research skills thanks to his constant encouragement of creative and independent thinking. He always motivated me to think a step ahead and work harder. He has always supported my career advancement. Engaging with him consistently yields positive effects by clearing the blocked scenario and producing superior scientific results. My research would not have been able to yield such positive outcomes without his constant supervision.

Additionally, I would like to express my deep gratitude to my SRC members: Prof. Krishna Mirle AchutaRao, Prof. A. D. Rao, Prof. Sumedha Chakma, for graciously providing their important suggestions and regularly assessing my progress. I would like to convey my highest regards to Prof. A. D. Rao for his invaluable guidance in enhancing my understanding of research ethics and aptitude through consistently overseeing him.

I express my gratitude to the Head of the Centre for Atmospheric Sciences at IIT Delhi for generously giving all the necessary logistical resources for the successful completion of my research work. I extend my thanks to IIT Delhi for granting me access to their high performance computing (HPC) facility, which was essential for conducting the numerical simulations necessary for my research. Additionally, I would like to express my gratitude to the Ministry of Human Resource and Development, Government of India for granting me a fellowship that allowed me to do my research with a calm and focused mindset.

I convey deep appreciation to my esteemed seniors, Dr. Sandeep K K, Dr. Tanuja Nigam, and Dr. Kumar Ravi Prakash, for their invaluable assistance throughout the initial stages of my doctoral studies. I would like to express my

gratitude to my colleagues from Ocean State Forecasting lab, including Dr. Vivek Seelanki, Dr. Badarvada Yadidya, Mr. Suraj Ravindran, Mr. Kunal Ajit Madkaikar, Mr. Sankar Prasad Lahiri, Mr. Pawan Tiwari, and Ms. Pragnya Makar, Mr. Arun Kumar and Ms. Anna Bella John for maintaining a positive and encouraging work atmosphere inside the lab. I would like to express my gratitude to my friends Dr. Tanvi Gupta, Mr. Amit Kumar Sharma, Mr. Rahul Chaurasia, Dr. Deepak Kumar, Dr. Varunesh Chandra for their unwavering support during the challenging periods of my PhD research.

I would like to express my gratitude to Dr. V. S. Prasad, Director of NCM-RWF, NOIDA, for his unwavering support during my PhD after my appointment as Project Scientist-II. I wish to convey my gratitude for the constant assistance and encouragement from Dr. Abhijit Sarkar, Dr. Raghavendra Ashrit, and Dr. Akhilesh Kumar Mishra my reporting officers at NCMRWF, who facilitated my seamless transfer from academia to an operational environment.

I would want to convey heartfelt gratitude to my life partner, Dr. Barnali Das, for consistently demonstrating unwavering trust in me and always standing by my side. Additionally, I would want to express my gratitude to my parents and family members for their unwavering support and encouragement throughout my doctoral studies. I would want to express my sincere gratitude to my esteemed brother, Dr. Vipin Chandra, for consistently serving as a source of inspiration in my life, encouraging me to always strive for greatness.

Place: New Delhi

Date: 16 May, 2025

Navin Chandra

ABSTRACT

Mesoscale oceanic eddies are a fundamental component of the oceanic circulation system. They play a key role in the process of mixing oceanic tracers, including temperature, salinity, and nutrients. Mesoscale eddies are ubiquitous in the oceans and they have an essential role in facilitating the horizontal and vertical mixing. At any given time, approximately 20% of the global ocean surface is occupied by the eddies. Eddies with positive relative vorticity are referred to as cyclonic eddies (CE), whereas those with negative relative vorticity are known as anticyclonic eddies (AE). In the northern hemisphere, the AE rotates clockwise, while the CE rotates anticlockwise. Mesoscale eddies refer to eddies with a space-scale ranging from 10 to 100 km, whereas submesoscale eddies refer to eddies with a space-scale ranging from 1 km to 10 km. Features with a spatial scale of less than 1 km are referred to as microscale. Mesoscale eddies can have kinetic energy that is ten times higher than the parent current from which they originate. The formation, lifespan, and kinetic energy of these swirling currents are primarily influenced by the intensity of surface currents, the stratification of the ocean, and the bathymetry of the area.

The dynamics of the Bay of Bengal (BoB) is highly complicated. It goes through a semi-annual reversal of monsoon winds leading to significant change in surface circulation. During the winter season, a large clockwise circular formation known as an anticyclonic gyre develops throughout the whole BoB. During the summer, this pattern transforms into an anticlockwise circular pattern known as a cyclonic gyre. During the transition period from summer to winter or vice versa, two counter-rotating gyres forms. The BoB receives a huge amount of freshwater discharge from rivers in the northern part during the monsoon and postmonsoon periods. The dynamics of the BoB is mainly controlled by stratification and the formation of barrier layer (BL) during the monsoon and postmonsoon periods. The surplus freshwater it receives from the rivers is exchanged with the Indian Ocean

(IO) from the south of the BoB with the help of the Indian Monsoon Current (IMC) and the East India Coastal Current (EICC). The BoB dynamics is not only influenced by local forcings but also by forcings generated in the equatorial IO region, e.g., Kelvin Waves (KW) and Rossby Waves (RW). During an Indian Ocean Dipole (IOD) event, an equatorial IO phenomenon, the oscillation of sea surface temperature (SST) influences both the local forcings, e.g., wind and precipitation, and the remote forcings, e.g., KW, RW, and coastally trapped KW. Under the varying IOD conditions, the nature of the forcings also undergoes changes, which in turn impact the circulation and mesoscale activities in the BoB.

The study involves the climatological analysis of the mesoscale oceanic eddies of the BoB using a regional numerical ocean model (ROMS). Using a high-resolution ($\frac{1}{18^\circ} \times \frac{1}{18^\circ}$) Regional Ocean Modelling System (ROMS) output, the mesoscale eddies in the BoB were detected, and their variability was examined. The model results show good agreement with the available observations for different variables on the surface as well as for the subsurface. An investigation is conducted on the seasonal distribution of eddies, examining their geographical characteristics and propagation path. The formation of eddies in the western BoB is dictated by the variability in EICC. In the northern BoB (NBoB) the freshwater discharge from the rivers and bathymetry are important factors in the formation of eddies and their characteristics. Throughout the year, the radius of AEs is consistently larger than that of CEs, with its peak occurring in the pre-monsoon season. AEs exhibit a more pronounced association between their size and energy when compared to CEs. The contribution of mesoscale eddies to the total kinetic energy of the BoB's varies from 7.2% in March to 19.1% in November. The numerical experiments with positive and negative IOD phases of atmospheric forcing reveal the influence of anomalous circulation during IOD years on mesoscale eddies and their kinetic energy in the BoB relative to a normal year. A notable disparity in the eddies' characteristics was observed in both negative IOD (nIOD) and positive IOD (pIOD) years when compared to normal years. In pIOD or nIOD, the number of eddies was increased, but their average lifespan was reduced in the BoB. The increase in eddies was higher (38%) in nIOD than pIOD (11.2%) when compared to normal (non-IOD) years. The contribution of eddies to the total

eddy kinetic energy (EKE) of the BoB increased from about 10% in normal years to about 25% in either of the IOD phases. The most significant impact of the IOD is observed at the thermocline depth. During the IOD years, the Andaman Sea (AdS) region experienced the most significant variations at thermocline depth over eddies' zones.

Oceans acts as the repository for the atmosphere, and the atmospheric motions drives the ocean. To study the effects of oceanic mesoscale eddies on the atmosphere, a fully coupled atmosphere-ocean model (COAWST) was used. The atmospheric columns lying over the AEs and CEs was analyzed for their thermodynamical properties. Model results reveal that the lower atmosphere is highly influenced by the relative vorticity of the oceanic mesoscale eddies. Different variables, such as relative humidity, moist static energy (MSE), water vapor mixing ratio, and equivalent potential temperature in the lower atmosphere, show a significant difference for the air column over AEs and CEs. There is a significant correlation between the relative vorticity of oceanic mesoscale eddies and the atmospheric column over them.

The presence of AEs or CEs modulates ocean heat content over their effective depth in the ocean. This thermal energy significantly contributes to the tropical cyclone heat potential (TCHP) of the ocean, which is crucial for the intensity and longevity of a cyclone whenever it traverses over the AEs or CEs. Presence of AEs in the path of a cyclone can rapidly intensify it and can change its category from severe to very severe in a short time, the vice-versa occurs in case of CEs. To study the role of mesoscale eddies in influencing the intensity and longevity of tropical cyclone, numerical experiments with the coupled model COAWST were performed for the case of FANI cyclone which formed in the BoB on 26 April 2019 and remained active till 5 May 2019. It was a unique tropical cyclone that remained continuously intensified for a long duration in the shallow depth and made landfall in the extremely severe cyclonic storm (ESCS) category. The mean duration for cyclones in the BoB is normally 22 hours but FANI remained in the ESCS category for about 60 hours. The presence of very high tropical cyclone heat potential due to the presence of warm core eddies facilitated high latent heat flux

consistently at the air-sea interface resulting in availability of high MSE leading to prolonged intensified stage of FANI cyclone.

सारांश

मेसोस्केल समुद्री भंवर समुद्री परिसंचरण प्रणाली का एक मूलभूत घटक हैं। वे तापमान, लवणता और पोषक तत्वों सहित समुद्री ट्रेसर के मिश्रण की प्रक्रिया में महत्वपूर्ण भूमिका निभाते हैं। मेसोस्केल भंवर महासागरों में सर्वव्यापी हैं और क्षैतिज और ऊर्ध्वाधर मिश्रण को सुविधाजनक बनाने में उनकी आवश्यक भूमिका है। किसी भी समय, वैश्विक महासागर की सतह का लगभग 20% भाग भँवरों के कब्जे में होता है। सकारात्मक सापेक्ष भंवर वाली भँवरों को चक्रवाती भँवर कहा जाता है, जबकि नकारात्मक सापेक्ष भंवर वाली भँवरों को प्रतिचक्रवाती भँवर कहा जाता है। उत्तरी गोलार्ध में, प्रतिचक्रवाती भंवर दक्षिणावर्त दिशा में घूमते हैं, जबकि चक्रवाती भंवर वामावर्त दिशा में घूमते हैं। मेसोस्केल एडीज़ से तात्पर्य 10 से 100 किमी तक के स्पेस-स्केल वाले एडीज़ से है, जबकि सबमेसोस्केल एडीज़ से तात्पर्य 1 किमी से 10 किमी तक के स्पेस-स्केल वाले एडीज़ से है। 1 किमी से कम स्थानिक पैमाने वाली विशेषताओं को माइक्रोस्केल कहा जाता है। मेसोस्केल भँवरों की गतिज ऊर्जा उस मूल धारा से दस गुना अधिक हो सकती है जिससे वे उत्पन्न होती हैं। इन घुमावदार धाराओं का निर्माण, जीवनकाल और गतिज ऊर्जा मुख्य रूप से सतही धाराओं की तीव्रता, महासागर के स्तरीकरण और क्षेत्र की समतापमापी से प्रभावित होती है।

बंगाल की खाड़ी की गतिशीलता अत्यधिक जटिल है। यह मानसूनी हवाओं के अर्ध-वार्षिक उलटफेर से गुजरती है जिससे सतही परिसंचरण में महत्वपूर्ण परिवर्तन होता है। सर्दियों के मौसम के दौरान, पूरे बंगाल की खाड़ी में एक बड़ी दक्षिणावर्त गोलाकार संरचना विकसित होती है जिसे एंटीसाइक्लोनिक गाइर के रूप में जाना जाता है। गर्मियों के दौरान, यह पैटर्न वामावर्त वृत्ताकार पैटर्न में बदल जाता है जिसे चक्रवाती गाइरे के नाम से जाना जाता है। गर्मियों से सर्दियों या इसके विपरीत संक्रमण काल के दौरान, दो विपरीत-घूर्णी गाइर बनते हैं। मानसून और मानसून के बाद की अवधि के दौरान बंगाल की खाड़ी को उत्तरी भाग की नदियों से भारी मात्रा में मीठे पानी का निर्वहन प्राप्त होता है। बंगाल की खाड़ी की गतिशीलता मुख्य रूप से स्तरीकरण और मानसून तथा मानसूनोत्तर अवधि के दौरान अवरोध परतों के निर्माण द्वारा नियंत्रित होती है। नदियों से प्राप्त अतिरिक्त मीठे पानी को भारतीय मानसून धारा और पूर्वी भारत तटीय धारा की सहायता से बंगाल की खाड़ी के दक्षिण से भारतीय तटीय जल के साथ आदान-प्रदान किया जाता है। बंगाल की खाड़ी की गतिशीलता न केवल स्थानीय दबावों से प्रभावित होती है, बल्कि भूमध्यरेखीय हिंद महासागर क्षेत्र में उत्पन्न दबावों से भी प्रभावित होती है, जैसे केल्विन तरंगों और रॉस्बी तरंगों। हिंद महासागर द्विध्रुवीय घटना के दौरान, भूमध्यरेखीय हिंद महासागर की घटना, समुद्र की सतह के तापमान का उतार-चढ़ाव स्थानीय बलों, जैसे हवा और वर्षा, और दूरस्थ बलों, जैसे केल्विन तरंगों, रॉस्बी तरंगों और तटीय रूप से फंसी केल्विन तरंगों दोनों को प्रभावित करता है। बदलती हिंद महासागर द्विध्रुवीय स्थितियों के तहत, बलों की प्रकृति में भी परिवर्तन होता है, जो बदले में बंगाल की खाड़ी में परिसंचरण और मेसोस्केल गतिविधियों को प्रभावित करता है।

इस अध्ययन में क्षेत्रीय संख्यात्मक महासागर मॉडल (ROMS) का उपयोग करके बंगाल की खाड़ी के मेसोस्केल महासागरीय भंवरो का जलवायु संबंधी विश्लेषण शामिल है। उच्च-रिज़ॉल्यूशन ($\frac{1}{18^\circ} \times \frac{1}{18^\circ}$) क्षेत्रीय महासागर मॉडलिंग प्रणाली (ROMS) आउटपुट का उपयोग करके, बंगाल की खाड़ी में मेसोस्केल भंवर का पता लगाया गया, और उनकी परिवर्तनशीलता की जांच की गई। मॉडल के परिणाम सतह के साथ-साथ उपसतह पर विभिन्न चरों के लिए उपलब्ध अवलोकनों के साथ अच्छे समझौते को दर्शाते हैं। ज्यामितीय और गतिशील दोनों दृष्टिकोणों का उपयोग भंवरो की पहचान करने और उन्हें ट्रैक करने के लिए किया जाता है, जो फ्रंटल जेट को हटाने में सहायता करते हैं। भंवरो के मौसमी वितरण पर एक जांच की जाती है, जिसमें उनकी भौगोलिक विशेषताओं और प्रसार पथ की जांच की जाती है। बंगाल की खाड़ी के पश्चिमी भाग में भंवरो का निर्माण पूर्वी भारत तटीय धारा की परिवर्तनशीलता से निर्धारित होता है। बंगाल की खाड़ी के उत्तरी भाग में नदियों से निकलने वाला ताजा पानी और बैथिमेट्री भंवरो के निर्माण और उनकी विशेषताओं में महत्वपूर्ण कारक हैं। पूरे वर्ष के दौरान, प्रतिचक्रवाती भंवरो की त्रिज्या चक्रवाती भंवरो की तुलना में लगातार बड़ी होती है, और इसका चरम मानसून-पूर्व मौसम में होता है। चक्रवाती भंवरो की तुलना में प्रतिचक्रवाती भंवर अपने आकार और ऊर्जा के बीच अधिक स्पष्ट संबंध प्रदर्शित करते हैं। BoB की कुल गतिज ऊर्जा में मेसोस्केल भंवरो का योगदान मार्च में 7.2% से लेकर नवंबर में 19.1% तक भिन्न-भिन्न है। वायुमंडलीय बल के सकारात्मक और नकारात्मक हिंद महासागर द्विध्रुव चरणों के साथ संख्यात्मक प्रयोगों से हिंद महासागर द्विध्रुव वर्षों के दौरान असामान्य परिसंचरण के प्रभाव का पता चलता है, जो सामान्य वर्ष की तुलना में बंगाल की खाड़ी में मेसोस्केल भंवरो और उनकी गतिज ऊर्जा पर पड़ता है। सामान्य वर्षों की तुलना में नकारात्मक हिंद महासागर द्विध्रुव और सकारात्मक हिंद महासागर द्विध्रुव दोनों वर्षों में भंवरो की विशेषताओं में उल्लेखनीय असमानता देखी गई। सकारात्मक हिंद महासागर द्विध्रुव या नकारात्मक हिंद महासागर द्विध्रुव में, भंवरो की संख्या में वृद्धि हुई, लेकिन BoB में उनका औसत जीवनकाल कम हो गया। सामान्य वर्षों की तुलना में नकारात्मक हिंद महासागर द्विध्रुव में भंवरो में वृद्धि (38%) सकारात्मक हिंद महासागर द्विध्रुव (11.2%) की तुलना में अधिक थी। BoB की कुल भंवर गतिज ऊर्जा में भंवरो का योगदान सामान्य वर्षों में लगभग 10% से बढ़कर हिंद महासागर द्विध्रुव के किसी भी चरण में लगभग 25% हो गया। हिंद महासागर द्विध्रुव का सबसे महत्वपूर्ण प्रभाव थर्मोकलाइन गहराई पर देखा जाता है। हिंद महासागर द्विध्रुव वर्षों के दौरान, अंडमान सागर क्षेत्र ने भंवर क्षेत्रों की तुलना में थर्मोकलाइन गहराई पर सबसे महत्वपूर्ण बदलाव का अनुभव किया। महासागर और वायुमंडल वायु-समुद्र इंटरफेस में विभिन्न गुणों का आदान-प्रदान करते हैं। महासागर वायुमंडल के भंडार के रूप में कार्य करते हैं, और वायुमंडलीय गति महासागर को संचालित करती है। वायुमंडल पर महासागरीय मेसोस्केल भंवरो के प्रभावों का अध्ययन करने के लिए, एक पूरी तरह से युग्मित वायुमंडल-महासागर मॉडल (COAWST) का उपयोग किया गया था। प्रतिचक्रवात भंवरो और चक्रवाती भंवरो के ऊपर स्थित वायुमंडलीय स्तंभों का उनके ऊष्मागतिकीय गुणों के लिए विश्लेषण किया गया। मॉडल के परिणाम बताते हैं कि निचला वायुमंडल महासागरीय मेसोस्केल भंवरो

की सापेक्ष भंवरता से अत्यधिक प्रभावित होता है। विभिन्न चर, जैसे सापेक्ष आर्द्रता, नम स्थैतिक ऊर्जा, जल वाष्प मिश्रण अनुपात और निचले वायुमंडल में समतुल्य संभावित तापमान, एंटीसाइक्लोनिक भँवरों और चक्रवाती भँवरों के ऊपर वायु स्तंभ के लिए एक महत्वपूर्ण अंतर दिखाते हैं।

महासागर और वायुमंडल आपस में अत्यधिक जुड़े हुए हैं और इन्हें स्वतंत्र रूप से कार्य करने वाली इकाई नहीं माना जा सकता है। महासागर वायुमंडल के भंडार के रूप में कार्य करता है, और वायुमंडलीय हलचल महासागर को चलाती है। वायुमंडल पर समुद्री मेसोस्केल भँवरों के प्रभावों का अध्ययन करने के लिए, एक पूर्णतः युग्मित क्षेत्रीय मॉडल (COAWST) का उपयोग किया गया था। प्रतिचक्रवाती भंवर और चक्रवातीय भंवर के ऊपर स्थित वायु स्तंभों का उनके थर्मोडायनामिक गुणों के लिए विश्लेषण किया गया था। यह पता चला है कि निचला वातावरण समुद्री मेसोस्केल भँवरों की सापेक्ष भंवर से अत्यधिक प्रभावित होता है। विभिन्न चर, जैसे कि सापेक्ष आर्द्रता, नम स्थैतिक ऊर्जा, जल वाष्प मिश्रण अनुपात, और निचले वायुमंडल में समतुल्य संभावित तापमान, प्रतिचक्रवाती और चक्रवातीय भंवर पर स्थित वायु स्तंभ के लिए एक महत्वपूर्ण अंतर दिखाते हैं। समुद्री मेसोस्केल भँवरों की सापेक्ष भंवरशीलता और उनके ऊपर स्थित वायुमंडलीय वायु स्तंभ के बीच एक महत्वपूर्ण संबंध है।

प्रतिचक्रवाती भँवरों या चक्रवाती भँवरों की उपस्थिति महासागर में उनकी प्रभावी गहराई पर महासागर की ऊष्मा सामग्री को नियंत्रित करती है। यह ऊष्मीय ऊर्जा महासागर की उष्णकटिबंधीय चक्रवाती ऊष्मा क्षमता में महत्वपूर्ण रूप से योगदान देती है, जो चक्रवात की तीव्रता और दीर्घायु के लिए महत्वपूर्ण है, जब भी यह प्रतिचक्रवाती भँवरों या चक्रवाती भँवरों से होकर गुजरता है। चक्रवात के मार्ग में प्रतिचक्रवाती भँवरों की उपस्थिति उसे तेजी से तीव्र कर सकती है तथा कुछ ही समय में उसकी श्रेणी गंभीर से बहुत गंभीर में बदल सकती है, चक्रवाती भँवरों के मामले में इसके विपरीत होता है। उष्णकटिबंधीय चक्रवात की तीव्रता और दीर्घायु को प्रभावित करने में मेसोस्केल भँवरों की भूमिका का अध्ययन करने के लिए, FANI चक्रवात के मामले में युग्मित मॉडल COAWST के साथ संख्यात्मक प्रयोग किए गए, जो 26 अप्रैल 2019 को बंगाल की खाड़ी में बना और 5 मई 2019 तक सक्रिय रहा। यह एक अनूठा उष्णकटिबंधीय चक्रवात था जो उथली गहराई में लंबे समय तक लगातार तीव्र बना रहा और अत्यंत गंभीर चक्रवाती तूफान की श्रेणी में आया। बंगाल की खाड़ी में चक्रवातों की औसत अवधि सामान्यतः 22 घंटे होती है, लेकिन FANI लगभग 60 घंटे तक अत्यंत गंभीर चक्रवाती तूफान की श्रेणी में रहा। गर्म कोर भँवरों की उपस्थिति के कारण बहुत उच्च उष्णकटिबंधीय चक्रवात ताप क्षमता की उपस्थिति ने वायु-समुद्र इंटरफेस पर लगातार उच्च गुप्त ऊष्मा प्रवाह को सुगम बनाया, जिसके परिणामस्वरूप उच्च आर्द्र स्थैतिक ऊर्जा की उपलब्धता हुई, जिसके कारण FANI चक्रवात की तीव्र अवस्था लंबे समय तक बनी रही।

Contents

ACKNOWLEDGEMENTS	i
ABSTRACT	iii
LIST OF TABLES	xvi
LIST OF FIGURES	xxii
ABBREVIATIONS	xxiii
NOTATION	xxvii
Chapter 1: Introduction.	1
1.1 Introduction	3
1.2 Diversity of the Northern Indian Ocean	4
1.3 Bay of Bengal	6
1.4 Oceanic Mesoscale Eddies	7
1.5 Literature Survey	10
1.5.1 Oceanic Mesoscale Eddy Generation Mechanism	10
1.5.2 Mesoscale Eddy and it's Energy	11
1.5.3 Mesoscale Eddies and Indian Ocean Dipole	13
1.5.4 Mesoscale Eddies and Atmospheric Interaction	16
1.6 Research Gap	18
1.7 Motivation Behind the Study	19
1.8 Research Goals and Objectives	20
1.9 Thesis Outline	20
Chapter 2: Data, Model and Methodology.	23
2.1 Regional Ocean Modeling System (ROMS)	25
2.1.1 The Governing equations of ROMS	26
2.1.2 Vertical Boundary Conditions for ROMS	28
2.1.3 Horizontal Boundary Condition	29

2.1.4	Vertical Coordinate System of ROMS	30
2.1.5	Horizontal Curvilinear Coordinate System	31
2.1.6	ROMS sub-grid scale parameterization	33
2.2	Coupled Ocean Atmosphere Wave Sediment Transport (COAWST) Model	34
2.2.1	The Model Coupling Toolkit (MCT)	35
2.2.2	Spherical Coordinate Remapping Interpolation Package (SCRIP)	35
2.2.3	The Weather Research and Forecasting (WRF) Model .	36
2.2.4	Available Physics schemes in WRF-ARW	40
2.2.4.1	Microphysics	40
2.2.4.2	Cumulus Parameterization	40
2.2.4.3	Planetary Boundary Layer (PBL)	40
2.2.4.4	Land-Surface Model (LSM)	41
2.2.4.5	Atmospheric Radiation	41
2.3	Data	42
2.4	ROMS Model set up	44
2.5	ROMS Model verification	47
2.6	Eddy Detection and Tracking	52
2.7	Different Statistics Used	55
2.7.1	Coefficient of Determination (R^2)	55
2.7.2	Pearson Correlation Coefficient (PCC)	55
2.7.3	Welch's t-test	56
2.8	Summary	57
Chapter 3: Variability of Mesoscale Eddies and their Kinetic Energy in the Bay of Bengal		59
3.1	Introduction	61
3.2	Data and Methodology	63
3.2.1	Numerical Model Configurations	63
3.2.2	Model Verification	64
3.3	Detection and Tracking of Eddies	64
3.4	Results and Discussion	65
3.4.1	Seasonal Mesoscale Eddy Distribution	65

3.4.2	Kinetic Energy of Eddies	72
3.5	Summary	76
Chapter 4: Impact of Indian Ocean Dipole on the Mesoscale eddies in the Bay of Bengal.		79
4.1	Introduction	81
4.2	Data, Model, and Methodology	83
4.2.1	Numerical Model	83
4.2.2	Experiment Design	84
4.2.3	Model validation	85
4.3	Detection and Tracking of Mesoscale Oceanic Eddies	86
4.4	Results and Discussion	86
4.4.1	IOD impact on Eddies	86
4.4.2	Impact of IOD on Surface Kinetic Energy by Eddies	90
4.5	Summary	96
Chapter 5: Role of Oceanic Mesoscale Eddies in Air-Sea Interaction.		97
5.1	Introduction	99
5.2	Influence of Mesoscale Eddies on Atmospheric Column using a coupled Atmosphere-Ocean Model.	103
5.2.1	Data Model and Methodology	103
5.2.1.1	Model Configuration	103
5.2.2	Model Verification	106
5.2.3	Results	110
5.2.3.1	Eddy Detection and Tracking	110
5.2.3.2	Impact of Mesoscale Eddies on Air Column	111
5.3	Role of a Warm Core Eddy in Cyclone Intensification: A Test Case for FANI	118
5.3.1	Model Details and Configuration	118
5.3.2	Verification and Results	119
5.3.2.1	Simulation of Track and Intensity of Fani Cyclone	119
5.3.2.2	Impact of Abnormal Atmospheric and Oceanic Conditions	123

5.4 Summary and Conclusion	128
Chapter 6: Summary, Conclusion and Future Scope of the Work	131
6.1 Summary	133
6.2 Conclusion	134
6.3 Future Scope	136
REFERENCES	139
LIST OF WEBSITES	163
LIST OF PUBLICATIONS	165
CURRICULUM VITAE	167

List of Tables

2.1	Different variables used in the description of ROMS model . . .	26
2.2	Different components of COAWST3.7 model with their respective versions available to be used.	35
2.3	Different datasets used to achieve the objectives of the thesis with their respective source	43
2.4	Different boundary condition used in the ROMS setup for open boundary	45
2.5	Different physical and dynamical scheme/parameter used in ROMS model setup	46
2.6	Statistics of ROMS simulated temperature profile against the daily climatology of RAMA temperature profile	51
2.7	Statistics of ROMS simulated salinity profile against the daily climatology of RAMA salinity profile	52
3.1	Median and standard deviation of eddy radius in km during different seasons	69
3.2	Coefficients of Determination (R^2) and p-value for CEs and AEs during different seasons	73
4.1	Classification of years into normal, positive and negative IOD years based on Bureau of Meteorology Australia (http://www.bom.gov.au/climate/iod/content/years-iod-enso.html), from 1980 to 2018.	84
4.2	Table shows the number of unique detected eddies, the average life in days and eddy day for nIOD year normal years and for pIOD years. The values for eddy day are rounded off to lower integer value.	86
5.1	Important physical and dynamical option used to configure the WRF model. Keyword in brackets shows the namelist.input options.	105
5.2	PCC and RMSE of ROMS Temperature and Salinity against RAMA buoy Temperature and Salinity, at the three locations marked in Figure 5.1 by RB1, RB2, and RB3.	109

5.3	PCC and Root Mean Square Error (RMSE) between WRF wind speed (ms^{-1}) at 10 meter and SLP (hPa) against RAMA wind speed at 10 meters and SLP, at the locations RB1, RB2, and RB3 shown in Figure 5.1.	110
5.4	Welch's t-test results for different atmospheric variables of air column above CEs and AEs.	115
5.5	The PCC and p-value from the Pearson's correlation Test between the relative vorticity (RV) of oceanic mesoscale eddies and the atmosphere lying above them at 10 m height and at PBLH height.	115
5.6	PCC and p-value from Pearson Correlation Test between the relative vorticity (RV) of oceanic mesoscale eddies and the atmosphere lying above at 10m height and at PBLH height.	117

List of Figures

1.1	Map of the IO with the ETOPO2 bathymetry data from NOAA NGDC (Talley et al., 2011).	3
1.2	Major currents in the IO for the surface circulation, depicted schematically The main currents during the Southwest Monsoon (July-August) are depicted in the upper panel, while those during the Northeast Monsoon (January-February) are illustrated in the lower panel. Blue currents do not undergo seasonal reversal, whereas orange surface currents in the upper panel (July-August) reverse direction in accordance with the season in the lower panel (January-February) in green (Phillips et al., 2021).	5
1.3	Schematic 3-D structure of (a) CE (b) AE. Colors represents water temperature (red being the hottest part and blue is the coldest part) (Liu et al., 2021a).	8
1.4	Diagram illustrating the significant oceanic phenomena in relation to the dimensions of space and time (Glenn et al., 2013). . .	9
1.5	The picture illustrates the areas of high EKE in the BoB, depicted by shaded regions. The arrows in the diagram describe the driving mechanisms behind these high EKE zones. The green arrows indicate the major current systems, while the blue line arrows represent the different planetary waves (Chen et al., 2018).	15
1.6	Schematic illustration of the impact of oceanic mesoscale eddies on the atmosphere in the vicinity of the Earth’s surface, namely in the Southern Hemisphere. The Warm Core AE is represented by the red color, whereas the Cold Core CE is represented by the blue color (Frenger et al., 2013).	17
2.1	(a) Horizontal and (b) Vertical Arakawa-C grids. Temperature, salt density, and other tracer parameters are in the middle, while velocity components u , v , and w are along the edges (Skamarock et al., 2019).	33
2.2	Exchange of different data fields among the different components of COAWST model (Li et al., 2022).	34
2.3	Vertical η grid used in WRF. (a) shows the traditional η grid, whereas (b) shows the hybrid η grid (Skamarock et al., 2019)	37
2.4	Model domain and bathymetry(m), in colored scale, derived using ETOPO2v2	44

2.5	Distribution of vertical sigma levels in the model in the entire ocean depth (a), upper 500 m depth (b) along $10^{\circ}N$ latitude	45
2.6	Spatial comparison of simulated ROMS SST ($^{\circ}C$) in the first row and observed NIOA SST ($^{\circ}C$) in the middle row and the difference (ROMS-NIOA) in the lower row. Subplots a, b, c, and d represent ROMS SST for DJF, MAM, JJA, and SON seasons, respectively. Subplots e, f, g, and h represent the NIOA seasonal SST, and subplots i, j, k, and l represent the seasonal bias (ROMS-NIOA).	47
2.7	Spatial comparison of simulated ROMS SSS (psu) in the first row and observed NIOA SSS (psu) in the middle row and the difference (ROMS-NIOA) in the lower row. Subplots a, b, c, and d represent ROMS SSS for DJF, MAM, JJA, and SON seasons, respectively. Subplots e, f, g, and h represent the NIOA seasonal SST, and subplots i, j, k, and l represent the seasonal bias (ROMS-NIOA).	48
2.8	Comparison of simulated surface currents (ROMS) (ms^{-1}) with observed surface currents (OSCAR) (ms^{-1}) on a seasonal basis. Subplots a, b, c, and d represent the DJF, MAM, JJA, and SON seasons from the ROMS output, whereas subplots e, f, g, and h represent observed (OSCAR) seasonal surface currents for the DJF, MAM, JJA, and SON seasons, respectively.	49
2.9	Comparison of ROMS-simulated SSHA (m) with observed (AVISO) SSHA (m) on a seasonal basis. Subplots a, b, c, and d represent the DJF, MAM, JJA, and SON seasons for ROMS output, whereas subplots e, f, g, and h represent the observed (AVISO) SSHA for the DJF, MAM, JJA, and SON seasons, respectively.	50
2.10	Comparison of simulated ROMS temperature ($^{\circ}C$) profile against the long term daily climatology of RAMA buoy data at RB1 ($15^{\circ}N, 90^{\circ}E$), RB2 ($12^{\circ}N, 90^{\circ}E$) and RB3 ($8^{\circ}N, 90^{\circ}E$). Subplots (a), (c), and (e) shows the ROMS data while subplots (b), (d), and (f) shows the RAMA data.	50
2.11	Comparison of simulated ROMS salinity (psu) profile against the long-term daily climatology of RAMA buoy data at RB1 ($15^{\circ}N, 90^{\circ}E$), RB2 ($12^{\circ}N, 90^{\circ}E$) and RB3 ($8^{\circ}N, 90^{\circ}E$). Subplots (a), (c), and (e) show the ROMS data, while subplots (b), (d), and (f) show the RAMA data.	52
3.1	Tracks of mesoscale eddies during different seasons were obtained from the simulation. The red (blue) curves represent the paths of AEs (CEs). The dot indicates the eddy generation point. Panel (a) represents the DJF season, (b) represents the MAM season, (c) represents the JJA season, and (d) represents the SON season. The eddies having a lifespan of minimum 5 days are shown.	65

3.2	Seasonal distribution of mesoscale eddy radius (km).The upper-left is for DJF months, the upper-right is for MAM months, the lower left is for JJA months, and the lower right represents SON months. The red (blue) shaded box represents AEs (CEs). The median value is represented by a horizontal black line inside a box. . . .	68
3.3	The lifespan of detected eddies is represented on the x-axis, while the y-axis shows the number of CE (blue) and AE (red) that fall inside each lifespan bin. The longest living eddy is an AE, whose lifespan is 198 days and is marked in the plot by the arrow. . . .	70
3.4	View of the eddies when they have their largest diameter (in km) during their life cycle. The size of the eddies is shown by the color of the bubble, not by the bubble size. The largest detected eddy is shown inside the black rectangular box.	71
3.5	Eddy radius (km) vs. eddy energy ($\frac{m^2}{s^2}$): a scatter plot for different seasons, CEs (AEs) are shown by the color blue (red). The linear relationship between the eddy radius and the eddy energy is shown by the straight lines.	72
3.6	Monthly percentage of EKE contributed by CEs (AEs) to the overall SKE of the BoB.	74
4.1	Flowchart of the numerical experiments designed to study the impact of IOD on eddies.	84
4.2	The x-axis in the plot represents the uniquely detected eddies in the decreasing order of their lifespan, and the y-axis represents the life of the eddy. Subplots a, b, and c represent the eddy lifespan in decreasing order for nIOD, normal, and pIOD years, respectively.	87
4.3	Comparison of daily detected eddy numbers, total covered surface area(m ²) and total kinetic energy (m^2s^{-2}) possessed by them in subplots a, b and c respectively. The blue color is for negative IOD (nIOD) years, pink for positive IOD (pIOD) years, and black for normal years. The lines are smoothed by 5 day running mean data.	88
4.4	Subplots a, b, and c show the detected eddies having a lifespan of 5 days or higher for normal, nIOD, and pIOD. The blue color represents the AEs tracks, and red represents the CEs tracks. Dots show the eddy generation point, and trails show the path they have traveled during their entire lifespan. Subplots d, e, and f show the maximum radius attained during their lifespan for the corresponding eddies. The colorbar range (in km) shows eddy size and the bubbles are the same size for all of the eddies.	89
4.5	Figure displays the percentage contribution of eddies to the SKE of BoB for AE in subplot a, CE in subplot b, and total (AE+CE) in subplot c. The red color is for the pIOD year, the blue color for the nIOD year, and the black color for the normal year.	90

4.6	EKE at the different depths of the entire BoB. The subplots (a), (b), (c), (d), and (e) represent the EKE at the surface at 50, 100, 150, and 200 meters, respectively. The pink line is for the positive IOD (pIOD) year, black for the normal year and blue for the negative IOD (nIOD) year	91
4.7	Four different regions of BoB shown by different colors. Over these different regions of BoB the P_{DIFF} for EKE was calculated. . .	93
4.8	EKE P_{DIFF} for the pIOD and nIOD years relative to the normal year, varying depth-wise along the y-axis. Subplots (a), (b), (c), (d), and (e) are the P_{DIFF} for the pIOD year computed for the entire year, DJF, MAM, JJA, and SON seasons, respectively. Subplots (f), (g), (h), (i), and (j) show the P_{DIFF} of the nIOD year for the entire year, DJF, MAM, JJA, and SON seasons. The black color represents the complete BoB, red represents the CBoB, blue represents the NBoB, green represents the AdS, and brown represents the SBoB regions shown in Figure 4.7.	94
5.1	The WRF and ROMS domains are shown in Figure. The green and red lines indicate WRF and ROMS domains, respectively. The vertical colorbar shows bathymetry of the ROMS model derived from. Locations of the three RAMA buoys (RB1 , RB2 , and RB3) in the BoB were used to validate the model output.	104
5.2	Different variables are exchanged at the air-sea interface between the ROMS and WRF with the help of MCT.	105
5.3	The Figure displays the bias of the ROMS model's SSS against the European Space Agency's multi-sensor SSS, as well as the bias of the ROMS model's SST against the Global High-Resolution Sea Surface Temperature (GHRSSST) from the UK Met Office. The subplot (a) shows the SSS data from ROMS, (b) the SSS data from ESA, and (c) the difference in SSS between ROMS and ESA (ROMS-ESA). The subplot labelled (d) displays the SST data from ROMS, while the subplot (e) shows the SST data from GHRSSST. Additionally, the subplot labelled (f) illustrates the difference in SST between ROMS and GHRSSST (ROMS-GHRSSST).	107
5.4	Vertical profile of ROMS temperature compared depth wise against the RAMA buoy temperature. The subplot (a), (b) shows the temperature at location RB1 ($15^{\circ}N - 90^{\circ}E$), (c),(d) at RB2 ($12^{\circ}N - 90^{\circ}E$), and (e), (f) at RB3 ($8^{\circ}N - 90^{\circ}E$) from RAMA and ROMS respectively.	108
5.5	Vertical profile of ROMS salinity compared depth wise against the RAMA buoy salinity. The subplot (a), (b) shows the temperature at location RB1 ($15^{\circ}N - 90^{\circ}E$), (c),(d) at RB2 ($12^{\circ}N - 90^{\circ}E$), and (e), (f) at RB3 ($8^{\circ}N - 90^{\circ}E$) from RAMA and ROMS respectively.	109

5.6	Comparison of WRF simulated wind speed (ms^{-1}) at 10m against RAMA buoy wind speed. The subplots (a), (b), and (c) show data at locations RB1 ($15^{\circ}N - 90^{\circ}E$), RB2 ($12^{\circ}N - 90^{\circ}E$), and at RB3 ($8^{\circ}N - 90^{\circ}E$) respectively.	110
5.7	Comparison of WRF simulated SLP (hPa) against RAMA buoy SLP for the location RB1 ($15^{\circ}N - 90^{\circ}E$).	110
5.8	Subplot (a) shows the tracks of detected eddies having a lifespan of at least 5 days. The AEs are shown in red, and the CEs are shown in blue. Dots show the generation point of eddies, whereas trails show the path they have traveled during their lifespan. The subplot (b) shows the maximum radius (km) of eddies shown in the subplot (a), attained during their entire lifespan.	111
5.9	The average of the vertical profiles of atmospheric variables above 384 (536) AE (CE) profiles shown in red (blue) color. Subplot (a) shows RH in %, (b) shows θ_e in K , and (c) shows MSE in $\frac{kJ}{kg}$. The subplots (d), (e), and (f) shows the difference of the average profiles (AEs-CEs) shown in (a), (b), and (c) respectively.	112
5.10	Subplot (a) shows the comparison of CAPE (Jkg^{-1}) distribution of AE's and CE's, whereas subplot (b) shows the comparison between CIN (Jkg^{-1}).	113
5.11	Comparison of W_{MR} ($kgkg^{-1}$) at PBLH height in subplot (a) and at 2m height in subplot (b).	114
5.12	Comparison in the distribution of PW (kgm^{-2}) above CEs and AEs.	114
5.13	PCC between the relative vorticity (RV) of oceanic mesoscale eddies and the atmosphere lying above them at 10 m height and at PBLH height. Texts in red color show the value for the PCC and p-value (p) from PCC test.	116
5.14	A comparison of Pearson correlation tests between RVs of AEs and CEs with MSE, RH at 1000 hPa, and PW for the entire air column. The text in red shows the PCC and p-value (p) from the Pearson Correlation Test.	117
5.15	Model domains of atmospheric (WRF) and ocean (ROMS) models. The outermost boundary shows the outer domain of the WRF model. The inner movable domain of the WRF model is shown with a dashed line. The ROMS model domain is shown with a continuous line with shades representing ocean bathymetry (m).	118
5.16	Model computed Fani cyclone track (00 UTC on 29 April to 00 UTC 3 May) along with IMD best-track. Locations of buoys are marked with different symbols and colors. The light blue circle represents the cone of uncertainty at different hours from IMD data.	120

5.17	Comparison of model simulation (red) and observed (black) wind speed (a,b) (m/s) and SLP pressure (c,d) (hPa) at buoys BD11 and BD13 (buoy locations marked in Figure 5.16)	121
5.18	Comparison of SST ($^{\circ}C$) simulated by model (red) against drifting buoy measured (black). The location of the drifting buoy is marked in Figure 5.16	121
5.19	(a) Sea level anomaly (m) from AVISO climatology, (b) standard deviation of sea level anomaly (m) for April calculated from AVISO data, (c) sea level anomaly on 29 April 2019 overlay with OSCAR current vectors and IMD best-track of cyclone Fani, (d) OSCAR current vectors and IMD best-track with intensity (knots) shown in color shades. The black dots marked with A, B, C, D, E in panel (c) highlight the locations where the cyclone enters into or exits from a CE or AE	122
5.20	(a) Standard deviation of tropical cyclone heat potential (TCHP in $\frac{kJ}{cm^2}$) during April for the period of 2008–2018, (b) climatological TCHP ($\frac{kJ}{cm^2}$) calculated for the 2008–2018 period for 25 April–10 May, (c) TCHP during the passage of Fani cyclone over the BoB (25–28 April 2019).	124
5.21	Model-simulated moist static energy ($kJkg^{-1}$) over the locations A, B, C, D, E (marked in Figure 5.19) in panels (a-e), respectively.	125
5.22	Model-simulated daily wind shear gradient (Nm^{-2}) (850-300 hPa) at 00 GMT each day for 29 April to 4 May 2019, during the passage of cyclone Fani over the BoB.	126
5.23	Model-simulated daily latent heat flux (Wm^{-2}) at 00 GMT each day for 29 April to 4 May 2019, during the passage of cyclone Fani over the BoB.	126
5.24	Time series of model-simulated profiles of temperature ($^{\circ}C$) at locations A, B, C, D, and E (marked in Figure 5.15 shown in panels (a-e)), respectively. Stratification (buoyancy frequency) computed from model data at points A, B, C, D, and E is shown in panels (f-j), respectively.	127

ABBREVIATIONS

ACC	Antarctic Circumpolar Current
AdS	Andaman Sea
AE	Anticyclonic Eddy
AEs	Anticyclonic Eddies
AI	Andaman Island
AS	Arabian Sea
BL	Barrier Layer
BoB	Bay of Bengal
BOMA	Bureau of Meteorology, Australia
CAPE	Convective Available Potential Energy
CBoB	Central Bay of Bengal
CC	Correlation Coefficient
CE	Cyclonic Eddy
CEs	Cyclonic Eddies
COAWST	Coupled Ocean-Atmosphere Wave Sediment Transport Model
CIN	Convective Inhibition
DJF	December-January-February
EKE	Eddy Kinetic Energy
EPE	Eddy Potential Energy
EICC	East India Coastal Current
ENSO	El Nino Southern Oscillation
IO	Indian Ocean
IOD	Indian Ocean Dipole
IMC	Indian Monsoon Current
ISM	Indian Summer Monsoon
JJA	June-July-August
KPP	K-Profile Parameterization

KW	Kelvin Wave
LSM	Land Surface Model
LFC	Level of Free Convection
LHF	latent Heat Flux
MAM	March-April-May
MCT	Model Coupling Toolkit
MLD	Mixed Layer Depth
MSE	Moist Static Energy
NBoB	Northern Bay of Bengal
NEC	North Equatorial Current
NIOA	North Indian Ocean Atlas
ON	October-November
PBL	Planetary Boundary Layer
PCC	Pearson Correlation Coefficient
PW	Precipitable Water
RAMA	Research Moored Array for African-Asian-Australian
RH	Relative Humidity
RV	Relative Vorticity
RMSE	Root Mean Square Error
ROMS	Regional Ocean Modelling System
RW	Rossby Waves
SBoB	Southern Bay of Bengal
SCRIP	Spherical Coordinate Remapping Interpolation Package
SHF	Sensible Heat Flux
SKE	Surface Kinetic Energy
SLP	Sea Level Pressure
SMC	Summer Monsoon Current
SNR	Signal to Noise Ratio
SON	September-October-November
SSH	Sea Surface Height
SSHA	Sea Surface Height Anomaly
SST	Sea Surface Temperature

SSS	Sea Surface Salinity
TCHP	Tropical Cyclone Heat Potential
THF	Turbulent Heat Flux
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