

VARIABILITY OF INTERNAL WAVES IN THE ANDAMAN SEA

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**CENTRE FOR ATMOSPHERIC SCIENCES
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VARIABILITY OF INTERNAL WAVES IN THE ANDAMAN SEA

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DEDICATION

To my family

THESIS CERTIFICATE

This is to certify that the thesis entitled “**Variability of Internal Waves in the Andaman Sea**”, submitted by **Mr. Badarvada Yadidya**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is an original bonafide record of the research work done by him under our guidance and supervision. He has fulfilled the requirements for the submission of this thesis. 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.

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ABSTRACT

The Andaman Sea in the Indian Ocean is known for the presence of large-amplitude Internal waves (IW). Internal tides (ITs) are IWs of tidal frequency whose temporal variability is unknown in this region. Therefore, we used *in-situ* observations collected at (10.5°N, 94°E) from March 2017 to February 2018. The analysis shows that the kinetic energy of semidiurnal ITs is dominant to that of diurnal ITs by a factor of 4–5. The ellipticity of both semidiurnal and diurnal motions is dominated by rectilinear zonal flow, indicating generation at the slopes of the Andaman and Nicobar islands. Maximum isopycnal displacement reached 46 *m* for semidiurnal ITs. The semidiurnal ITs displayed significant seasonal variability — stronger in summer and autumn but weaker in spring and winter, whereas the diurnal ITs are relatively stronger in summer and winter. Furthermore, salinity plays a dominant role in controlling the near-surface stratification, whereas the temperature variations control the subsurface stratification. This led to the formation of a strong double pycnocline during autumn and winter. Baroclinic coherent semidiurnal (diurnal) variance accounts for 49% (27%) of the semidiurnal (diurnal) motions.

Furthermore, we explored the interannual variations of the internal wave activity in this complex region. We found that the Dipole Mode Index, which represents the Indian Ocean Dipole, influences the circulation in the Andaman Sea, which in turn impacts its density stratification on interannual scales. Ocean Reanalysis System 5 data (1993–2018) is used to see an increasing trend in the sub-surface stratification, whereas

it showed a decreasing trend in the near-surface waters.

We used a global climate model (CanESM5) to investigate the long-term variability of internal waves in the Andaman Sea under a range of shared socioeconomic pathway (SSP) scenarios. SSPs are future societal development pathways related to emissions and land use scenarios. We project that mean values of depth-averaged stratification will increase by approximately 6% (SSP1-2.6), 7% (SSP2-4.5), and 12% (SSP5-8.5) between 1871-1900 and 2081-2100.

Model simulations carried out for March, June, September, and December of 2017 using the Massachusetts Institute of Technology General Circulation Model showed significant seasonal variability in the generation and dissipation of IT. The isopycnal displacement near the generation sites is about 88 *m*. The experiments suggest that the presence of the Andaman Nicobar Ridge contributes nearly 89% to the total IT generation. Numerical model simulations carried out from 2009 to 2018 have shown that the interannual variability in the generation of semidiurnal internal tides is governed by distinct parameters (tidal forcing and stratification) at different sites in different months. Enhanced upwelling (downwelling) is observed during positive (negative) IOD events. Sensitivity experiments conducted between extreme IOD events (2006 and 2016) revealed an increase in internal tide generation from positive IOD to negative IOD. Furthermore, a sharp decrease in local baroclinic dissipation is seen during negative IOD, increasing baroclinic flux into the Andaman Sea. An increase in the strength of positive IOD could lead to enhanced diapycnal mixing due to strong local dissipation, whereas an increase in the intensity of negative IOD could result in amplified propagation of internal waves. Simulating changes in internal tides between the present (2005-2014) and the end-century (2091-2100), we find that the increase in stratification will enhance

internal tide generation by approximately 4 to 8%. We project that the propagation of internal tides into the Andaman Sea and the Bay of Bengal will increase by 8 to 18% and 4 to 19%, respectively, under different SSP scenarios. Such changes in internal tides under global warming will have implications for primary production and ecosystem health not only in the Andaman Sea but also in the Bay of Bengal.

The changes in the physical properties of the ocean on a diurnal scale primarily occur in the surface mixed layer and the pycnocline. Price–Weller–Pinkel model, which modifies the surface mixed layer, and the internal wave model based on Garrett–Munk spectra that calculates the vertical displacements due to internal waves are coupled to simulate the diurnal variability in temperature and salinity, and thereby density profiles. The coupled model is used to simulate the hourly variations in density at RAMA buoy (15° N, 90° E), in the central Bay of Bengal, and at BD12 (10.5° N, 94° E), in the Andaman Sea. The simulations are validated with the *in-situ* observations from December 2013 to November 2014. The primary advantage of this model is that it could simulate spatial variability as well. An integrated model is also tested and validated by using the output of the 3D model to initialize the coupled model during January, April, July, and October. The 3D model can be used to initialize the coupled model at any given location within the model domain to simulate the diurnal variability of density. The simulations showed promising results which could be further used in simulating the acoustic fields and propagation losses which are crucial for Navy operations.

KEYWORDS: Internal Waves; Internal Tides; Andaman Sea; Internal tide energetics; Indian Ocean Dipole; Climate change; Corals.

सार

हिंद महासागर में अंडमान सागर बड़े आयाम वाली आंतरिक तरंगों (IWs) की उपस्थिति के लिए जाना जाता है। आंतरिक ज्वार (आईटी) ज्वारीय आवृत्ति के IW हैं जिनकी अस्थायी परिवर्तनशीलता इस क्षेत्र में अज्ञात है। इसलिए, हमने मार्च 2017 से फरवरी 2018 तक (10.5° N, 94° E) पर एकत्र किए गए इन-सीटू अवलोकनों का उपयोग किया। विश्लेषण से पता चलता है कि सेमीडायरनल आईटी की गतिज ऊर्जा 4-5 के कारक द्वारा दैनिक आईटी पर हावी है। अंडमान और निकोबार द्वीप समूह के ढलानों पर जनन का संकेत देते हुए अर्धदैनिक और दैनिक गति दोनों की दीर्घवृत्तीयता में सरलरेखीय क्षेत्रीय प्रवाह का प्रभुत्व है। सेमीडायरनल आईटी के लिए अधिकतम समस्थानिक विस्थापन 46 मीटर तक पहुंच गया। अर्धदैनिक आईटी ने महत्वपूर्ण मौसमी परिवर्तनशीलता प्रदर्शित की - गर्मियों और शरद ऋतु में मजबूत लेकिन वसंत और सर्दियों में कमजोर, जबकि गर्मियों और सर्दियों में दैनिक आईटी अपेक्षाकृत मजबूत होते हैं। इसके अलावा, लवणता निकट-सतह स्तरीकरण को नियंत्रित करने में एक प्रमुख भूमिका निभाती है, जबकि तापमान भिन्नता उपसतह स्तरीकरण को नियंत्रित करती है। इससे शरद ऋतु और सर्दियों के दौरान एक मजबूत डबल पाइक्नोक्लाइन का निर्माण हुआ। बैरोक्लिनिक सुसंगत अर्धदैनिक (दैनिक) विचरण अर्धदैनिक (दैनिक) गतियों के 49% (27%) के लिए होता है।

इसके अलावा, हमने इस जटिल क्षेत्र में आंतरिक तरंग गतिविधि की पारस्परिक विविधताओं का पता लगाया। हमने पाया कि डिपोल मोड इंडेक्स, जो हिंद महासागर डिपोल (आईओडी) का प्रतिनिधित्व करता है, अंडमान सागर में संचलन को प्रभावित करता है, जो इसके घनत्व स्तरीकरण को इंटरएनुअल स्केल पर प्रभावित करता है। महासागर पुनर्विश्लेषण प्रणाली 5 डेटा (1993-2018) का उपयोग उप-सतह स्तरीकरण में बढ़ती प्रवृत्ति को देखने के लिए किया जाता है, जबकि इसने निकट-सतह जल में घटते रुझान को दिखाया।

साझा सामाजिक आर्थिक मार्ग (SSP) परिदृश्यों की एक श्रृंखला के तहत अंडमान सागर में आंतरिक तरंगों की दीर्घकालिक परिवर्तनशीलता की जांच के लिए हमने एक वैश्विक जलवायु मॉडल (CanESM5) का उपयोग किया। एसएसपी उत्सर्जन और भूमि उपयोग परिदृश्यों से संबंधित भावी सामाजिक विकास मार्ग हैं। हमारा अनुमान है कि 1871-1900 और 2081-2100 के बीच गहराई-औसत स्तरीकरण के मूल्यों में लगभग 6% (SSP1-2.6), 7% (SSP2-4.5), और 12% (SSP5-8.5) की वृद्धि होगी।

मैसाचुसेट्स इंस्टीट्यूट ऑफ टेक्नोलॉजी जनरल सर्कुलेशन मॉडल का उपयोग करके 2017 के मार्च, जून, सितंबर और दिसंबर के लिए किए गए मॉडल सिमुलेशन ने आईटी के उत्पादन और अपव्यय में महत्वपूर्ण मौसमी परिवर्तनशीलता दिखाई। उत्पादन स्थलों के पास समस्थानिक विस्थापन लगभग 88 मीटर है। प्रयोगों से पता चलता है कि अंडमान निकोबार रिज की उपस्थिति कुल आईटी उत्पादन में लगभग 89% का योगदान करती है। 2009 से 2018 तक किए गए संख्यात्मक मॉडल सिमुलेशन ने दिखाया है कि अर्धदैनिक आंतरिक ज्वार की पीढ़ी में अंतर परिवर्तनशीलता अलग-अलग महीनों में अलग-अलग साइटों पर अलग-अलग मापदंडों (ज्वारीय बल और स्तरीकरण) द्वारा नियंत्रित होती है। सकारात्मक (नकारात्मक) आईओडी घटनाओं के दौरान बढ़ी हुई अपवेलिंग (डाउनवेलिंग) देखी जाती है। चरम आईओडी घटनाओं (2006 और 2016) के बीच किए गए संवेदनशीलता प्रयोगों ने सकारात्मक आईओडी से नकारात्मक आईओडी तक आंतरिक ज्वार उत्पादन में वृद्धि का खुलासा किया। इसके अलावा, नकारात्मक आईओडी के दौरान स्थानीय बैरोक्लिनिक अपव्यय में तेज कमी देखी जाती है, जिससे अंडमान सागर में बैरोक्लिनिक प्रवाह बढ़ जाता है। सकारात्मक आईओडी की ताकत में वृद्धि से मजबूत स्थानीय अपव्यय के कारण डायपाइकल मिश्रण में वृद्धि हो सकती है, जबकि नकारात्मक आईओडी की तीव्रता में वृद्धि के परिणामस्वरूप आंतरिक तरंगों का प्रवर्धित प्रसार हो सकता है। वर्तमान (2005-2014) और अंत-शताब्दी (2091-2100) के बीच आंतरिक ज्वार में

परिवर्तन का अनुकरण करते हुए, हम पाते हैं कि स्तरीकरण में वृद्धि से आंतरिक ज्वार उत्पादन में लगभग 4 से 8% की वृद्धि होगी। हमारा अनुमान है कि विभिन्न एसएसपी परिदृश्यों के तहत अंडमान सागर और बंगाल की खाड़ी में आंतरिक ज्वार का प्रसार क्रमशः 8 से 18% और 4 से 19% तक बढ़ जाएगा। ग्लोबल वार्मिंग के तहत आंतरिक ज्वार में इस तरह के बदलाव का न केवल अंडमान सागर में बल्कि बंगाल की खाड़ी में भी प्राथमिक उत्पादन और पारिस्थितिकी तंत्र के स्वास्थ्य पर प्रभाव पड़ेगा।

दैनिक पैमाने पर महासागर के भौतिक गुणों में परिवर्तन मुख्य रूप से सतह मिश्रित परत और पाइक्नोक्लाइन में होता है। प्राइस-वेलर-पिंकल मॉडल, जो सतह मिश्रित परत को संशोधित करता है, और गैरेट-मंक स्पेक्ट्रा पर आधारित आंतरिक तरंग मॉडल जो आंतरिक तरंगों के कारण ऊर्ध्वाधर विस्थापन की गणना करता है, तापमान और लवणता में दैनिक परिवर्तनशीलता को अनुकरण करने के लिए युग्मित किया जाता है, और इस प्रकार घनत्व प्रोफाइल युग्मित मॉडल का उपयोग बंगाल की केंद्रीय खाड़ी में RAMA buoy (15° N, 90° E), और अंडमान सागर में BD12 (10.5° N, 94° E) पर घनत्व में प्रति घंटा भिन्नताओं का अनुकरण करने के लिए किया जाता है। सिमुलेशन दिसंबर 2013 से नवंबर 2014 तक इन-सीटू टिप्पणियों के साथ मान्य हैं। इस मॉडल का प्राथमिक लाभ यह है कि यह स्थानिक परिवर्तनशीलता का भी अनुकरण कर सकता है। जनवरी, अप्रैल, जुलाई और अक्टूबर के दौरान युग्मित मॉडल को आरंभ करने के लिए 3डी मॉडल के आउटपुट का उपयोग करके एक एकीकृत मॉडल का परीक्षण और सत्यापन भी किया जाता है। 3डी मॉडल का उपयोग घनत्व के दैनिक परिवर्तनशीलता को अनुकरण करने के लिए मॉडल डोमेन के भीतर किसी दिए गए स्थान पर युग्मित मॉडल को आरंभ करने के लिए किया जा सकता है। सिमुलेशन ने आशाजनक परिणाम दिखाए जिनका उपयोग ध्वनिक क्षेत्रों और प्रसार हानियों को अनुकरण करने में किया जा सकता है जो नौसेना के संचालन के लिए महत्वपूर्ण हैं।

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ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
ADCP	Acoustic Doppler Current Profiler
ANR	Andaman Nicobar Ridge
ASAR	Advanced Synthetic Aperture Radar
CFL	Courant–Friedrichs–Lewy condition
CMIP	Coupled Model Intercomparison Project Phase
cph	cycles per hour
CTD	Conductivity-Temperature-Depth
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ENVISAT	Environmental Satellite
EOF	Empirical Orthogonal Functions
EOS	Equation of State
ERS	European Remote Sensing satellite
GC	Great Channel
GEBCO	General Bathymetric Chart of the Oceans
GM	Garrett-Munk spectra/model
HPC	High Performance Computing
IOD	Indian Ocean Dipole

ITs	Internal Tides
IWs	Internal Waves
K₁	Diurnal solar
KPP	K-profile parameterization
M₂	Principal lunar semidiurnal
MITgcm	Massachusetts Institute of Technology general circulation model
MPI	Message Passing Interface
MY82	Mellor and Yamada, 1982
NEAS	North East Andaman Sea
nIOD	negative Indian Ocean Dipole
NIOT	National Institute of Ocean Technology
O₁	Diurnal lunar
OMNI	Ocean Moored Buoy Network for northern Indian Ocean
ORAS	Ocean Reanalysis System
PC	Preparis Channel
pIOD	positive Indian Ocean Dipole
POM	Princeton Ocean Model
PP81	Pacanowski and Philander, 1981
RCP	Representative Concentration Pathway
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
RMSE	Root Mean Square Error
ROMS	Regional Ocean Modeling System
S₂	Principal solar semidiurnal

SAR	Synthetic Aperture Radar
SC	Sombrero Channel
SEAS	South East Andaman Sea
SSP	Shared Socioeconomic Pathway
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SUNTANS	Stanford Unstructured Non-hydrostatic Terrain-following Adaptive Navier-Stokes Simulator
TDC	Ten Degree Channel
TPXO	TOPEX/Poseidon global tidal model
XBT	eXpendable BathyThermograph