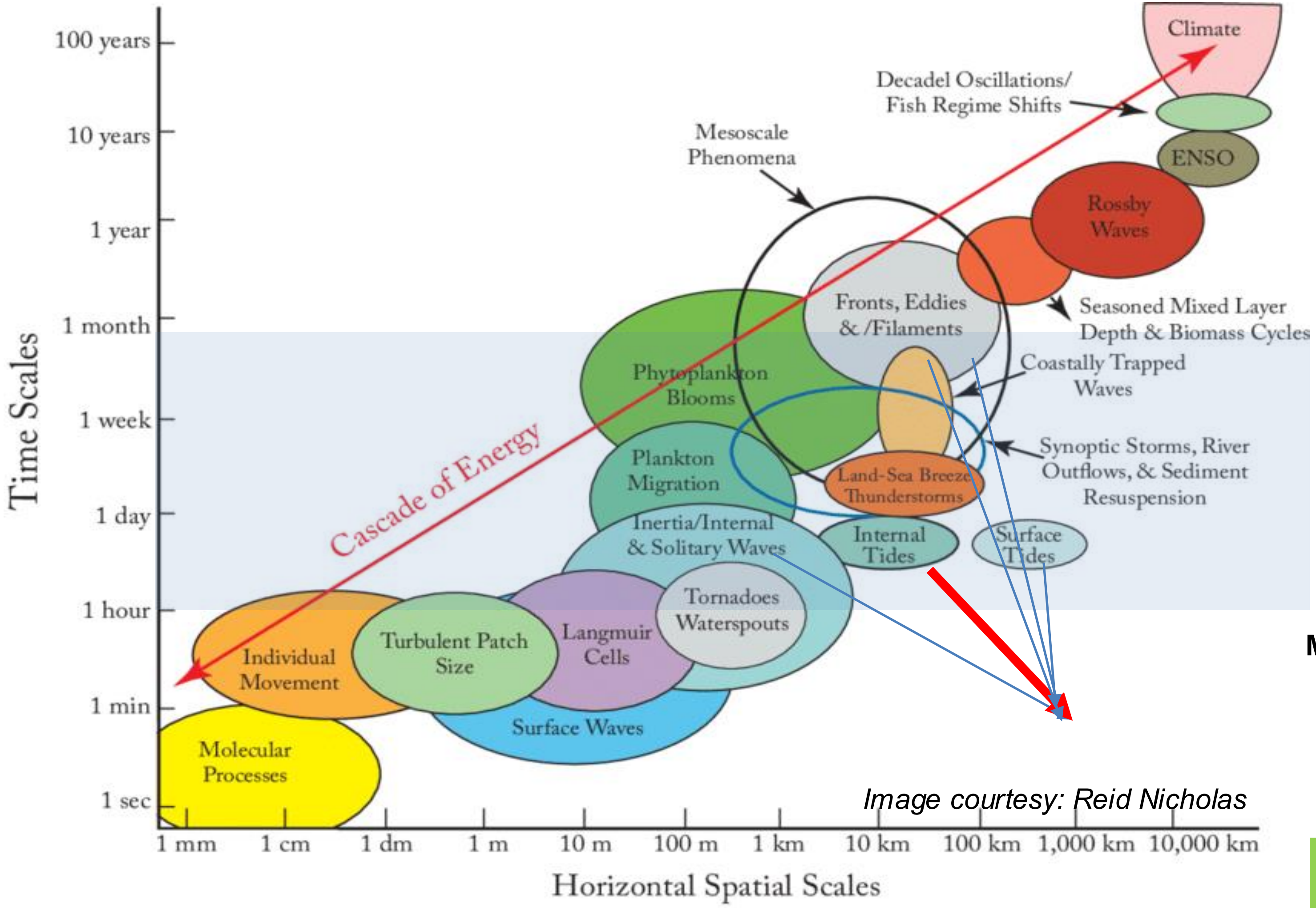


Image courtesy: Reid Nicholas

Dickey and Bidigare, 2005

Global and Seasonal Ocean Predictions for Tropical Area

Francis P. A.

Indian National Centre for Ocean Information Services

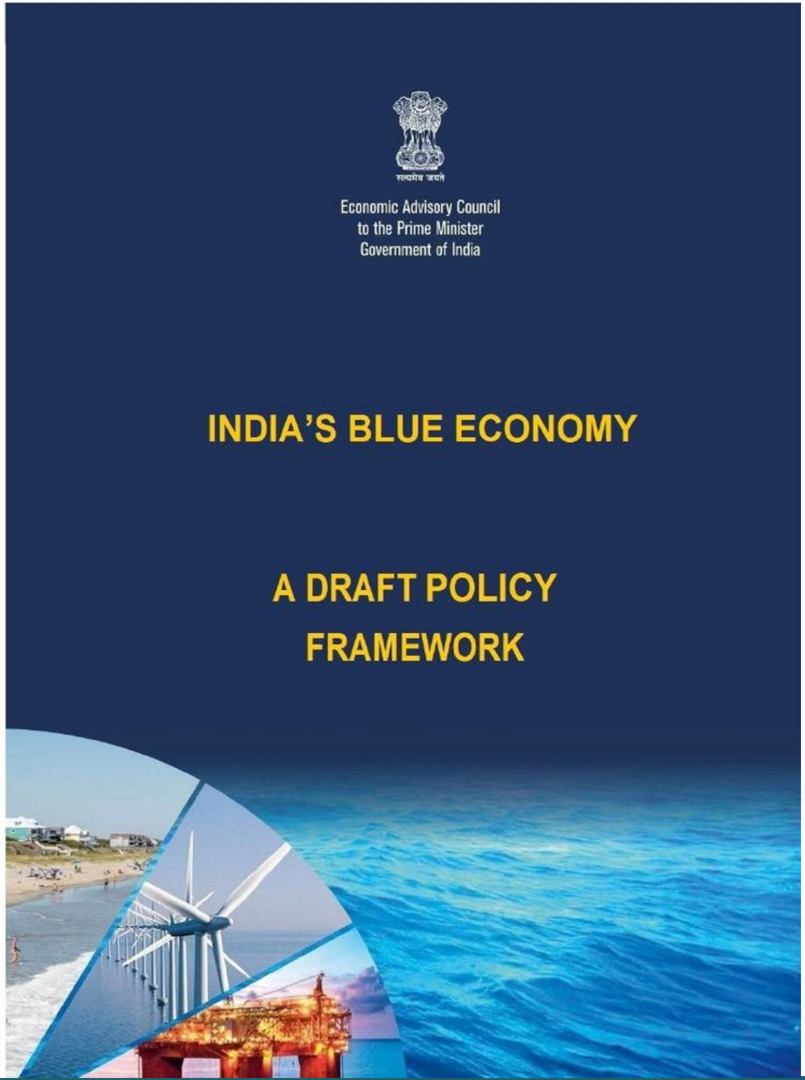
Ministry of Earth Sciences, Govt. of India.

Hyderabad-500090

DBCP Workshop, INCOIS

6th August 2025

The Oceans



- Worldwide, most of the economic and commercial activities in the ocean happen in the coastal waters (territorial waters of EEZs).
- In India 95% of the total volume of transport happens through sea route
- Proposed growth in the contribution of Blue Economy to the Indian GDP is above 10% from the present 4%.
- Pradhan Mantri Matsya Sampata Yojana, Sagarmala Project, Deep Ocean Mission etc.


The two most sought out forecasts are for the waves and the currents.



OceanPredict

Advancing the science of ocean prediction

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The Ocean at your fingertips

Our planet is a place of many wonders with the ocean being one of the largest, covering over 70% of the Earth's surface. Most of human life is located along the continent's coastlines, and people use the ocean in many different ways from fishing to transport, energy production to recreation.

Keeping the ocean healthy is essential for all and requires first and foremost knowledge of its status and functioning. OceanPredict is an international network and science programme that facilitates knowledge exchange between scientists and experts of operational oceanography from around the world to accelerate, strengthen and increase the impact of ocean prediction.

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cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici

INDOFOS

INCOIS

KIOST KOREA INSTITUTE OF OCEAN SCIENCE & TECHNOLOGY

Korea Hydrographic and Oceanographic Agency

MERCATOR OCEAN INTERNATIONAL

NMEFC

NOAA

REMO

NERSC NANSEN ENVIRONMENTAL AND REMOTE SENSING CENTER THE NANSEN CENTER · BERGEN · NORWAY

For more details on each of these systems, please visit https://oceanpredict.org

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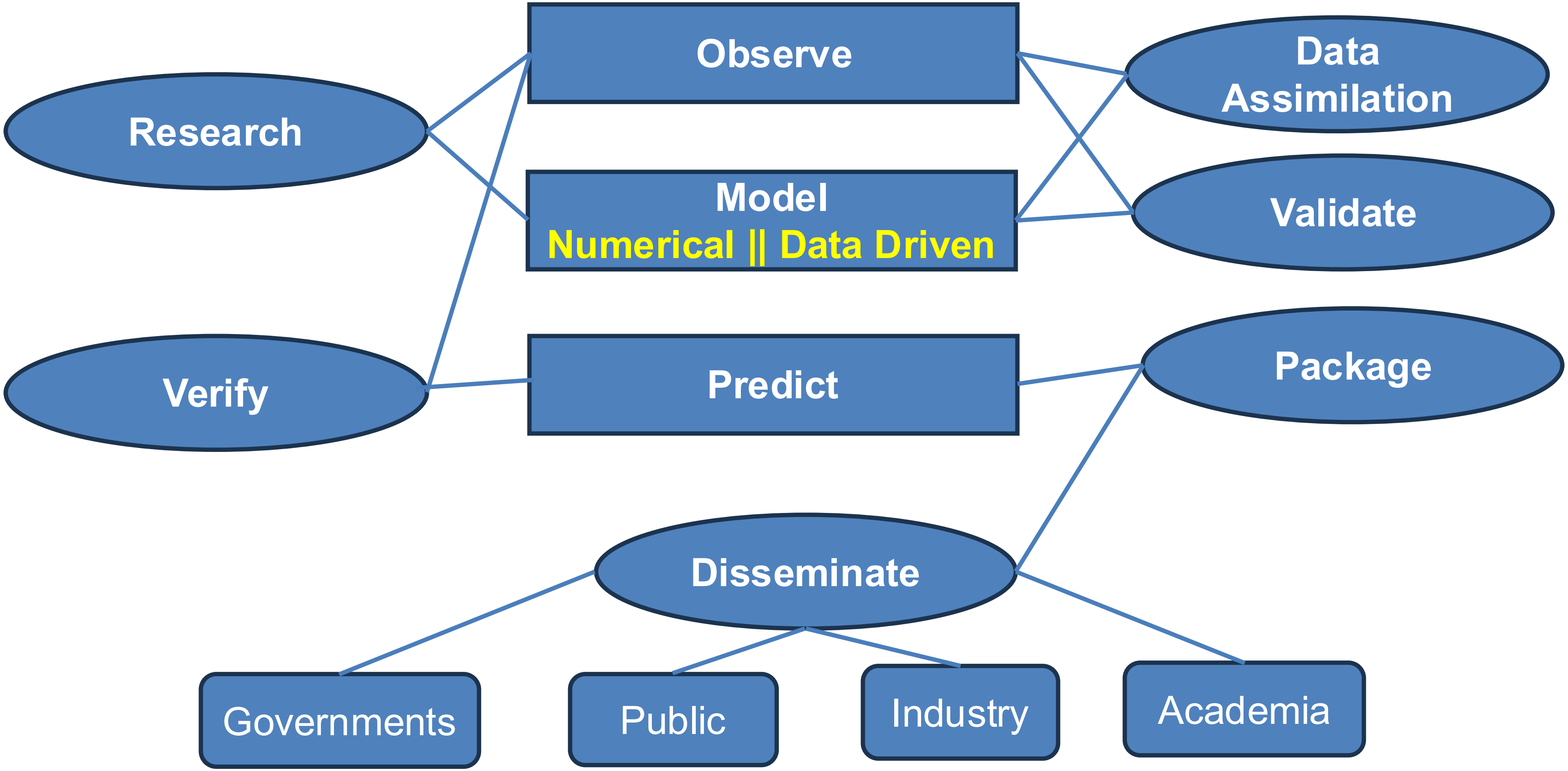
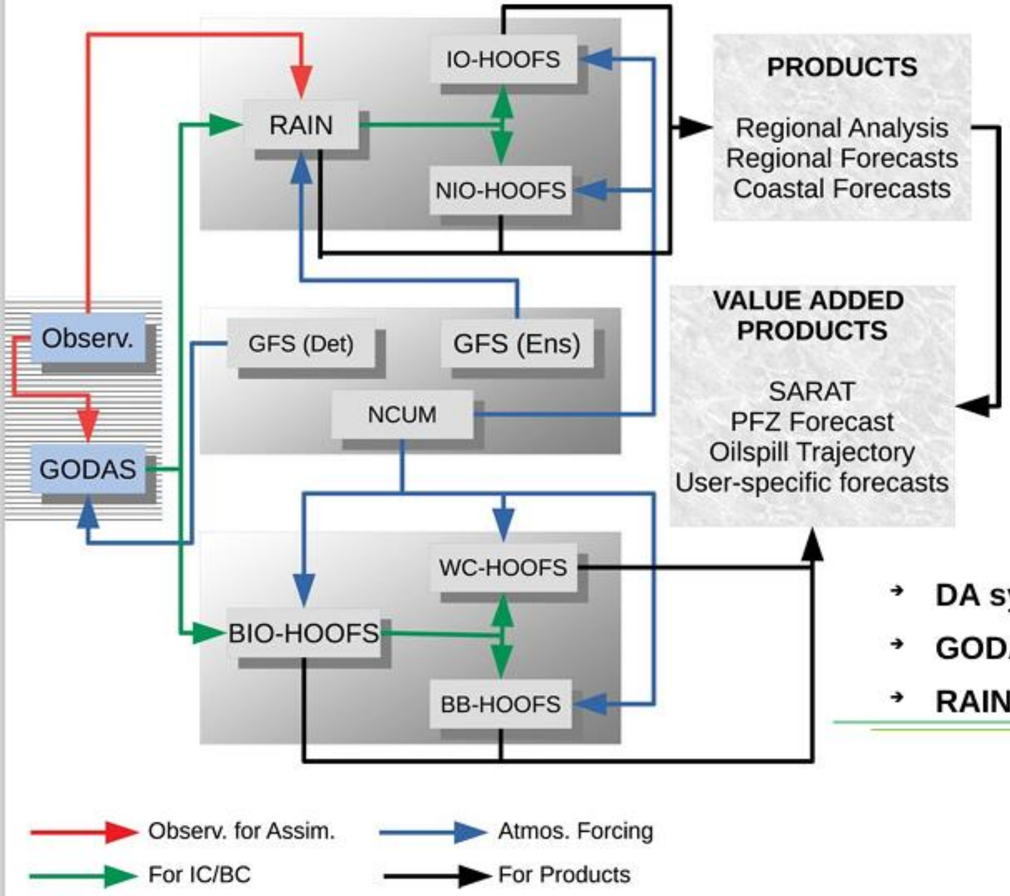
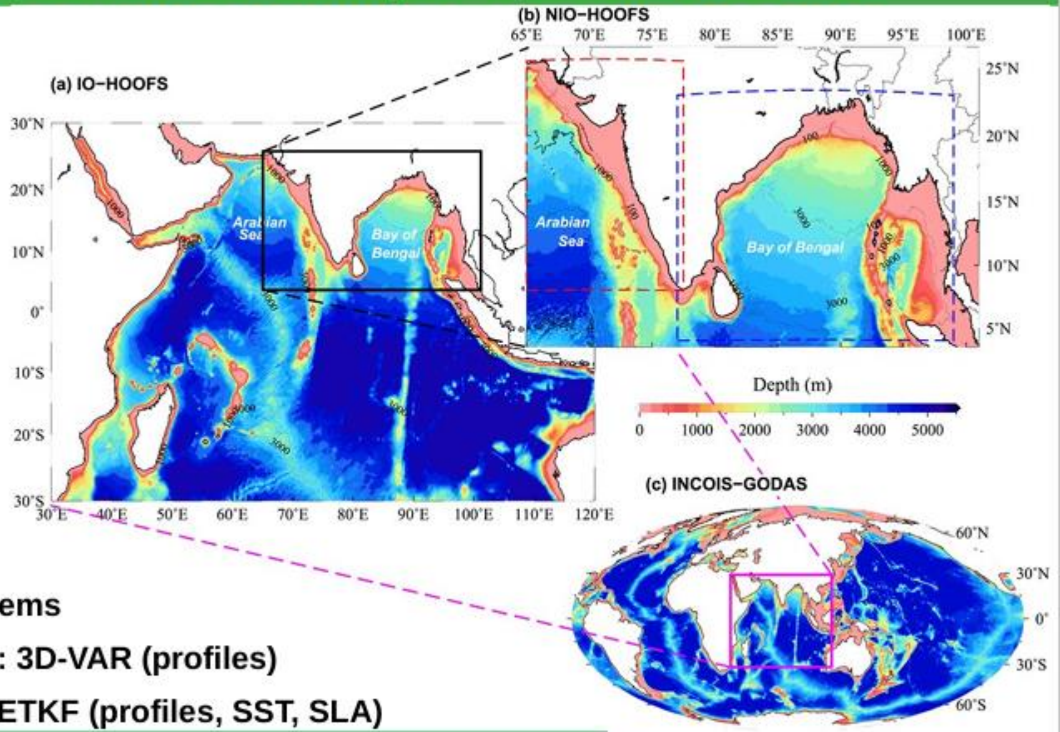
Operational Value Chain in Oceanography



Highresolution Operational Ocean Forecast and Reanalysis System-Overview





- DA systems
- GODAS: 3D-VAR (profiles)
- RAIN: LETKF (profiles, SST, SLA)

BAMS Article

High-Resolution Operational Ocean Forecast and Reanalysis System for the Indian Ocean

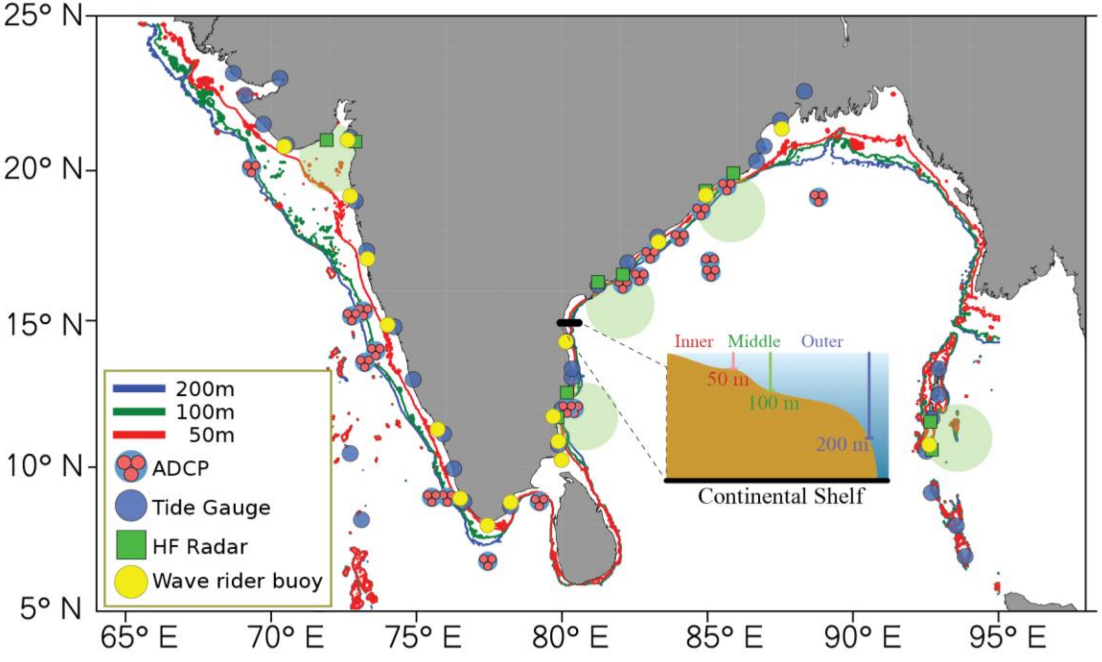
P. A. Francis, A. K. Jithin, J. B. Effy, A. Chatterjee, K. Chakraborty, A. Paul, B. Balaji, S. S. C. Shenoi, P. Biswamoy, A. Mukherjee, P. Singh, B. Deepsankar, S. Siva Reddy, P. N. Vinayachandran, M. S. Girish Kumar, T. V. S. Udaya Bhaskar, M. Ravichandran, A. S. Unnikrishnan, D. Shankar, A. Prakash, S. G. Aparna, R. Harikumar, K. Kaviyazhahu, K. Suprit, R. V. Shesu, N. Kiran Kumar, N. Srinivasa Rao, K. Annapurnaiah, R. Venkatesan, A. S. Rao, E. N. Rajagopal, V. S. Prasad, M. D. Gupta, T. M. Balakrishnan Nair, E. P. R. Rao, and B. V. Satyanarayana

INCOIS
INDOFOS

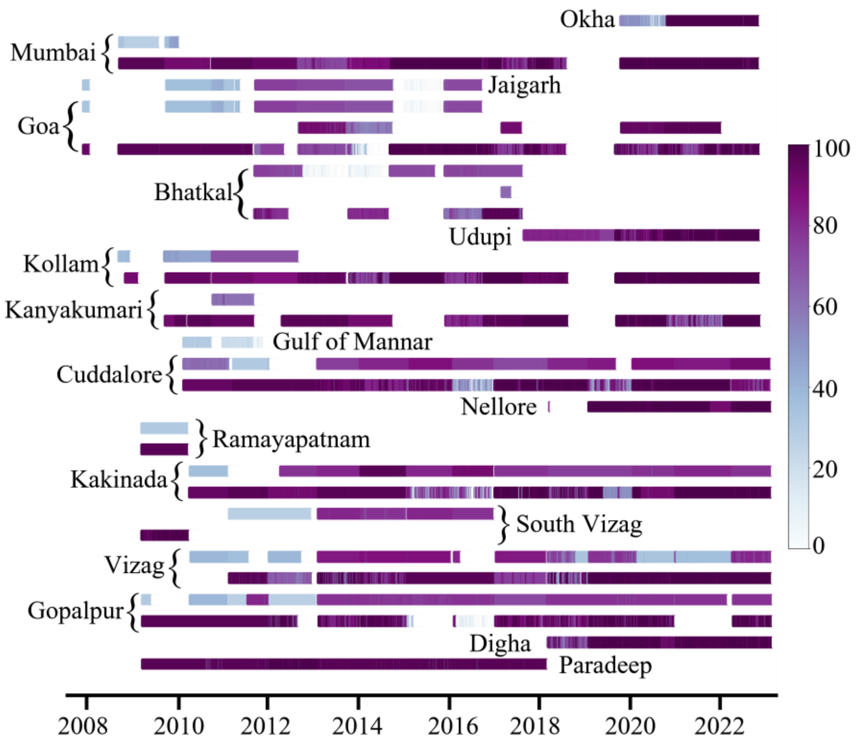
- **GODAS- Global Ocean Data Assimilation System**
- **RAIN- Regional Analysis for Indian Ocean**
- **HOOFS: High-resolution Operational Ocean Forecast System**

Observe

Available observational platforms along the Indian subcontinent



Acoustic Doppler Current Profiler (ADCP) Data Availability (%)

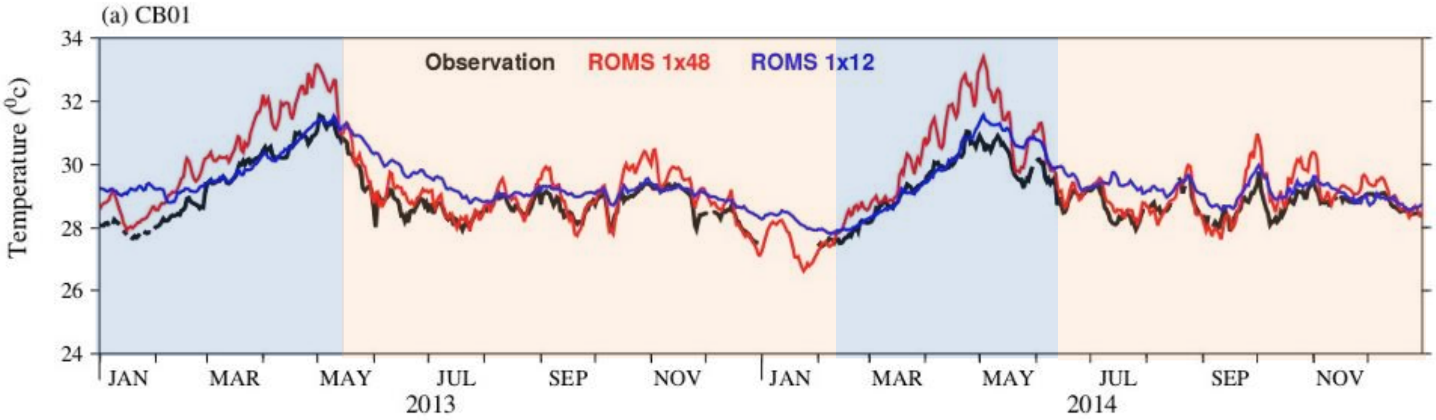


India has a coastline of ~ 11,098 km!

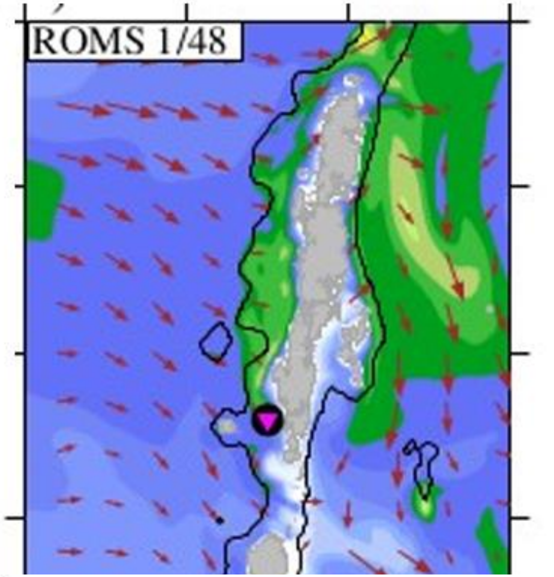
Coastal ADCPs provide extremely valuable long-term data of coastal circulation.

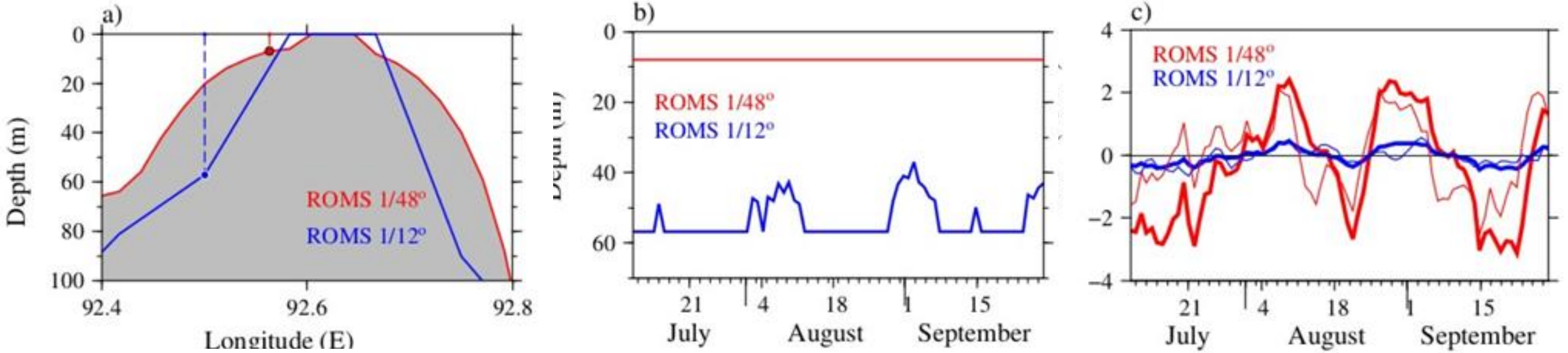
Thanks: Krishnapriya, Rohith

Model



Variation of 3m temperature at CB01 location (west of Andaman island)



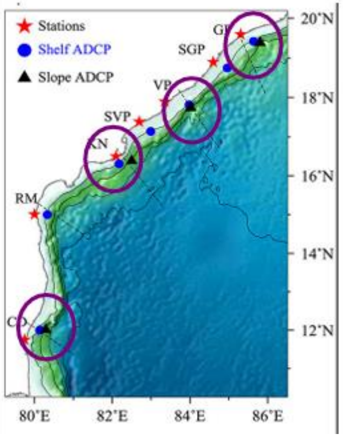


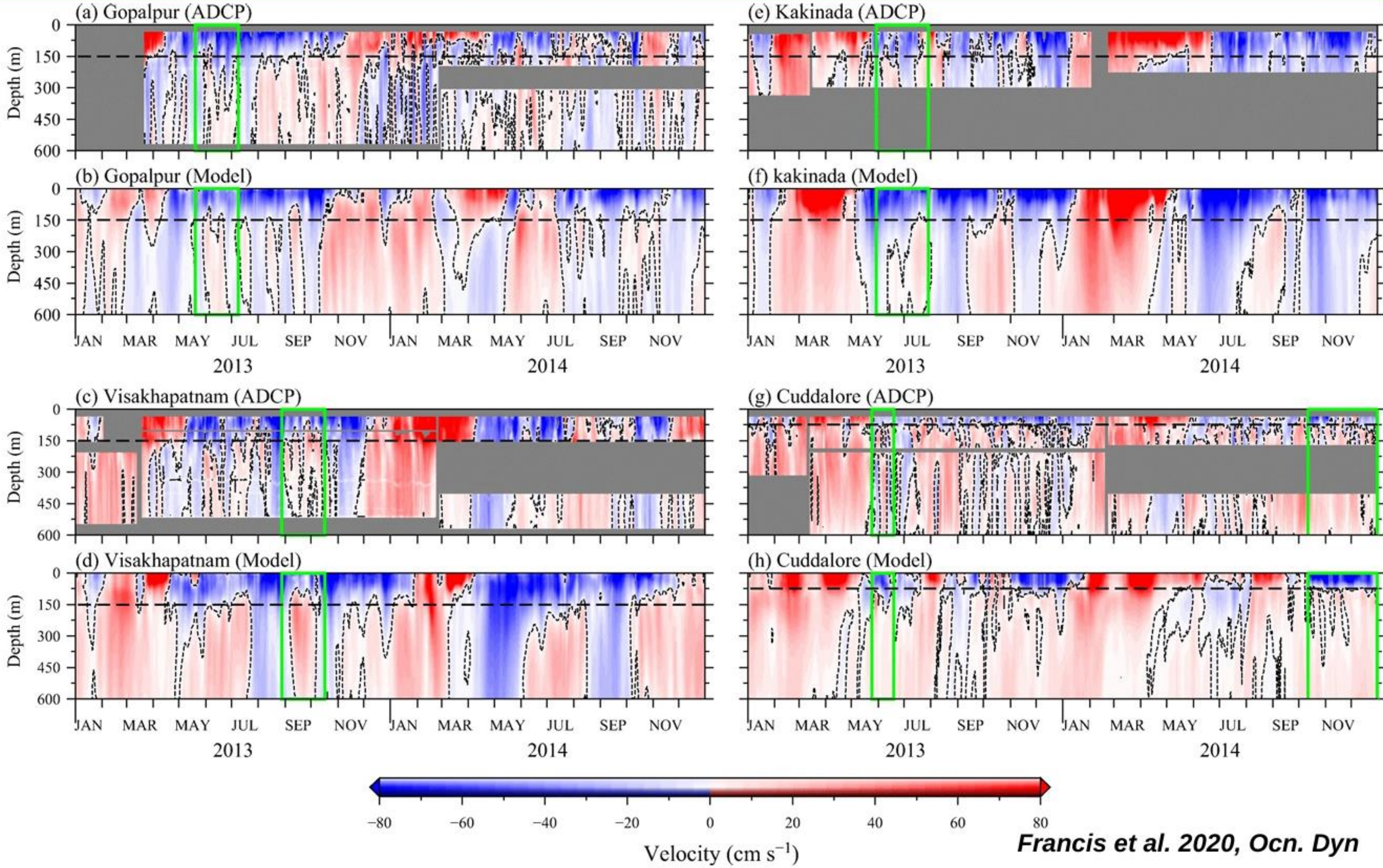
Jithin et al. 2025

Model

Presence of strong undercurrents in a direction opposite to the surface flow are observed all along the east coast of India.

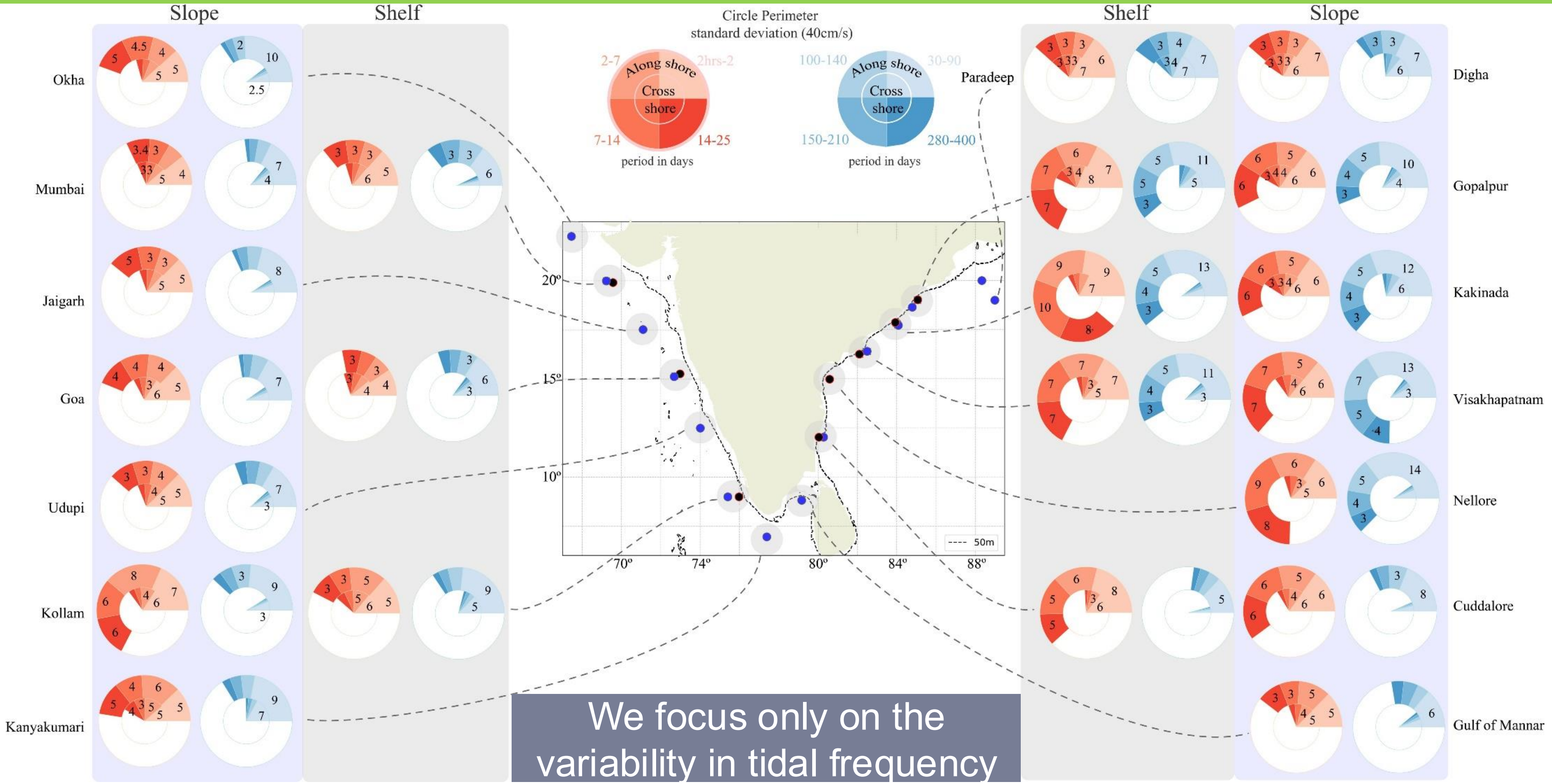
In general the reversal of flow takes place between 75-150m depth





Francis et al. 2020, Ocn. Dyn

Variability in coastal currents



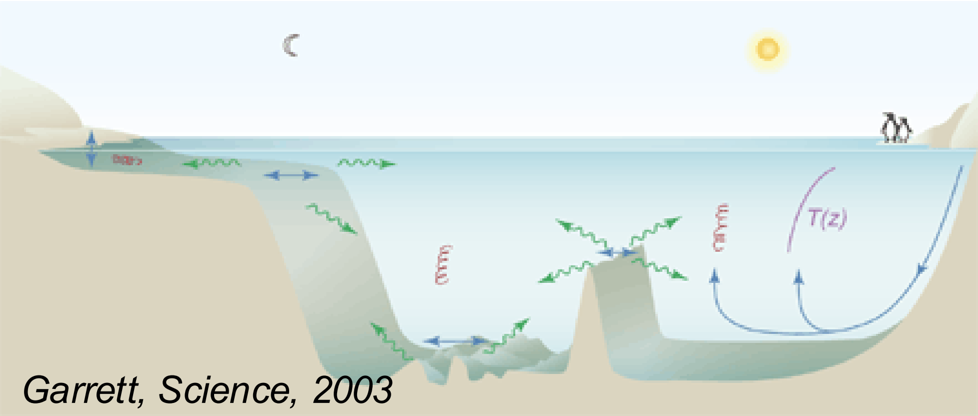
We focus only on the variability in tidal frequency

Krishnapriya

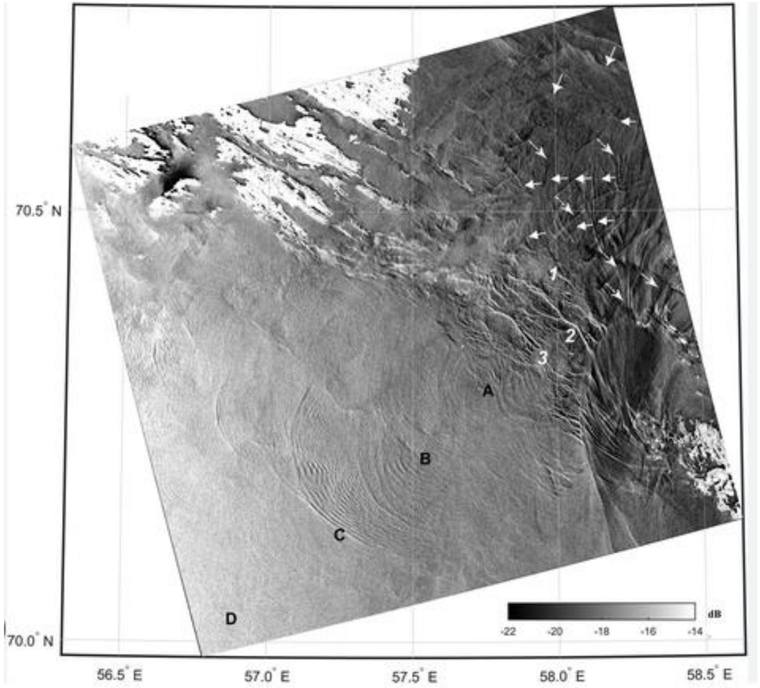
High-frequency variation in coastal currents are as strong as low-frequency variability

Internal Tides in the Ocean

- In a stratified ocean, periodic flow of barotropic tidal currents over topographic features such as continental slopes and ridges generate oscillations of isopycnal surfaces.
- One way to conceptualize this generation is to imagine that, instead of a tidally oscillating ocean with a fixed bottom, the water of the ocean is fixed and the bottom oscillates with tidal frequency. The oscillations of topography then behave as oscillating wave makers
- These oscillations having periodicity of that of tides are called internal tides.
- In other words, internal tides are internal waves (baroclinic) in tidal frequency that are generated by barotropic tides.
- Once generated, they propagate into far away distances.



Garrett, Science, 2003



Morozov 2018

Importance of Internal Waves in the Ocean

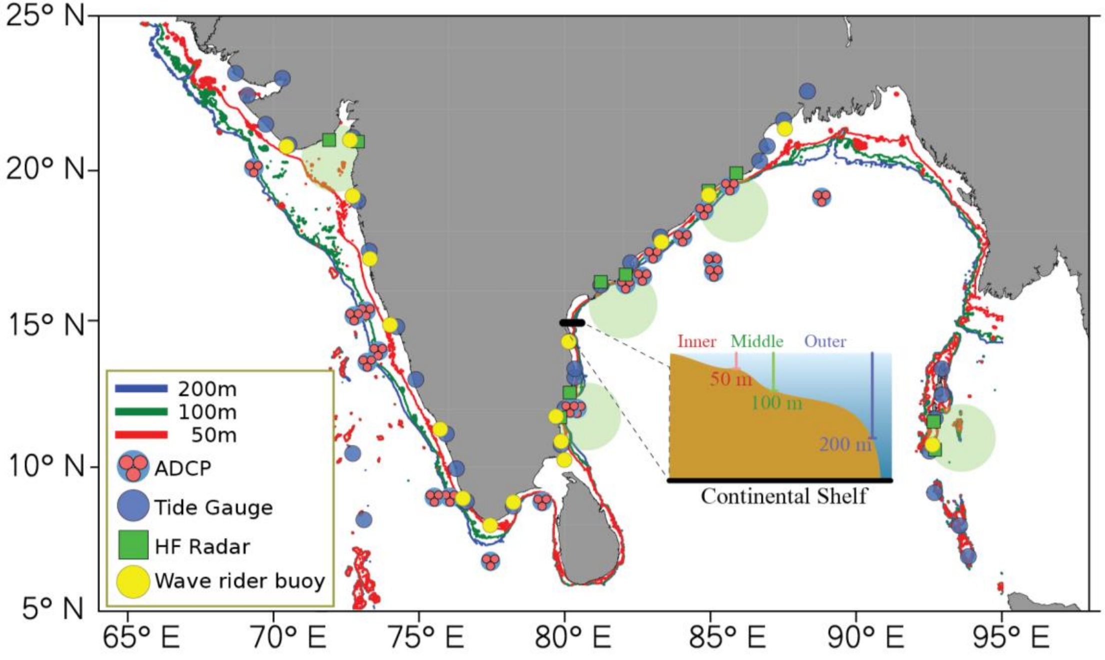
Satellite imagery shows alernating dark and light bands of smooth and rough waters formed at the ocean surface by an internal wave propagating deeper in the depths.

Internal waves on continental shelves are important because they can attain large amplitudes and affect

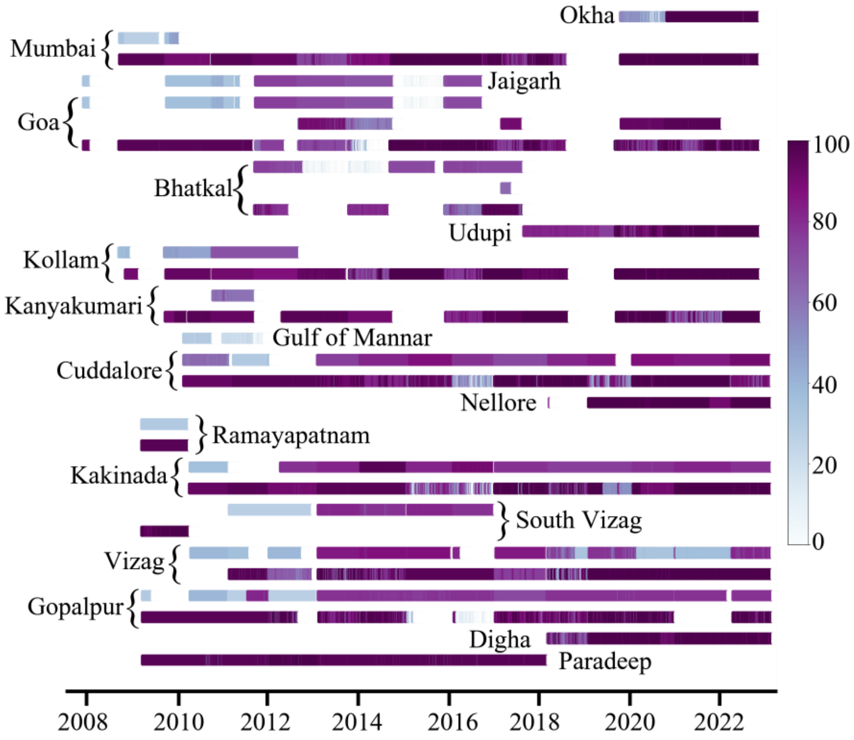
- acoustic wave propagation,
- submarine navigation,
- nutrient mixing to the euphotic zone,
- sediment resuspension,
- Cross-shore pollutant transport,
- coastal engineering, and oil exploration

Observe

Available observational platforms along the Indian subcontinent

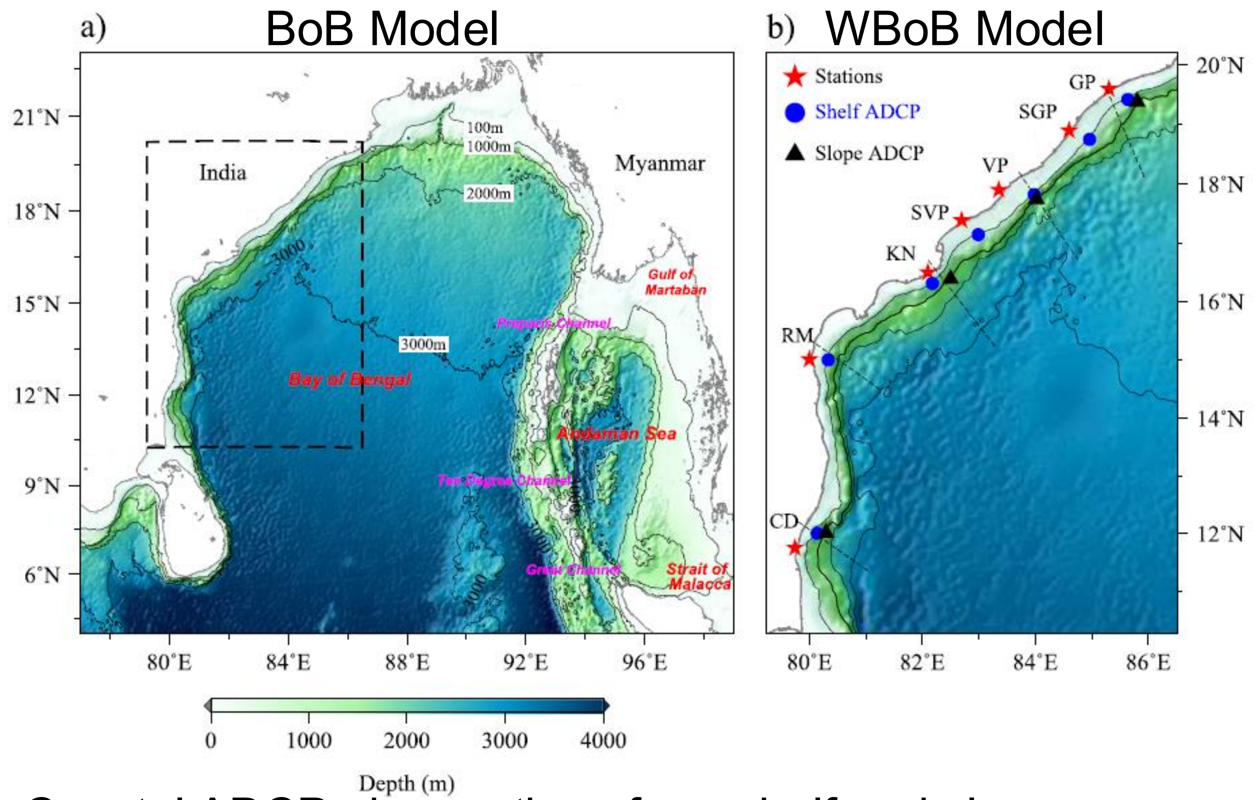


Percentage of data for Acoustic Doppler Current Profiler (ADCP)



Krishnapriya

• Data

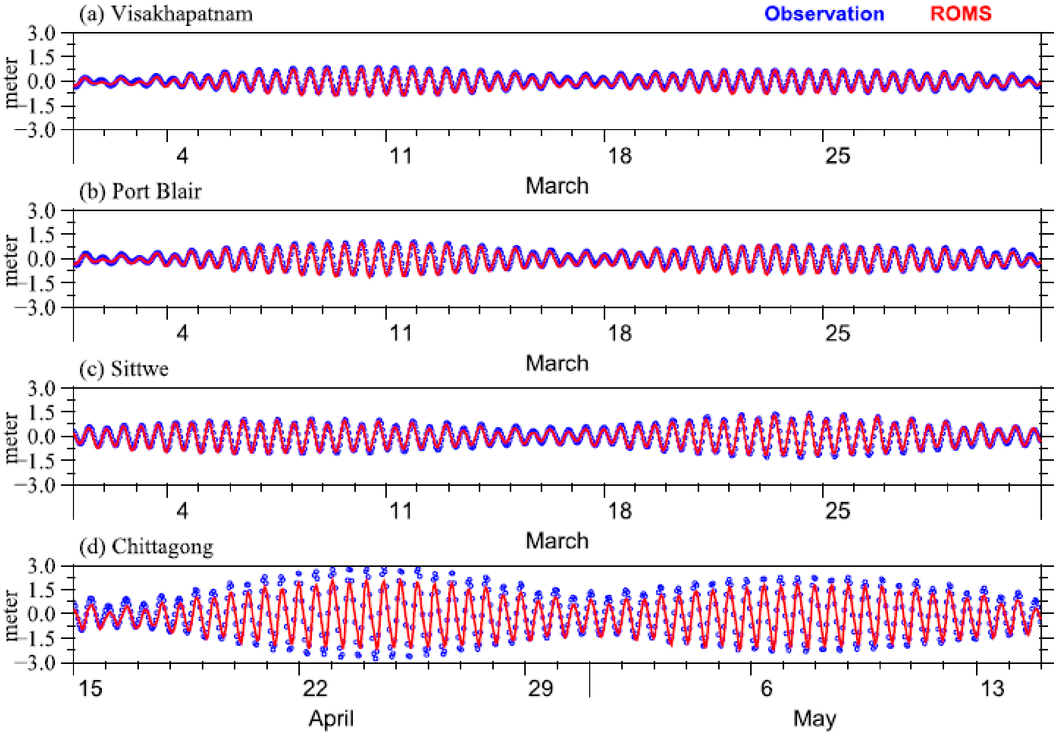


- Coastal ADCP observations from shelf and slope
- Temp/Salt profiles from Argo
- Altimeter data (SSH)
- BoB/Western BoB ROMS simulations (2.25km res.)

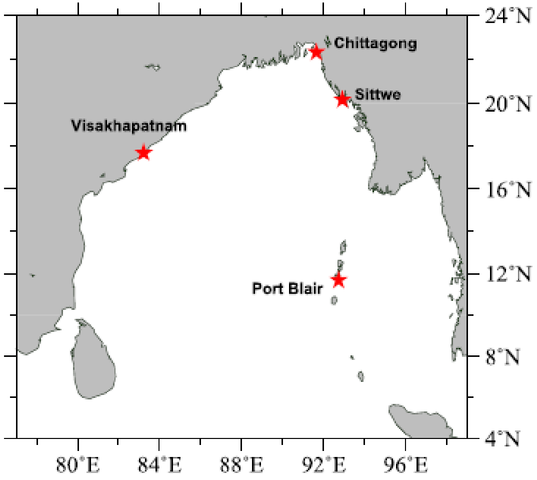
Model Configuration

- BoB configuration of ROMS has open boundary conditions at south (daily mean taken from IO configuration of ROMS with 1/12 degree resolution)
- WBoB configuration of ROMS has open boundary conditions at south and east (daily mean taken from BoB ROMS)
- 10 tidal constituents forced at the boundaries
- Forced with 3-hourly atmospheric fields
- Outputs saved at hourly interval
- SSS relaxed to monthly climatology
- KPP mixing scheme
- Period of integration 2010-2016.

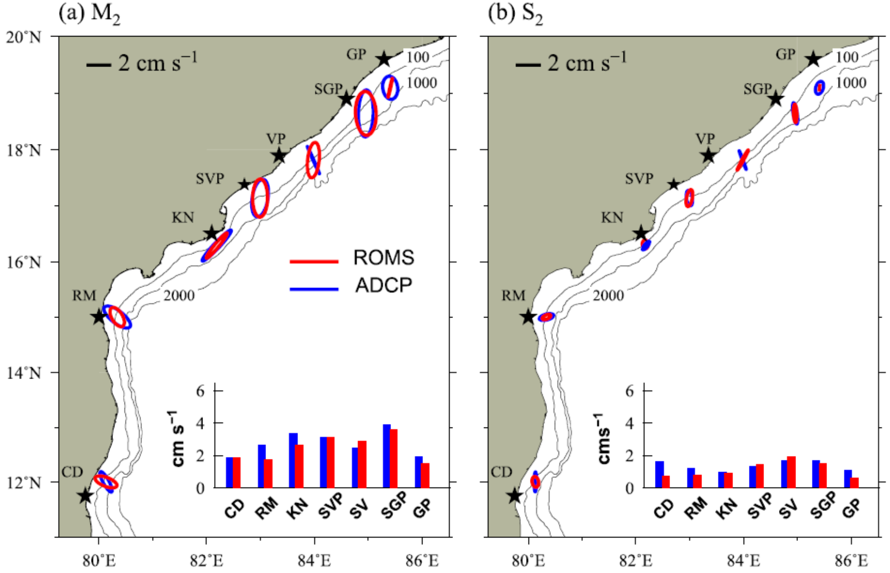
• Validation of model simulations



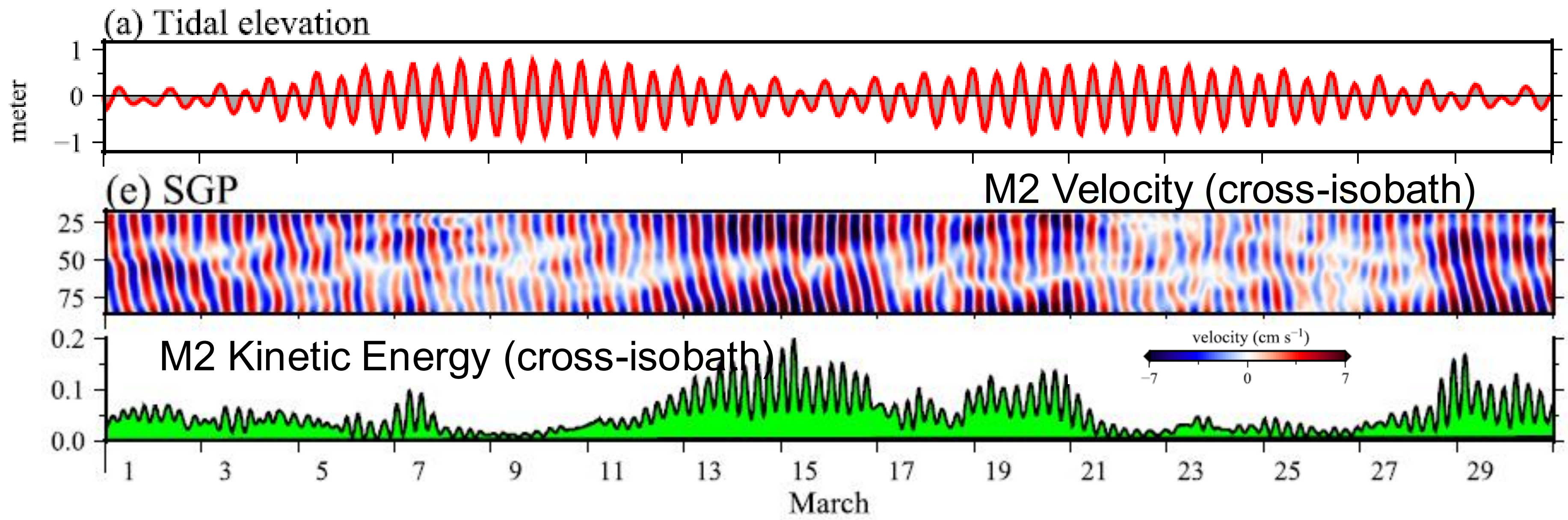
Amplitude and phase of tide simulated by model is compared with the observations from 4 tide gauge stations



Comparison of observed (blue) and simulated (red) barotropic ellipse for (a) M2 and (b) S2 constituents on the shelf.



• Variation of internal tides in WBoB

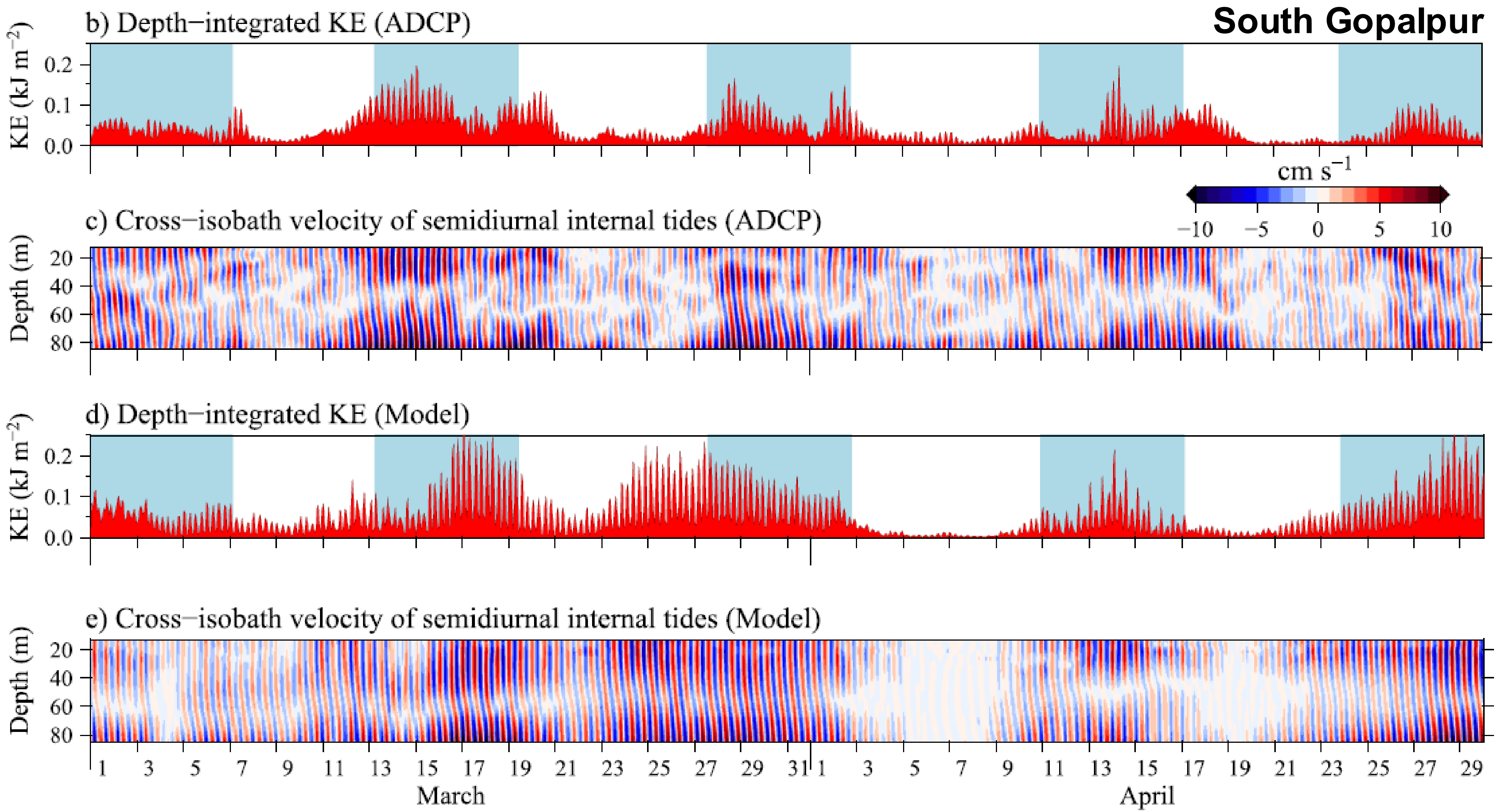


Tidal Elevation and Kakinada (top) and cross-isobath component of velocity in semi-diurnal frequency (middle) and depth-integrated Kinetic Enegry at South Gopalpur ADCP location.

The observed spring-neap variability of semidiurnal internal tides on the shelf off SGP and GP and the spring-neap variability of the local barotropic tide are not in same phase

Hence, the local conversion of barotropic to baroclinic energy cannot explain the variation of KE in the east-coast of India.

• Variation of internal tides in WBoB



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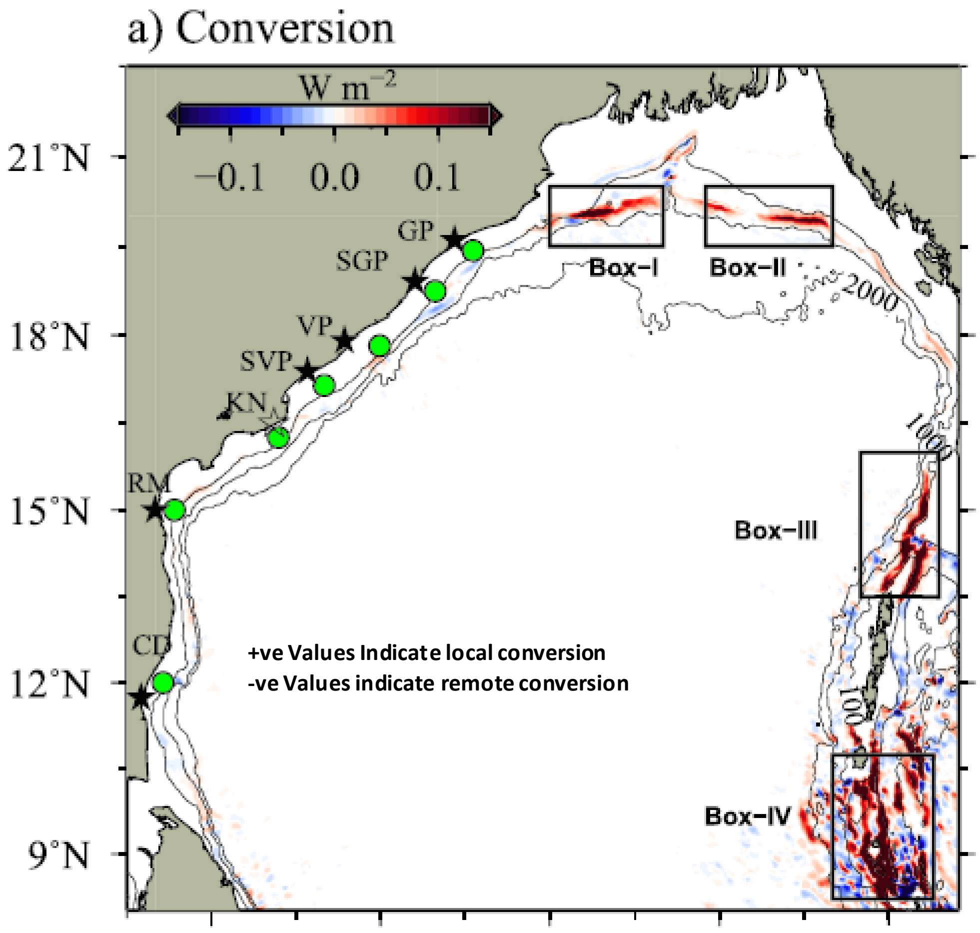
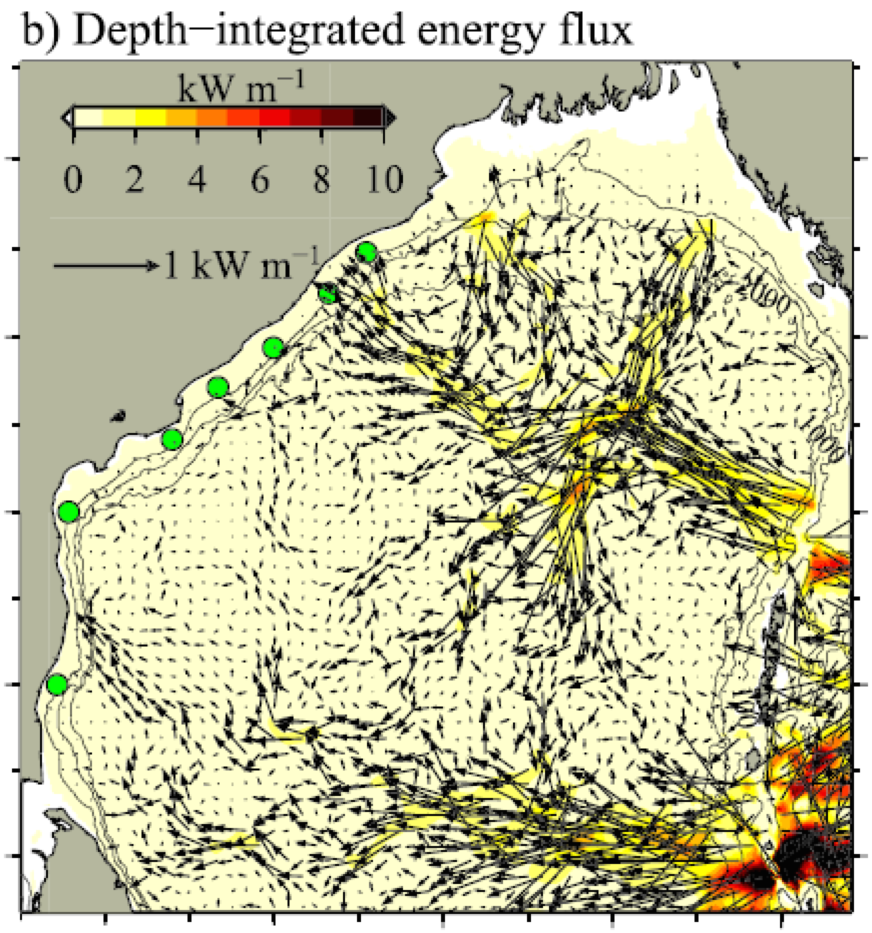
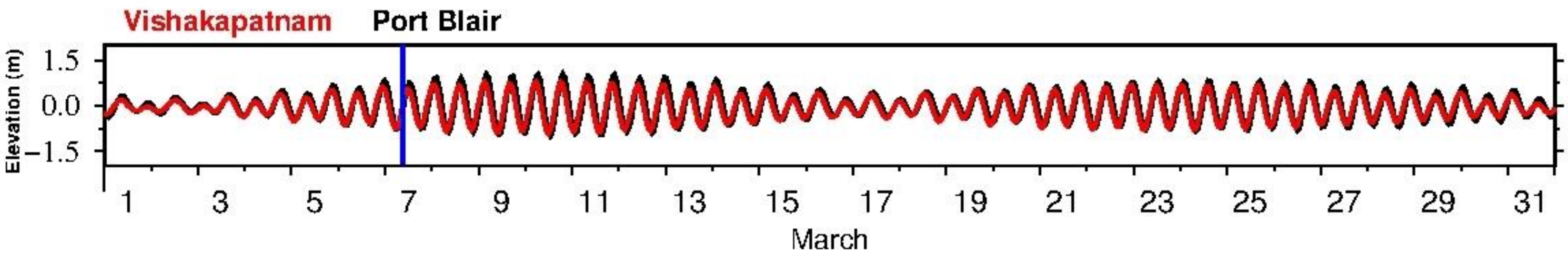
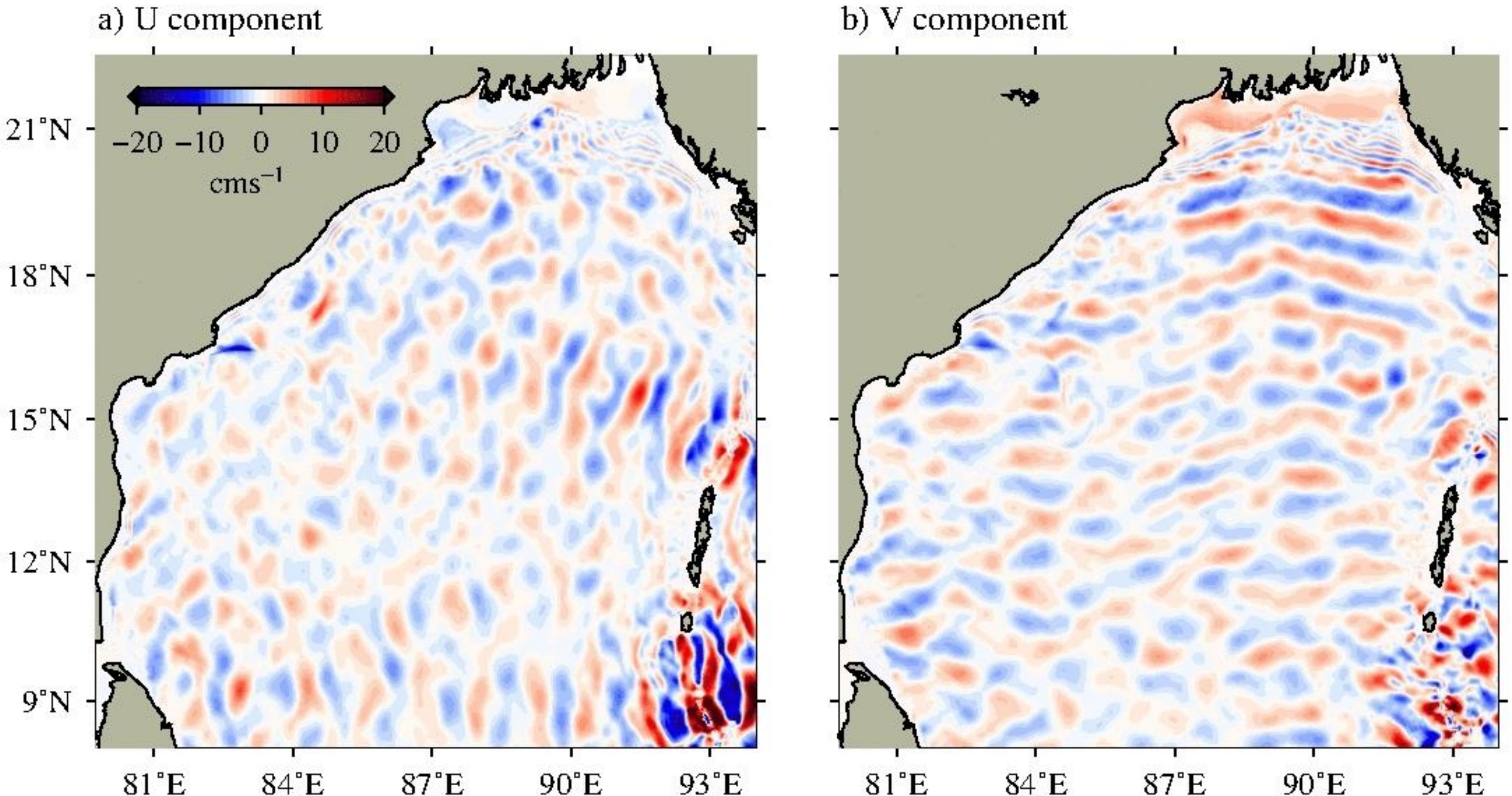


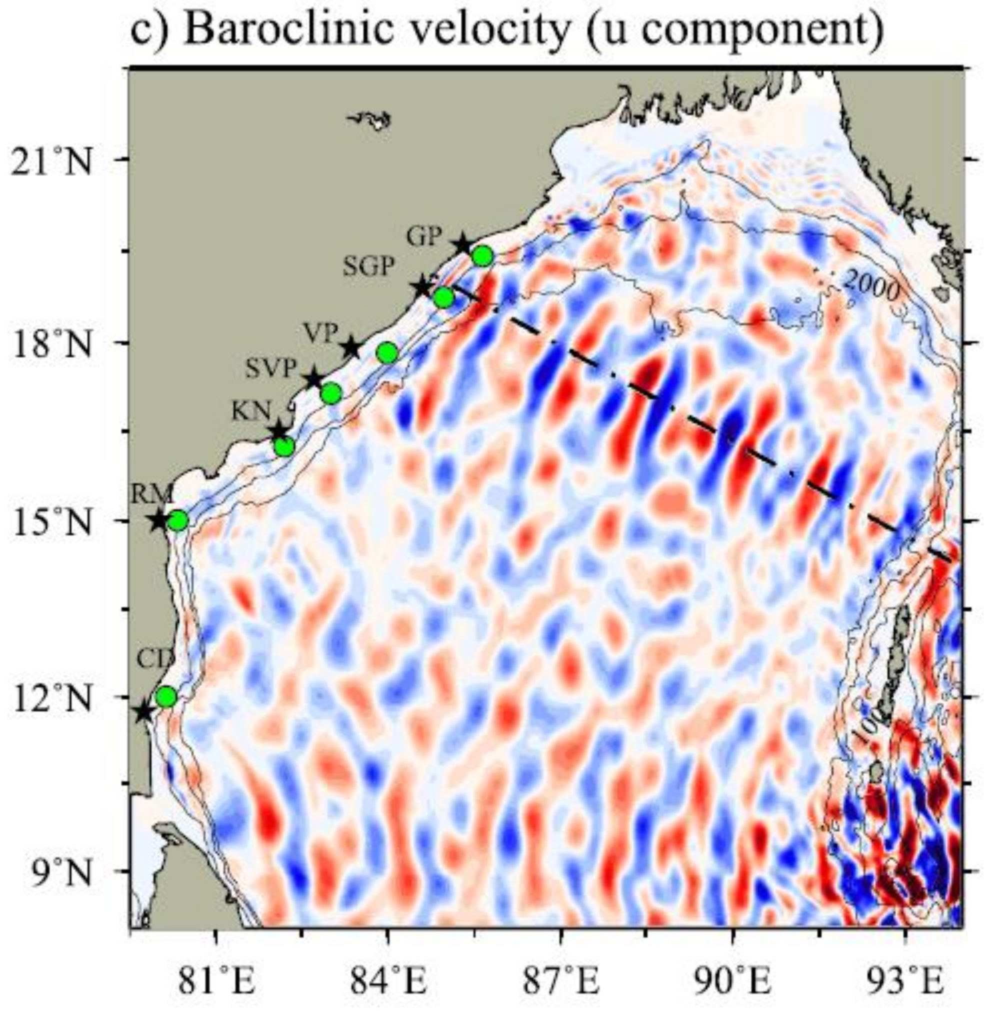


$$\mathbf{U}_B(t) = \frac{1}{H}\int_{-H}^{0} \mathbf{U}(z,t)\,dz \qquad C = <\nabla H \cdot \mathbf{U}_{bt} \quad p'_b> \qquad \mathbf{F} = \int_{-H}^{0} <\mathbf{u}'(z) \quad p'(z)>\,dz \qquad \nabla \cdot \mathbf{F} + D = C$$


Vishakapatnam
Port Blair
Elevation (m)
1.5
0.0
−1.5
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
March

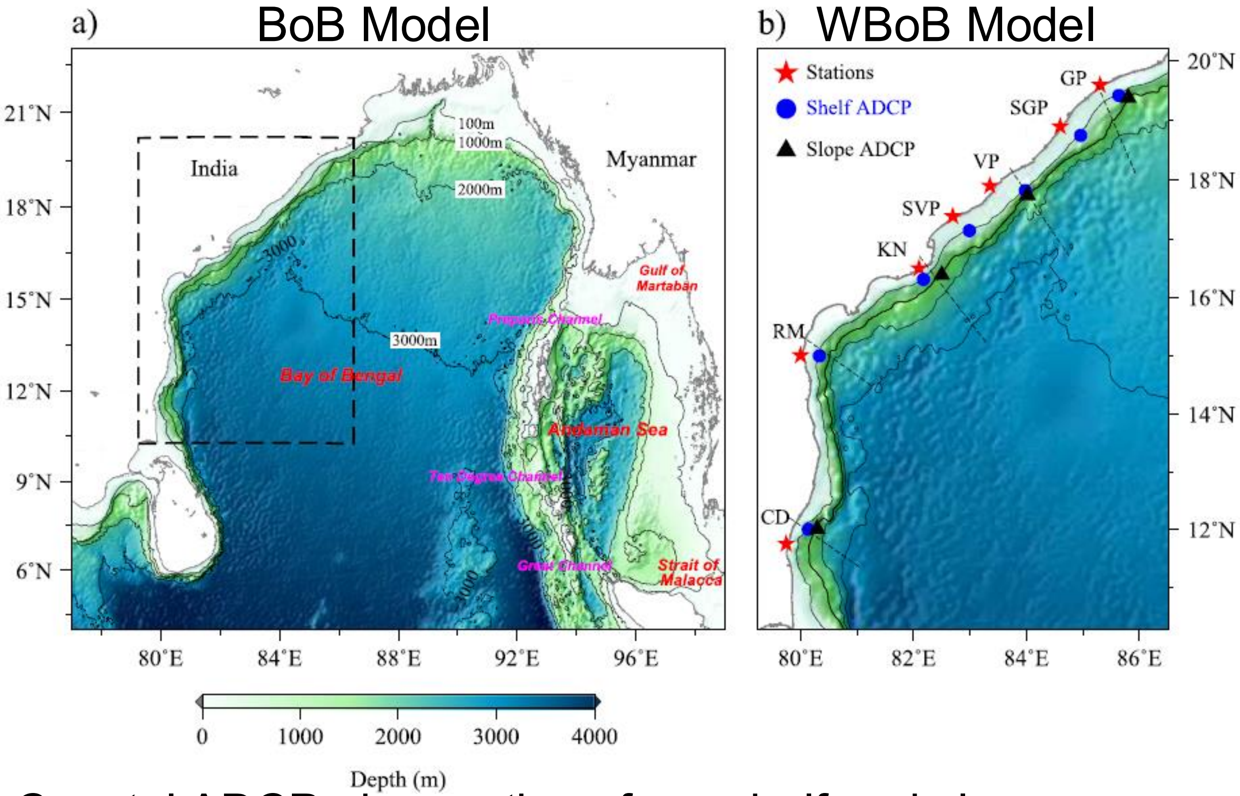

a) U component
b) V component
−20 −10 0 10 20
cms−1
21°N
18°N
15°N
12°N
9°N
81°E
84°E
87°E
90°E
93°E

Variation of internal tides in WBoB



- Strong radiation of internal tide energy onto the central and/or western BoB from the AN Ridge.
- This propagation of internal tides onto the western BoB from the AN Ridge over a distance of about 1,000–1,450 km.
- The first mode baroclinic waves take approximately 6-7 days to travel this distance.
- Hence, by the time these waves reach the WBoB, the phase of local barotropic tide would’ve reversed!

Data & Model



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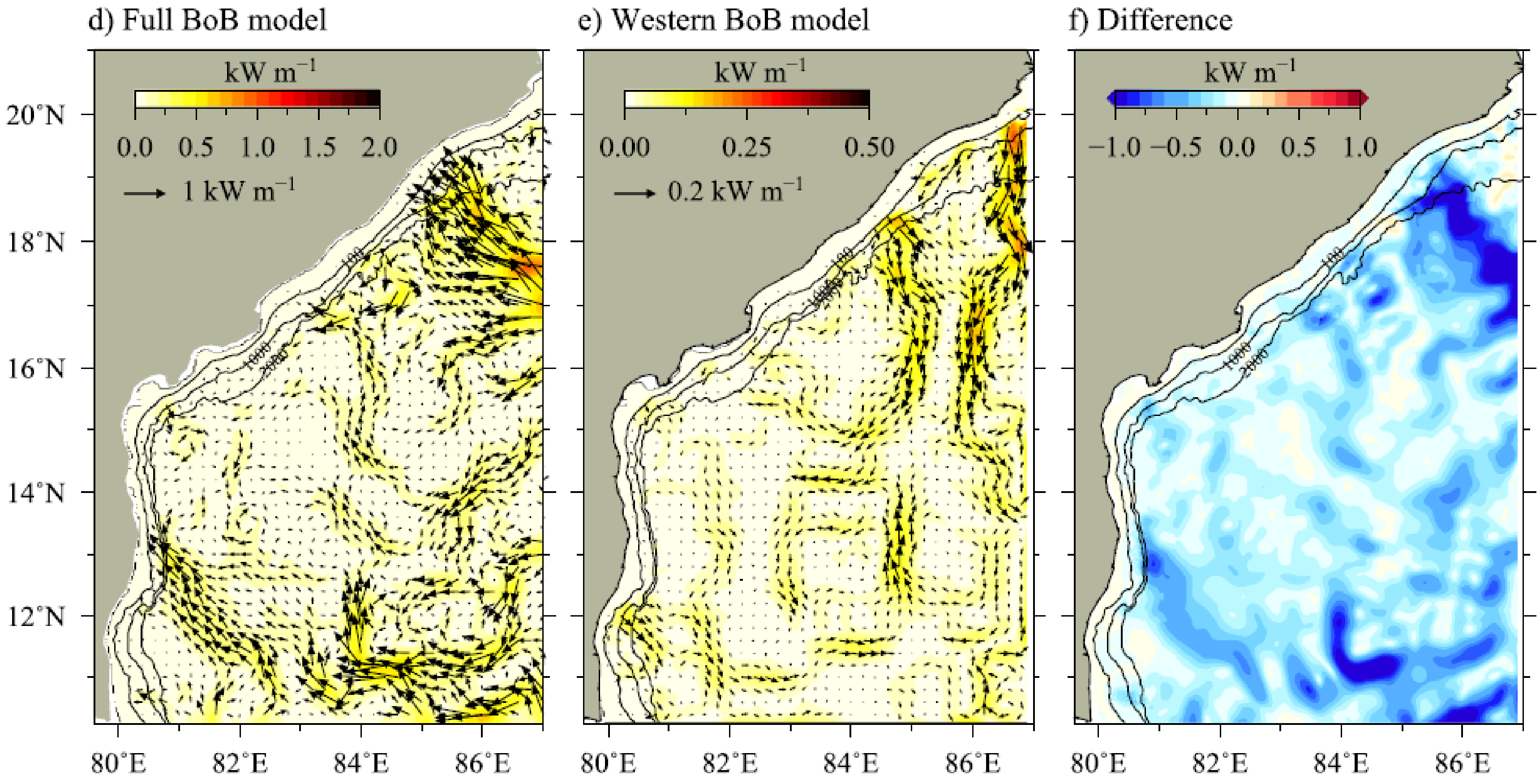
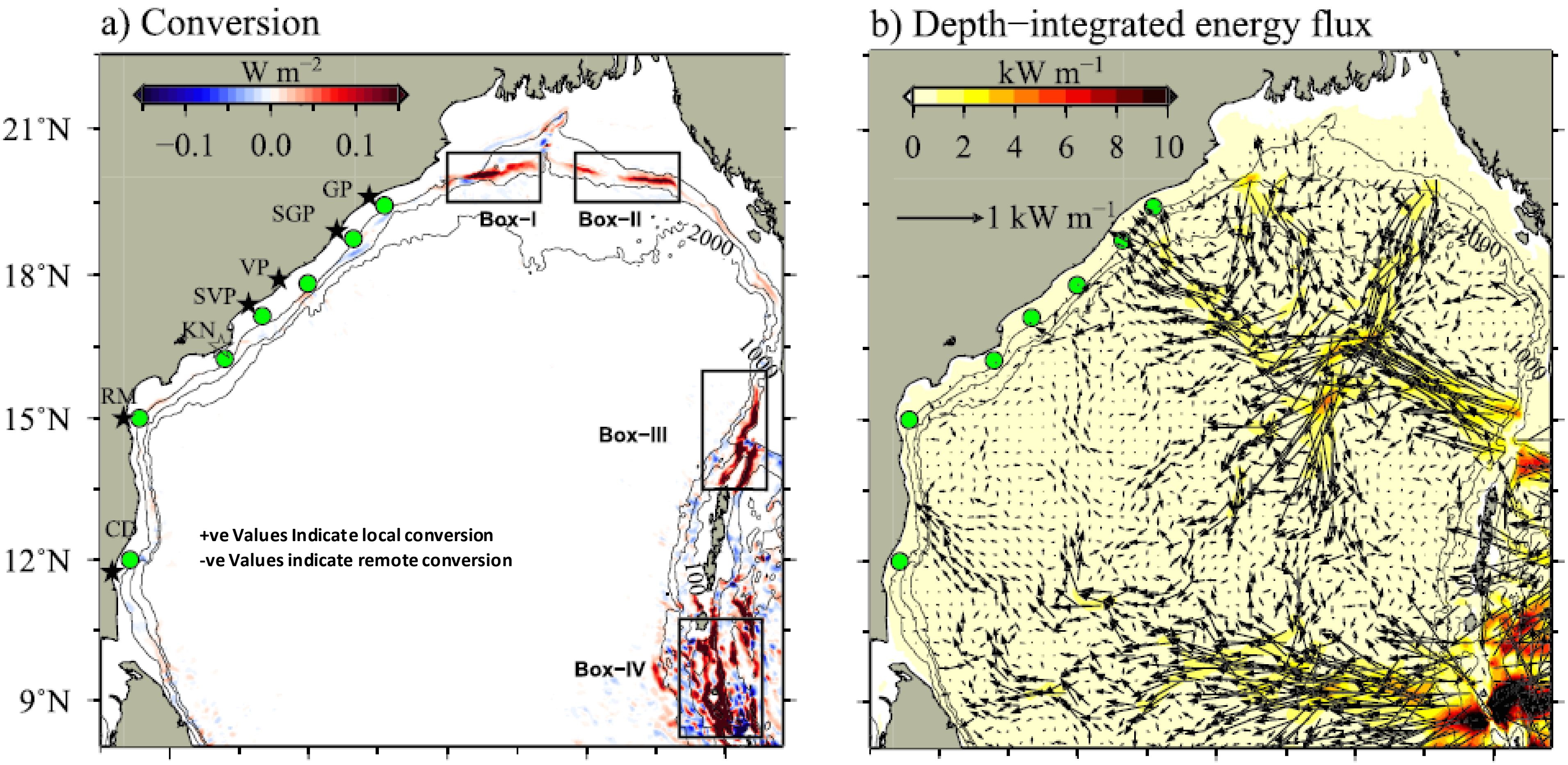
- Period of integration 2010-2016.

• Results from Model Experiment



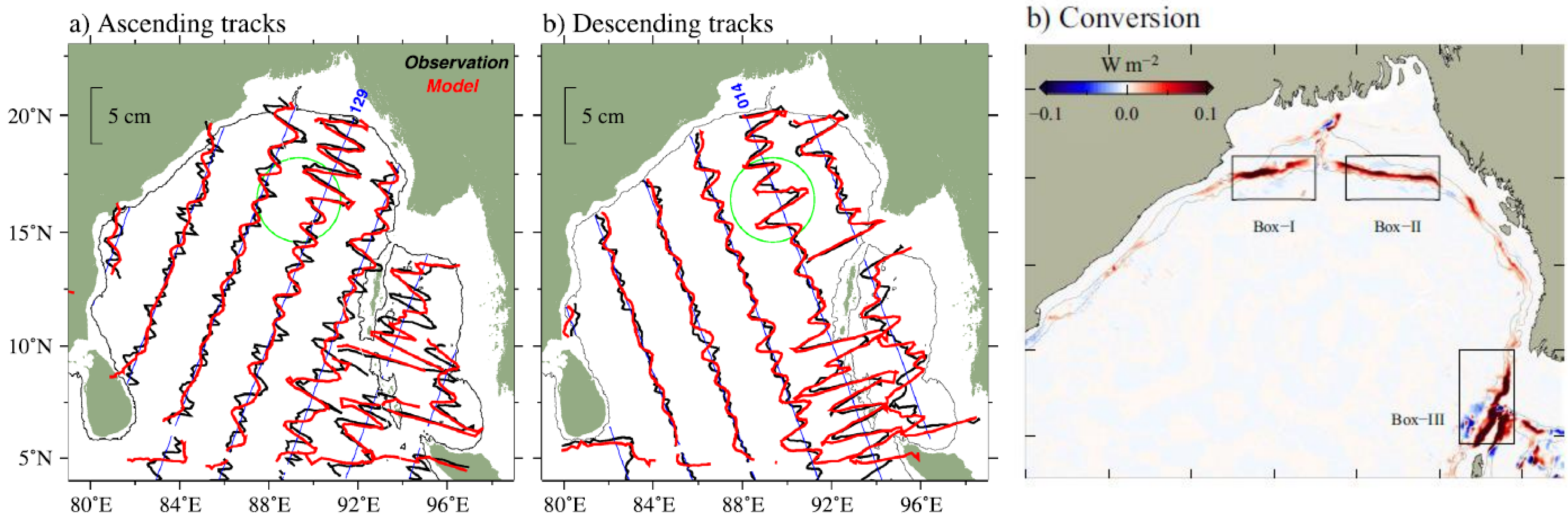
There is a clear difference in the westward propagation of depth-integrated baroclinic energy flux between the two model experiments.

• Variation of internal tides in WBoB



$$\mathbf{U}_B(t) = \frac{1}{H}\int_{-H}^{0} \mathbf{U}(z,t)\mathrm{d}z \qquad C = \langle \nabla H \cdot \mathbf{U}_{bt} \quad p'_b \rangle \qquad \mathbf{F} = \int_{-H}^{0} \langle \mathbf{u}'(z) \quad p'(z) \rangle \,\mathrm{d}z \qquad \nabla \cdot \mathbf{F} + D = C$$

• IT induced mixing in the central BoB

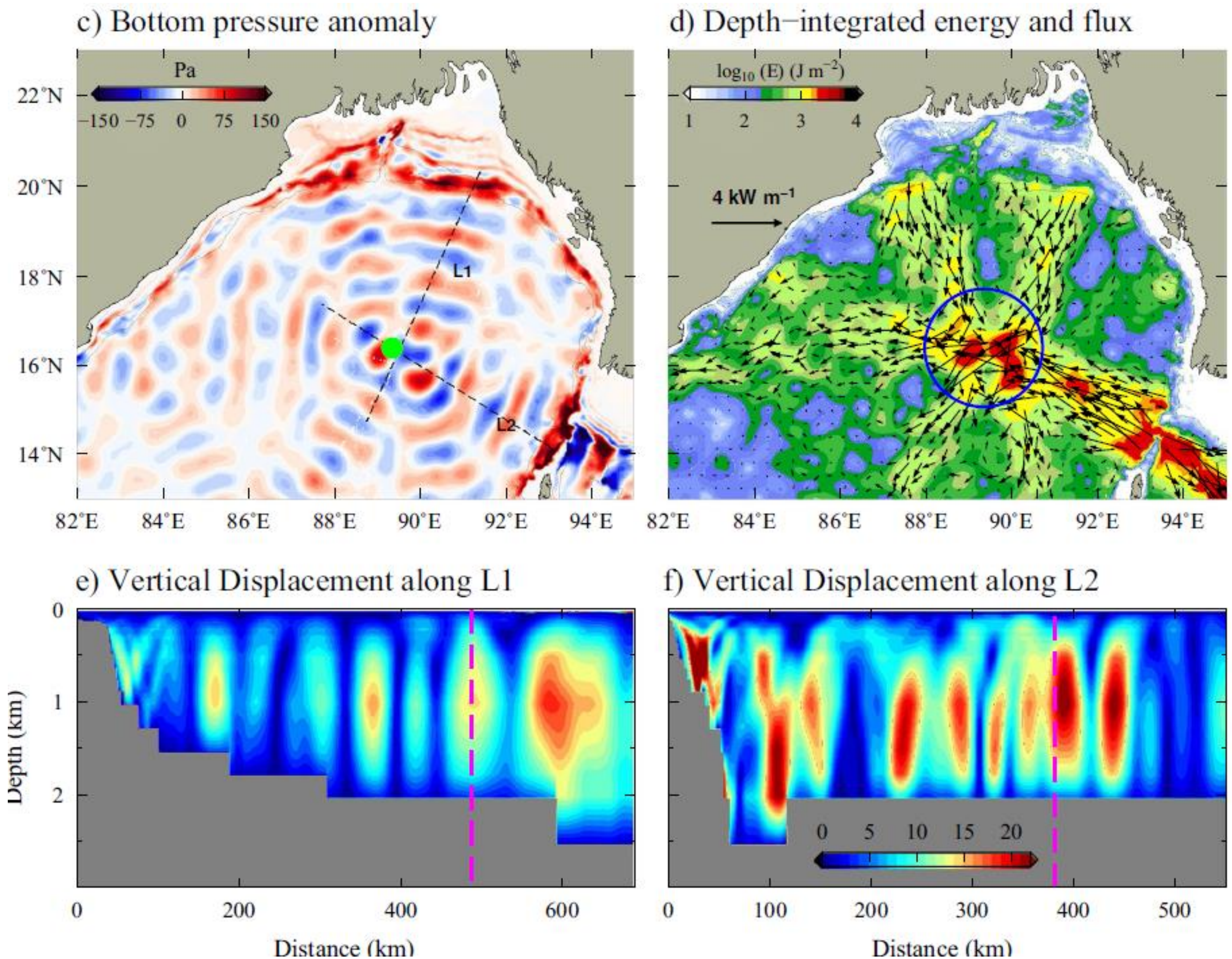


Elevated M2 signals are see in the north-central BoB, which is away from the IT generation sites both in the satellite observations and the model simulations.

Causes of these signals and their implications is intriguing.

• IT induced mixing in the central BoB

September 2013

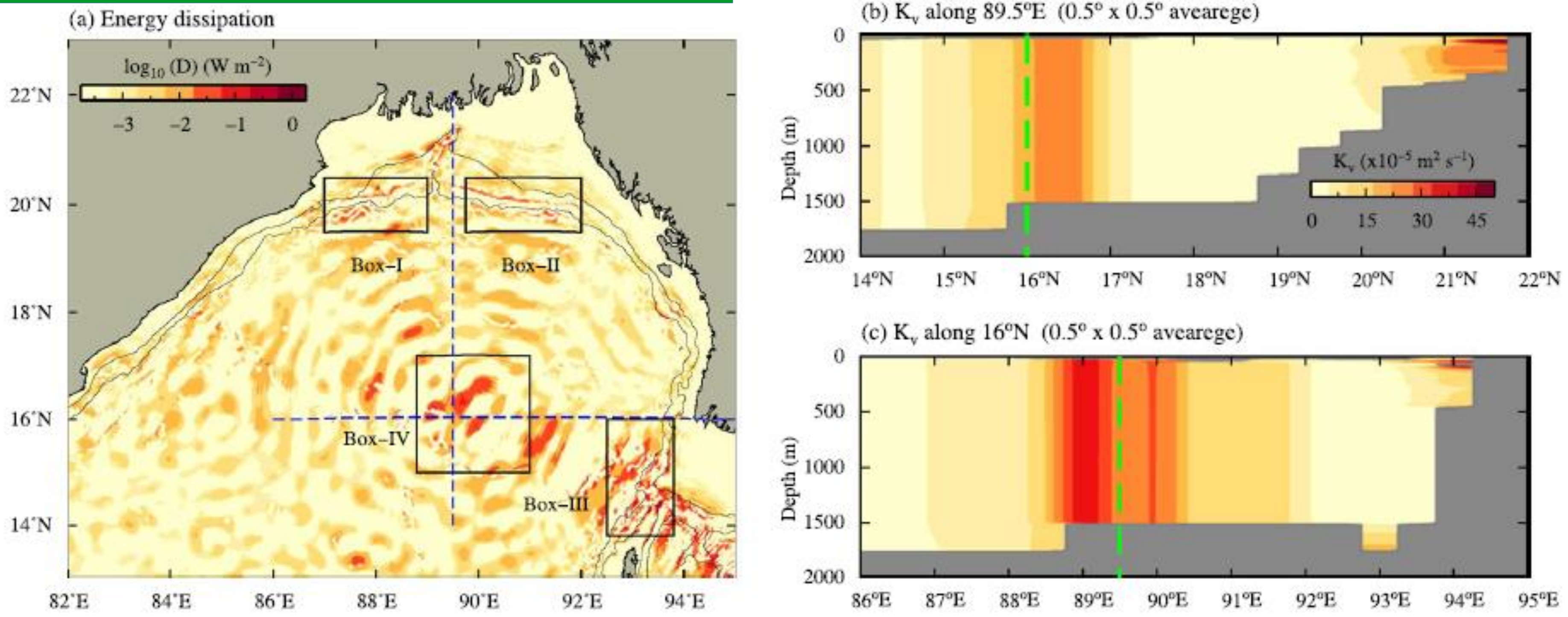


It appears that the ITs generated at different parts of the head Bay and the northern A&N island ridges converge to an imaginary focal point

At the centre of this convergence, the amplitude of displacement in isopycnals is as much as at the generation site (of the order of 20m!).

Vertical displacement of isopycnals associated with the M_2 internal tides along L1 and L2.

• IT induced mixing in the central BoB



Depth-integrated dissipation rate of M2 internal tides in the northern BoB (left)
Eddy diffusivity along the dashed lines (right)

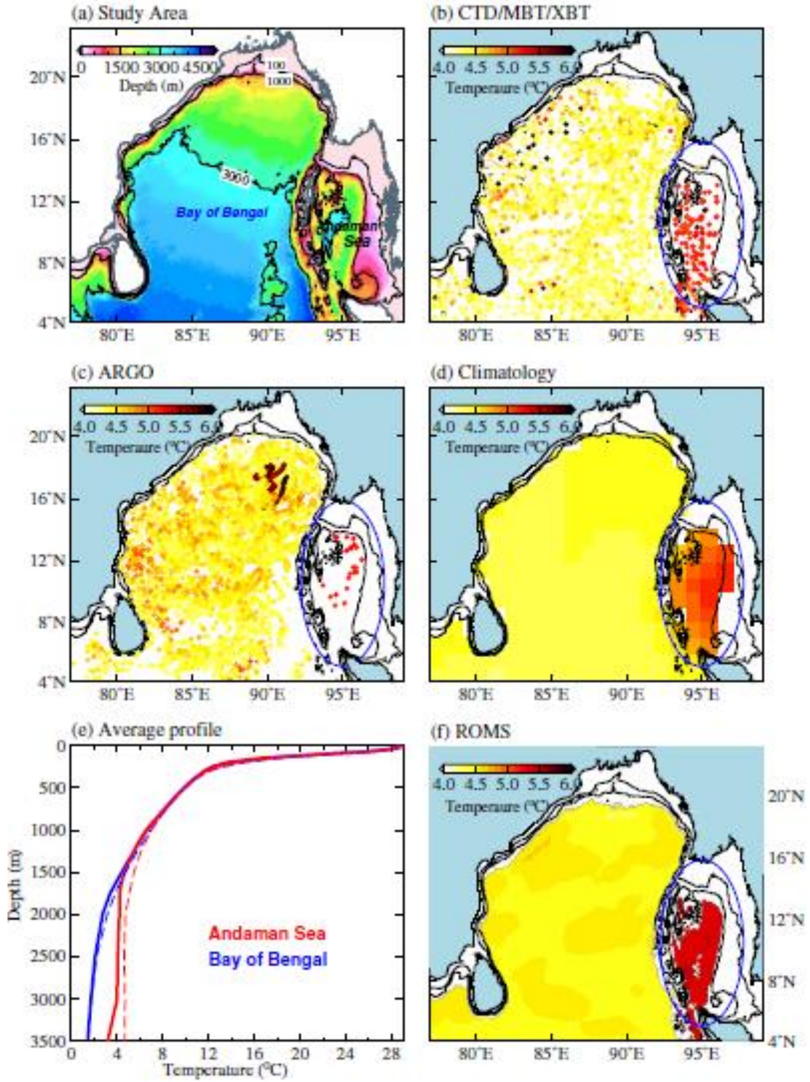
$$K_v = \Gamma \frac{qE(x,y)}{\rho \int N^2 dz} + K_0, \quad when\ dN/dz < 0$$

$$= \Gamma \frac{E(x,y)}{\rho N} + K_0, \quad when\ dN/dz > 0$$

Mixing efficiency: 0.2
Local dissipation efficiency: 0.3
K_0 : 10^{-5} $m^2 s^{-1}$
qE : 30%

St. Laurent et al. 2002, GRL

• IT induced mixing in the Andaman Sea



Temperature in the Andaman Sea at deeper levels (> 1500m) is higher than that of the Bay of Bengal

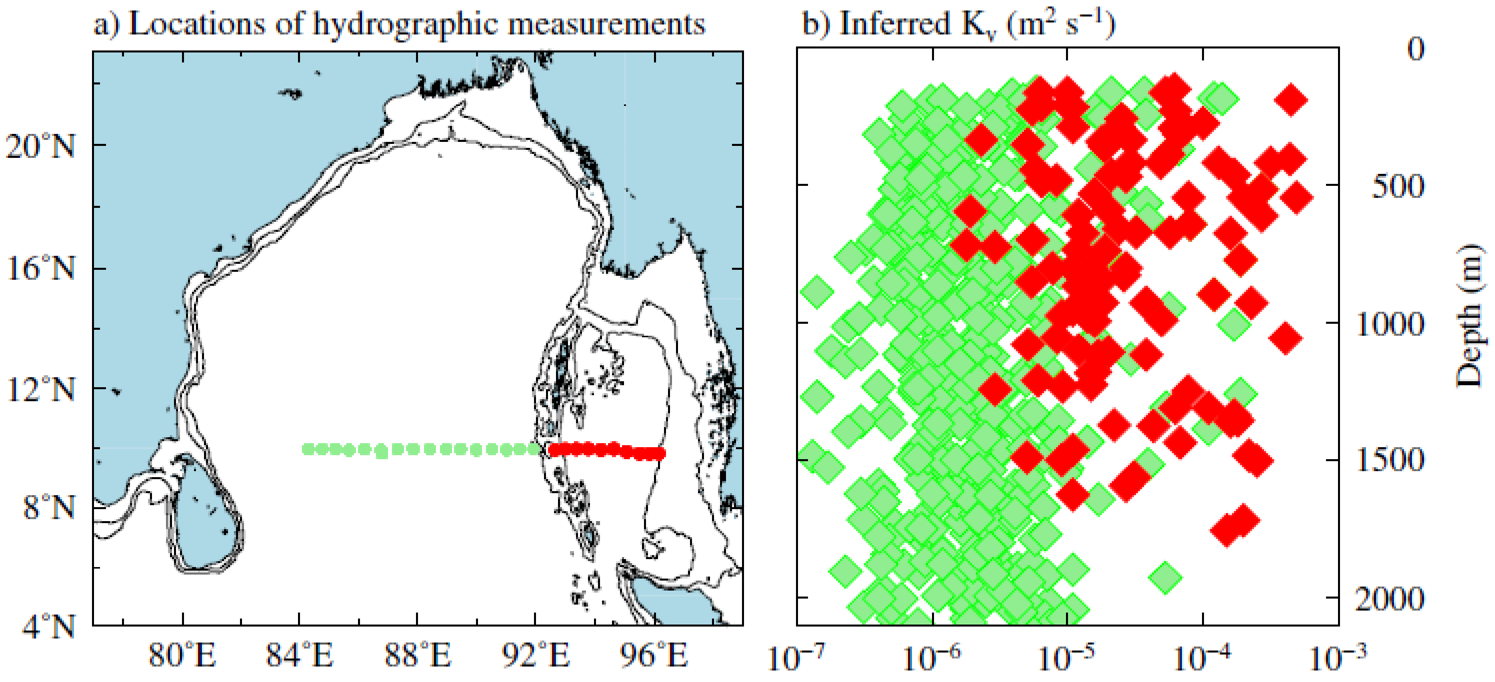
Temperature at 1,500 m in the Bay of Bengal and Andaman Sea from

Right, Top : all historical hydrographic observations
Left, Middle : Argo profiles
Right, Middle : revised WOA2009 climatology

Left, bottom : Average vertical profile of temperature in the Bay of Bengal (blue) and Andaman Sea (red) from CTD/XBT/MBT observation (think lines) and from the model (dashed lines).

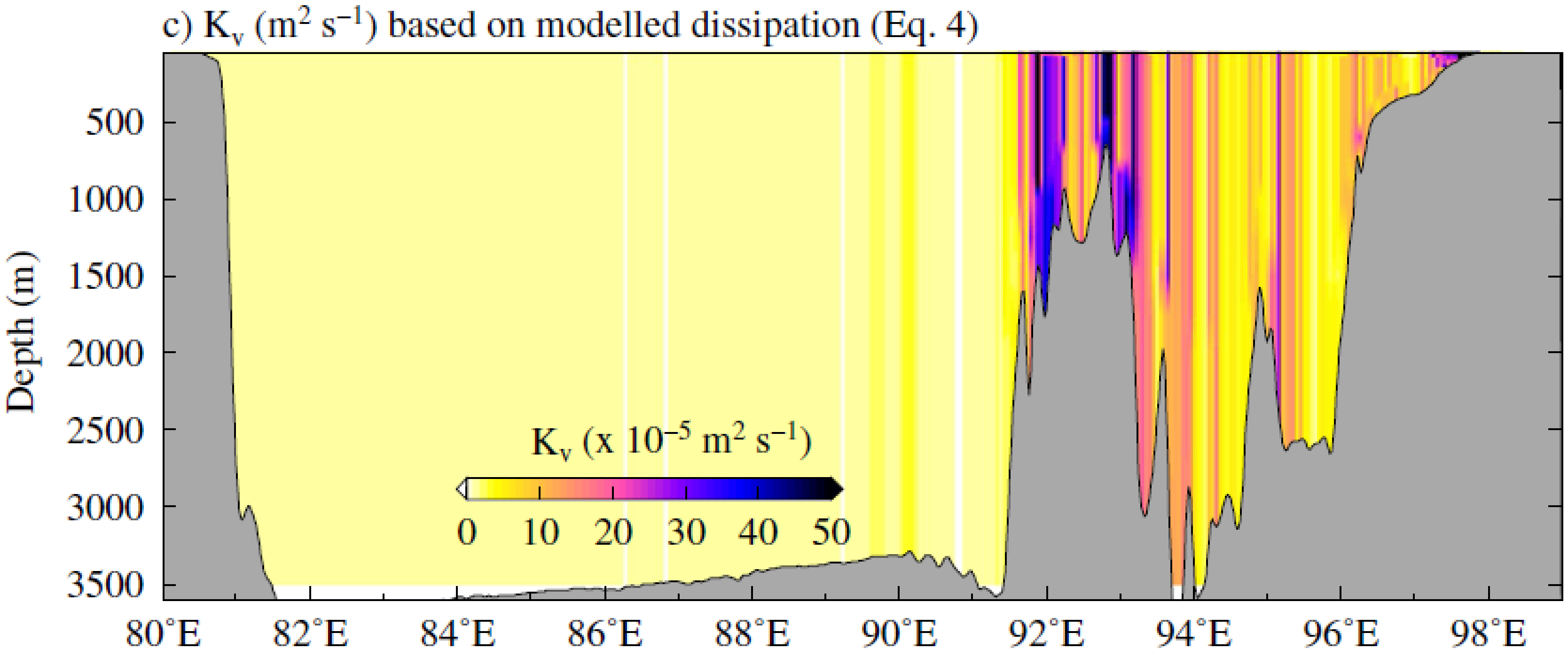
Bottom right: Spatial distribution of temperature at 1500 m in the model (ROMS). Note that a positive bias of 0.25 °C has been removed from the model simulations at 1,500 m.

• IT induced mixing in the Andaman Sea



Locations of Hydrographic casts in the BoB (green) and AS (red) used to calculate the vertical diffusivity (Kv) by Kunze et al. J. Phy. Ocean, 2017

• IT induced mixing in the Andaman Sea



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$$= \Gamma \frac{E(x,y)}{\rho N} + K_0, \ \ when\ dN/dz > 0$$

Mixing efficiency: 0.2
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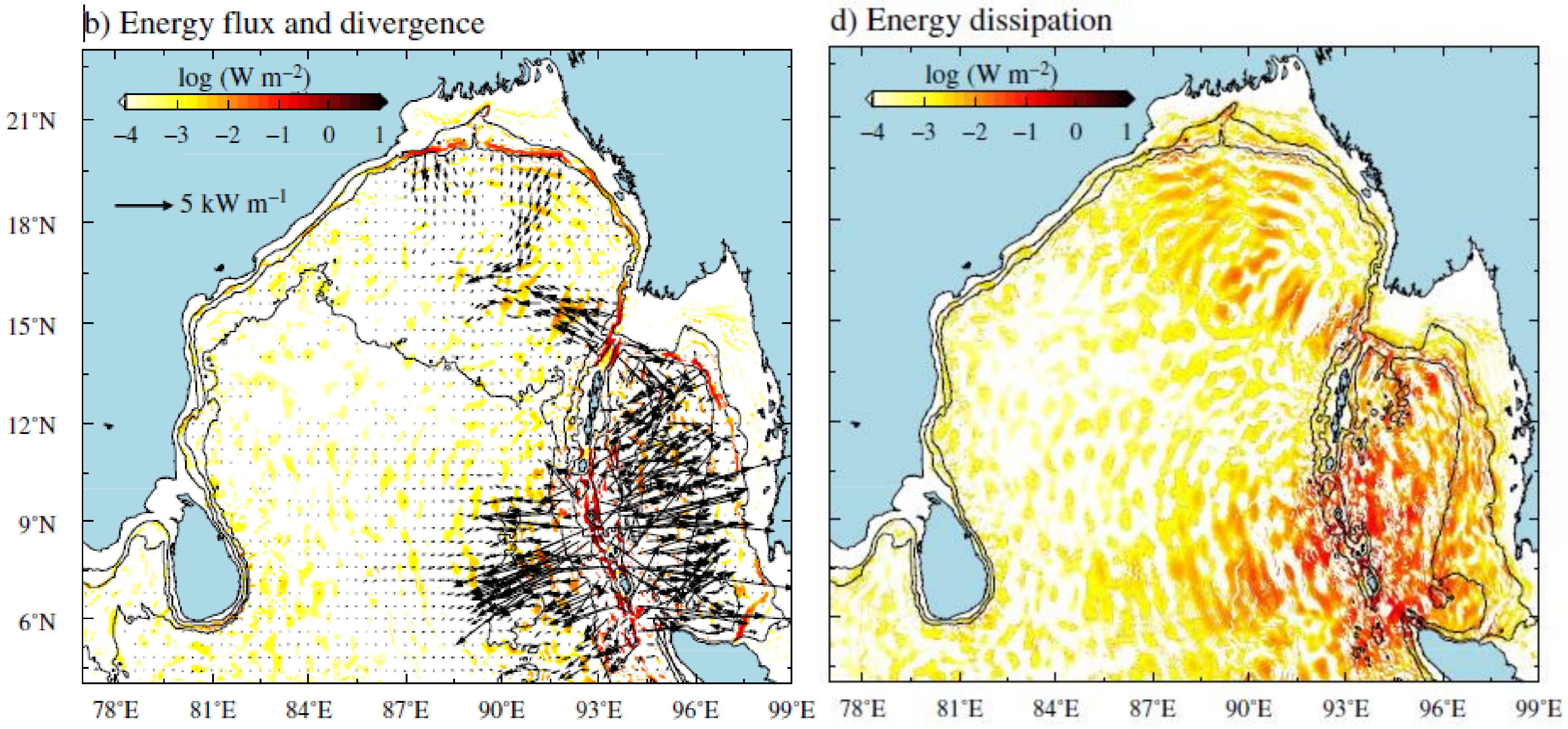
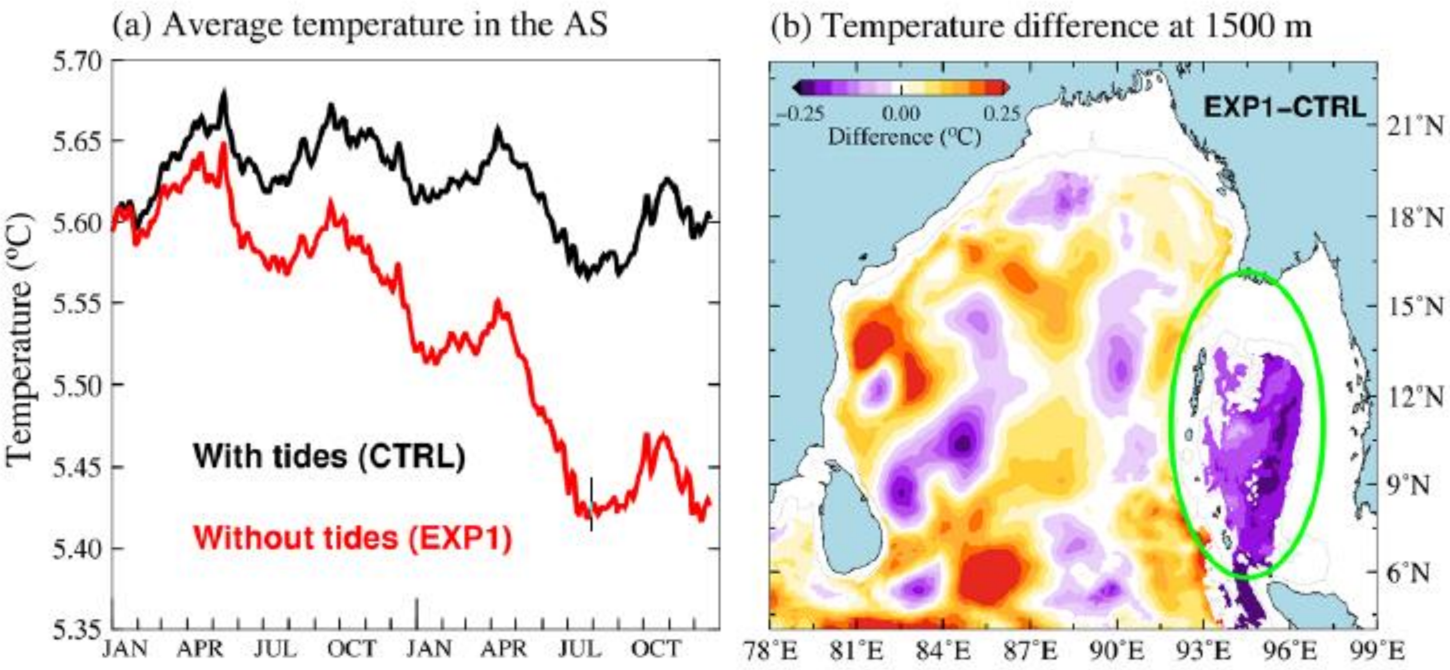
St. Laurent et al. 2002, GRL

- **IT induced mixing in the Andaman Sea**



Large internal tide energy dissipation over a small region can lead to larger diapycnal mixing in the AS compared to BoB

• IT induced mixing in the Andaman Sea

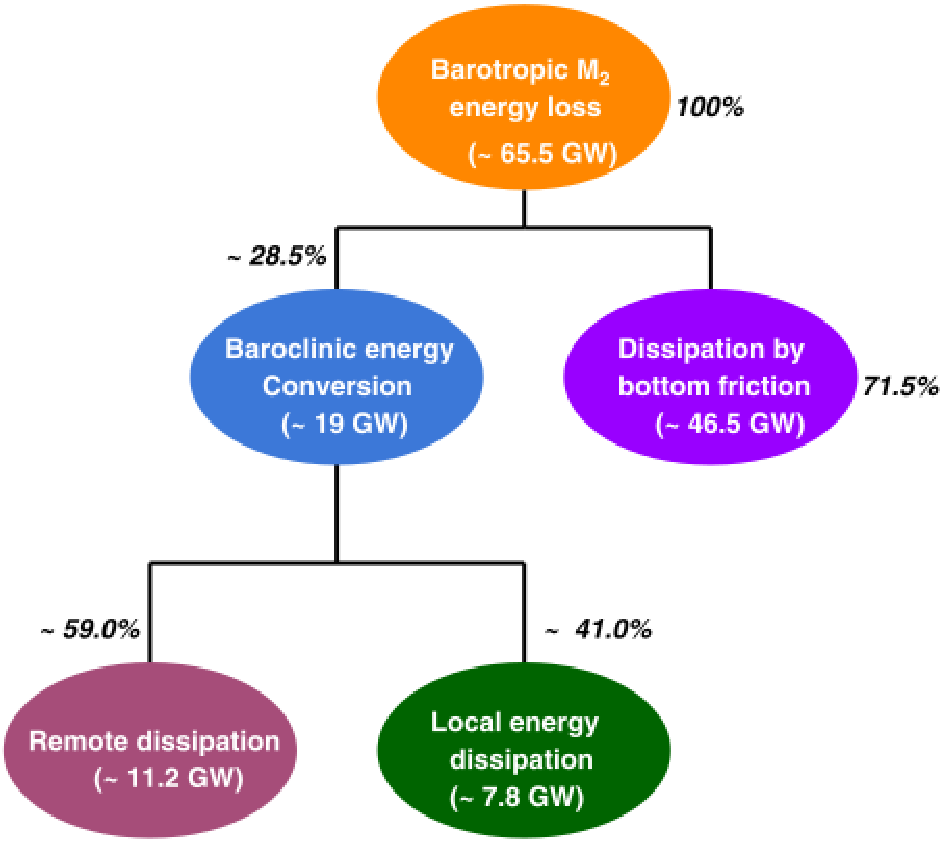


In the absence of internal tides, temperature in the deeper layers of AS starts decreasing.

While the cooling in the AS is consistent and uniform across the basin, that in the BoB does not show any spacific pattern.

Importance of Internal Waves in the Ocean

- Barotropic tides supply about **3.7 TW** (1 TW = 10^{12} watt) of energy into the ocean **globally**, and about **25%–30%** of this energy gets converted to **baroclinic energy** in the deep ocean due to the generation of internal tides
- **~2 TW** of mechanical energy is required to maintain the **abyssal stratification** and **meridional overturning circulation** in the ocean
- **Half** of this energy (0.7–1.3 TW) is supplied by breaking of **internal tides** and the **other half** is provided by the **near-inertial waves**, which are generated by the change in the wind stress acting on the ocean surface
- **Baroclinic tides** provides about **19GW** for mixing in the **Bay of Bengal and Andaman Sea**



M2 tidal energy budget in the BoB

Ocean State Forecast

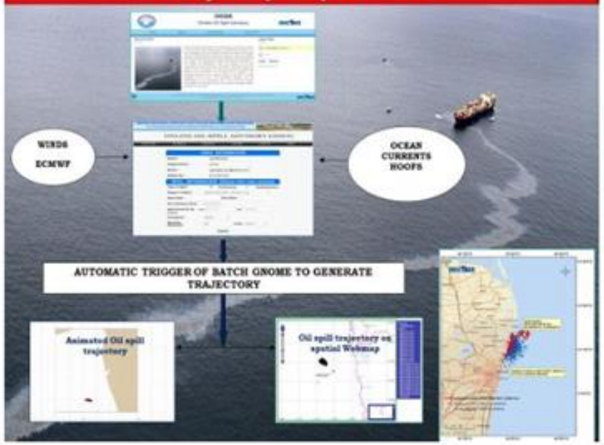
Major Goals

- Regional Ocean analysis
- Regional and coastal ocean forecasts
- R&D

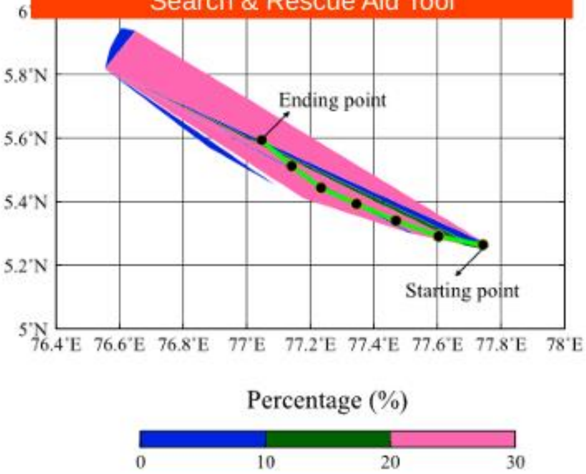
Indian Ocean Forecast System

Regional Ocean Analysis → Regional and coastal forecasts

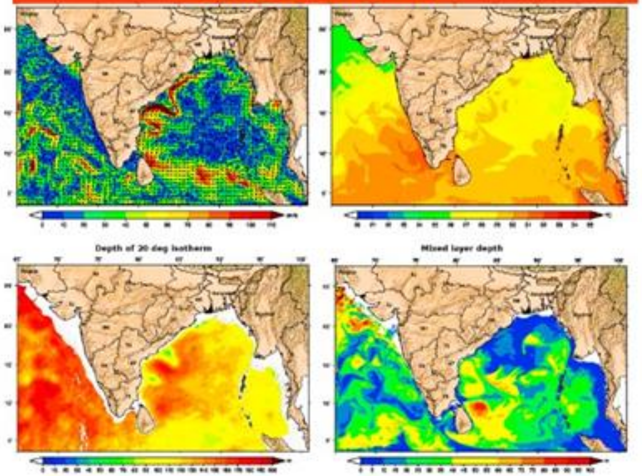
Oil spill trajectory Predictions



Search & Rescue Aid Tool



General circulation



Major Goals

- Global Ocean reanalysis for climate studies
- Ocean climate indices
- Global Ocean analysis for initializing seasonal monsoon forecast model (IITM-CFS)
- Global Ocean initial conditions for extended range predictions by IITM CFS
- I/C and B/C for regional forecast models

Global Ocean Data Assimilation System

Ocean Initial Conditions → Ocean Analysis & Reanalysis

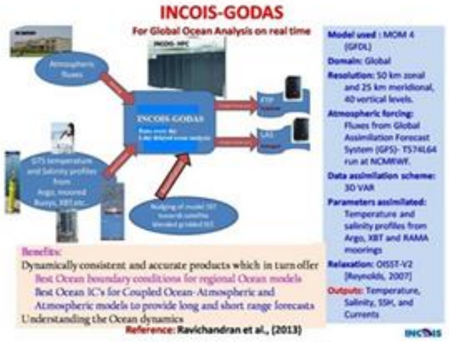
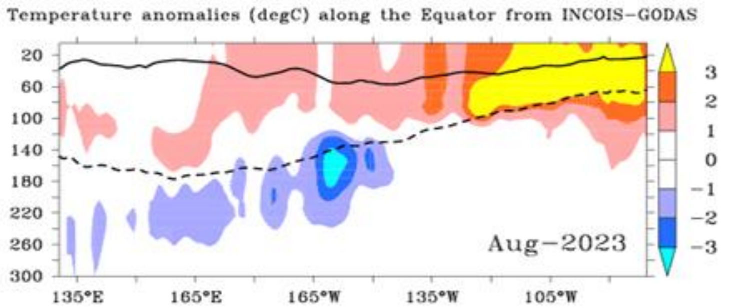


Figure Schematic diagram of INCOIS-GODAS



Deep Ocean Mission

Major Goals

- Advisories on the decadal-to-long term projections, trends and coastal impacts:
    - Sea Level Change
    - Intensity & frequency of tropical cyclones
    - Extreme waves and coastal erosion
    - Storm surge and inundation hazard
    - Primary productivity, harmful algal blooms and coastal hypoxia
- Modelling and Deep Ocean Observations
- Multi-hazard Vulnerability Maps for the coastal regions of India
- Climate assessment report

Ocean Modelling Mission

Ocean Modelling Mission

Global & Regional
MOM6 & Wavewatch III

- Ocean Circulation & Wave Predictions
- Downscaled Ocean Climate Projections
- R&D in Ocean Sciences

Coastal
FVCOM & ADCIRC

- Integrated coastal inundation prediction system
- Coastal/shelf-sea prediction system
- R&D in coastal processes

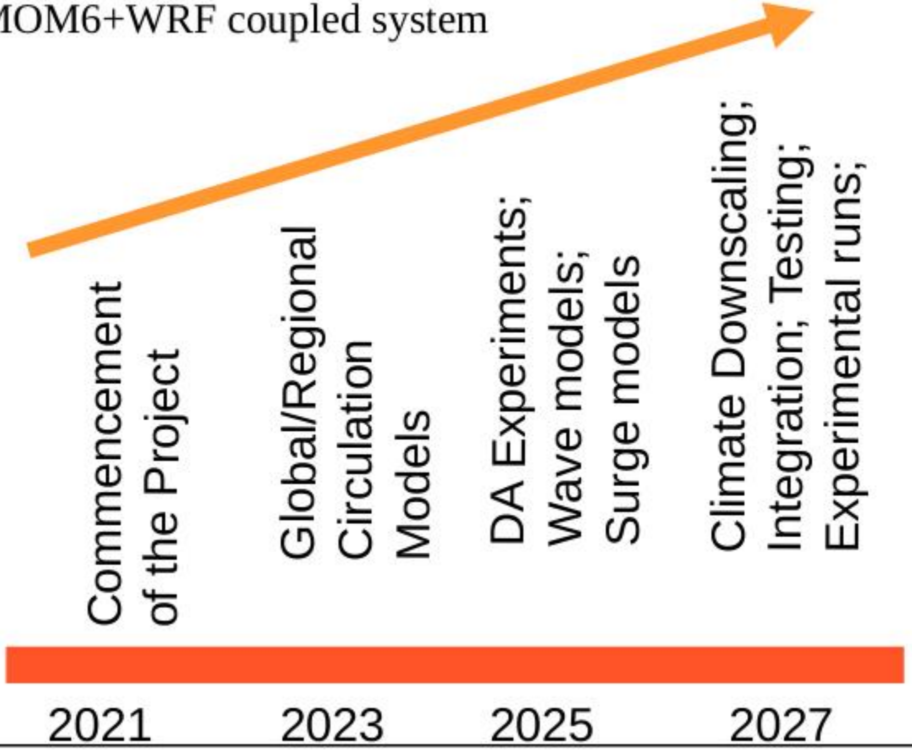
Data Assimilation
LETKF

- Ocean Analysis
- Ocean Reanalysis

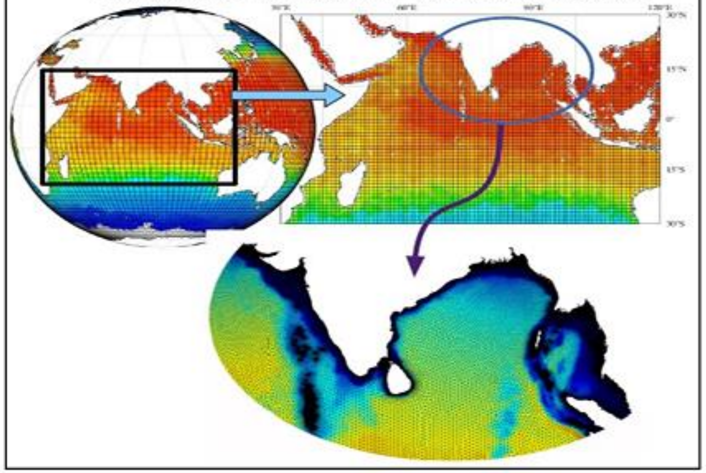
Unified Ocean Modeling and Forecasting System

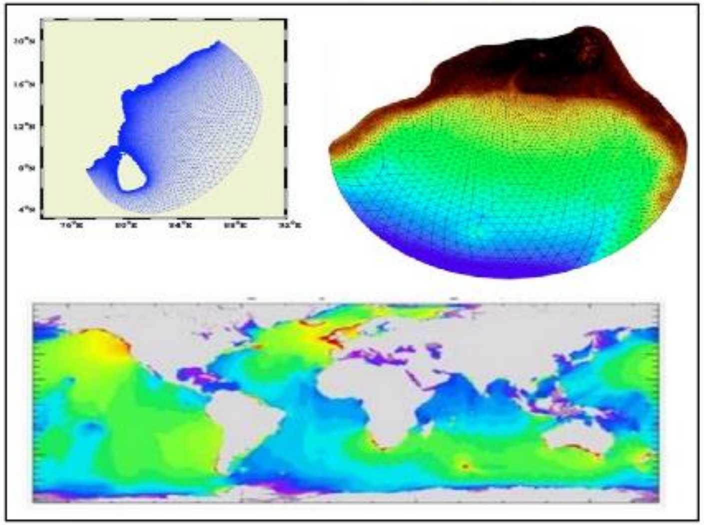
Proposed Ocean Modeling Framework

- MOM6 for global to regional level applications.
- LETKF based DA system in MOM6
- FVCOM for coastal/shelf sea/estuary applications.
- WAVEWATCH III for global to coastal wave forecast
- ADCIRC+SWAN for tsunami and storm surge predicton
- MOM6+WRF coupled system



General Circulation Forecast Models





Coastal Prediction Models