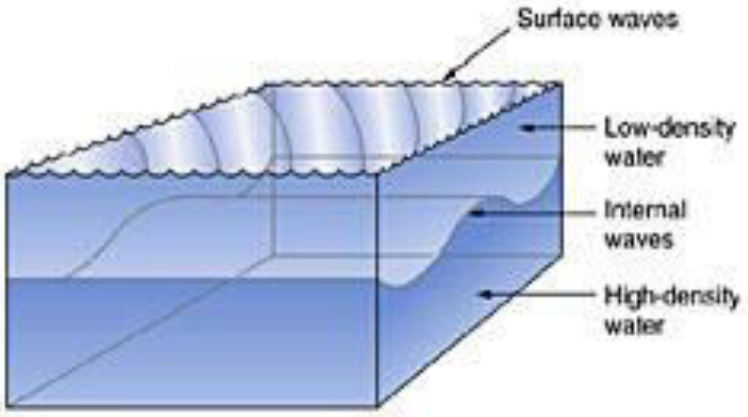
Identification of Internal Waves in the Western Bay of Bengal: Observations and Modelling

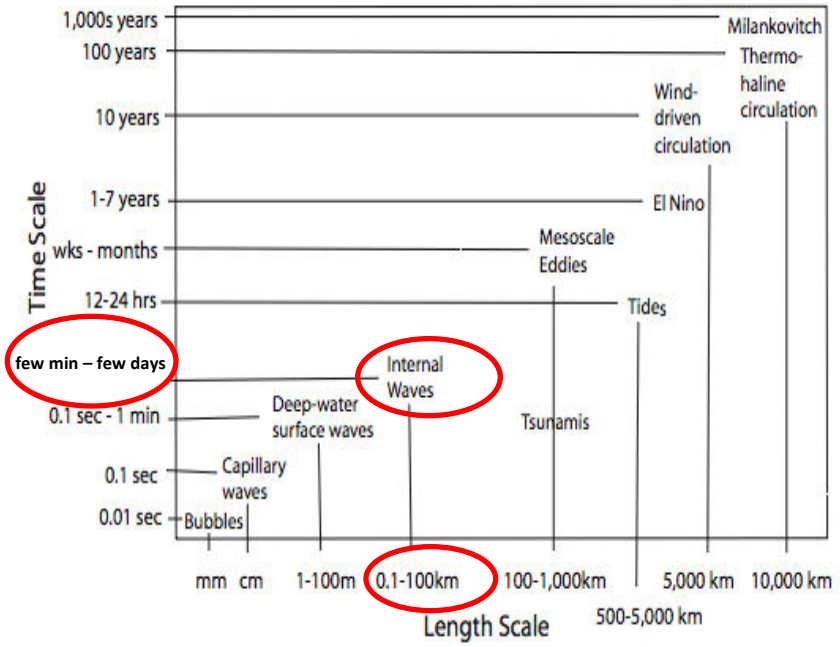
A. D. Rao

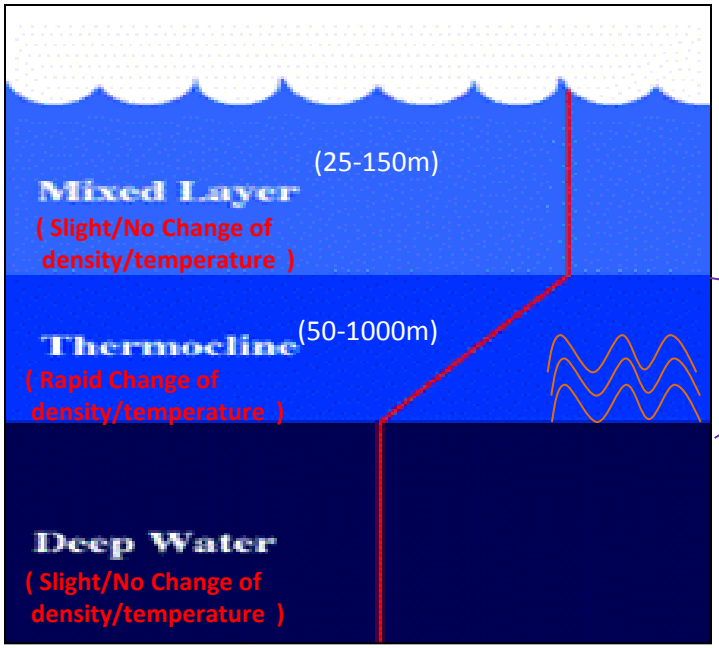
Centre for Atmospheric Sciences
Indian Institute of Technology Delhi

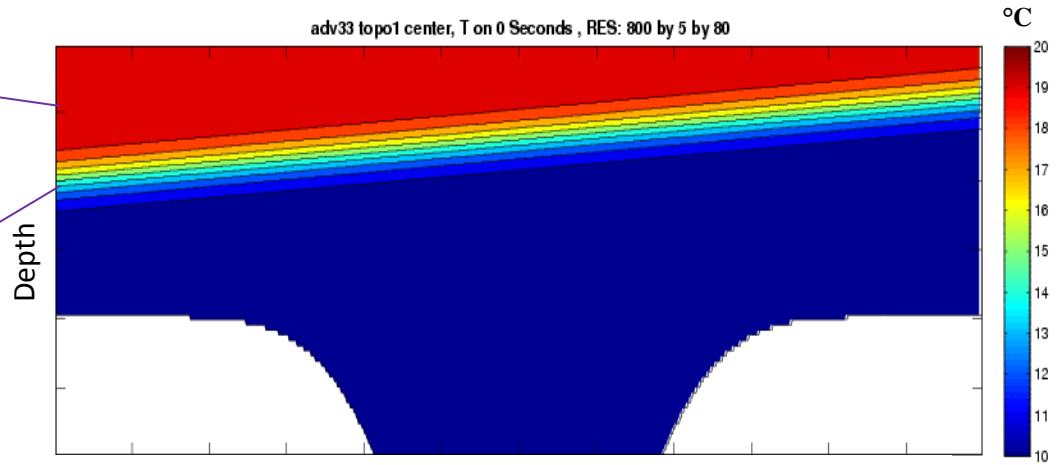


Internal Waves : Spatial and temporal scale



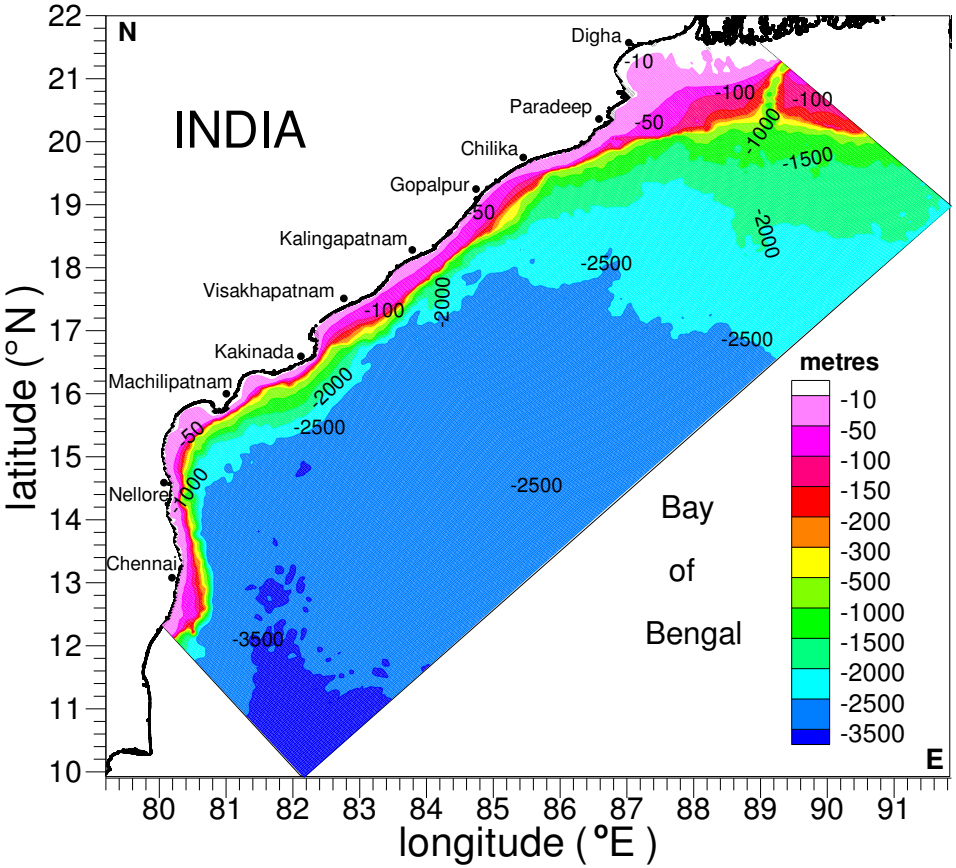






Model Domain for the Western shelf of the Bay of Bengal :

- Hor. resolution: 2-3 km
- Model matrix: 220x 280x 23.

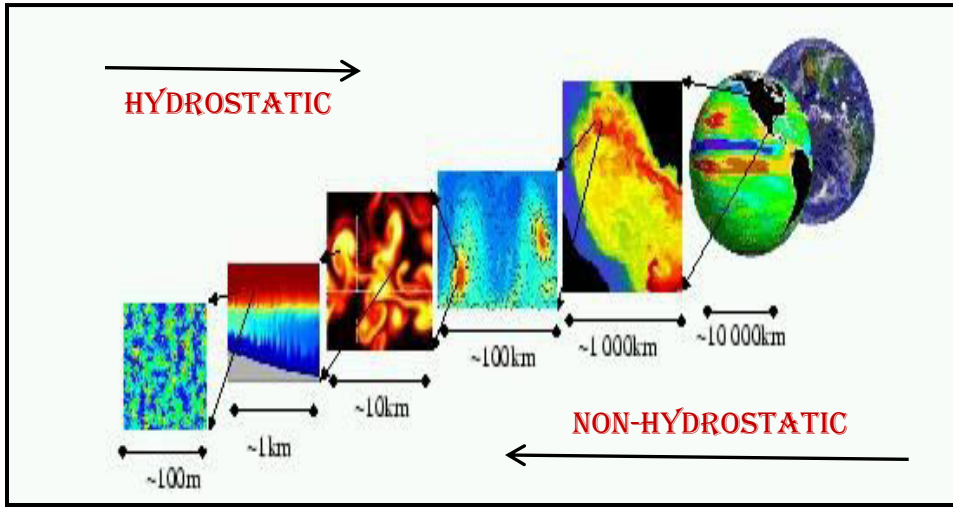


Model domain and bottom topography

MITgcm (Massachusetts Institute of Technology General Circulation Model ;Marshall et al, 1997)

✓ Designed ⇒ for oceanic and atmospheric phenomena.

✓ It resolves ⇒ large scale circulation, process studies (e.g. convection, eddies, internal waves) and laboratory studies.



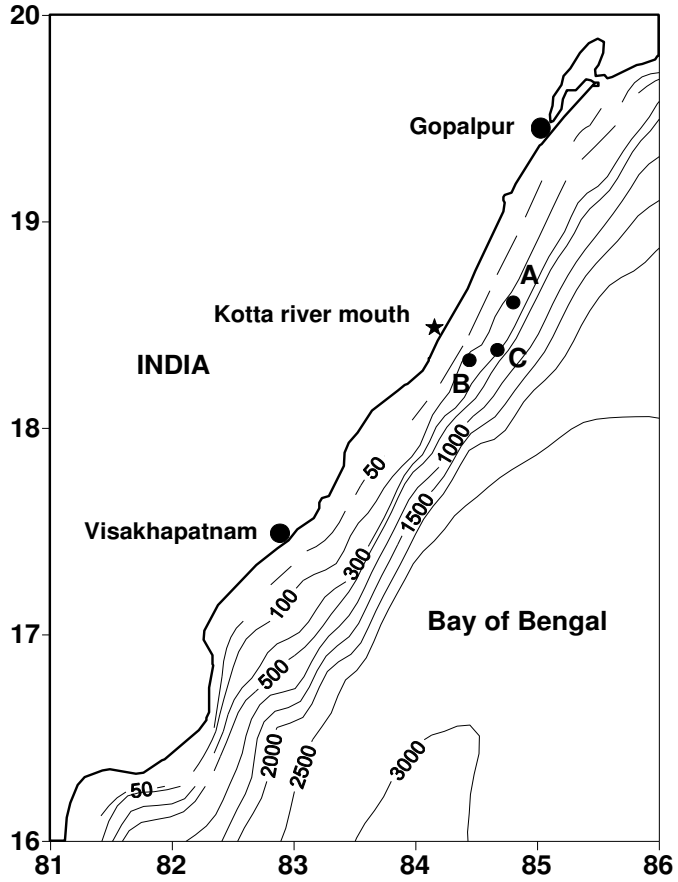
In-situ data collection location and period

Station locations:

- ✓ Stn. A: 84.80^{0}E 18.61^{0}N (100 m)
- ✓ Stn. B: 84.44^{0}E 18.33^{0}N (100 m)
- ✓ Stn. C: 84.67^{0}E 18.38^{0}N (500 m)

Data collection periods:

- ➢ 17-21 Feb 2012 (3d)
- ➢ 24 Aug – 5 Sept 2013 (11d)
- ➢ 20 Nov 2013 – 6 Jan 2014 (46d)
- ➢ 26 Feb – 23 Apr 2014 (56d)



Model Validation: for Feb 2012

Tide gauge and MODEL simulation

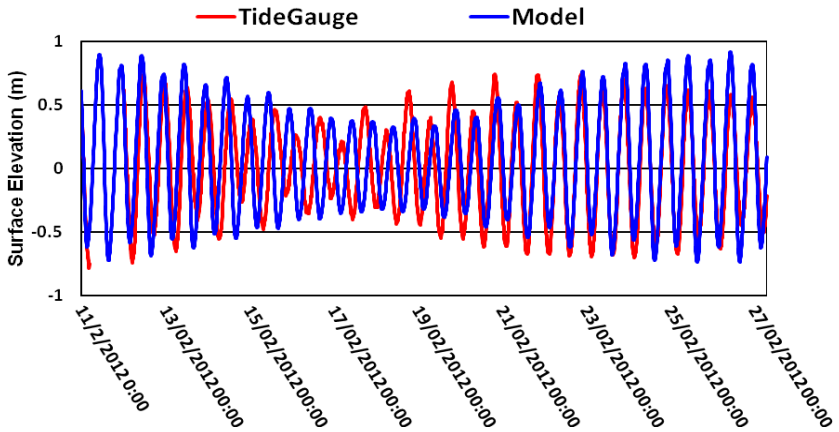


Figure: Comparison of model surface elevation (m) with tide gauge data February 2012.

TPXO data and MODEL simulation

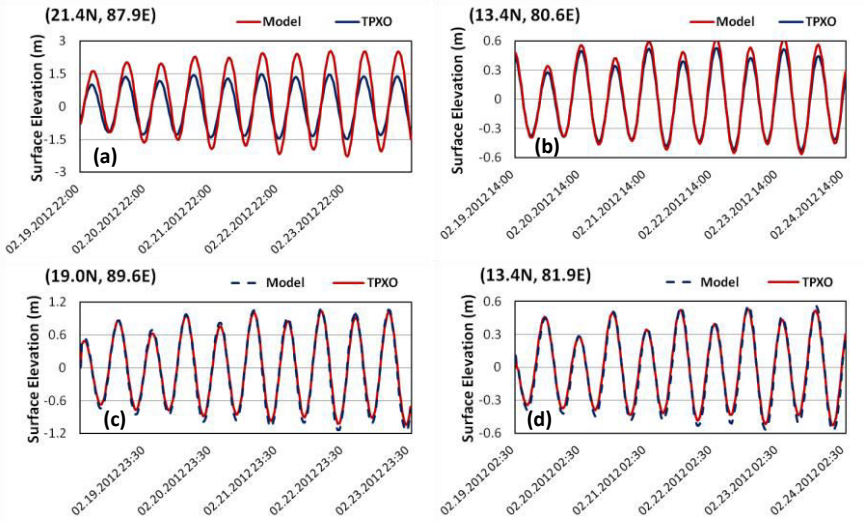


Figure: Comparison of model surface elevation (m) during observational period with TPXO data at local depths of (a) 50m ,(b) 300m, (c) 2000m and (d) 3000m.

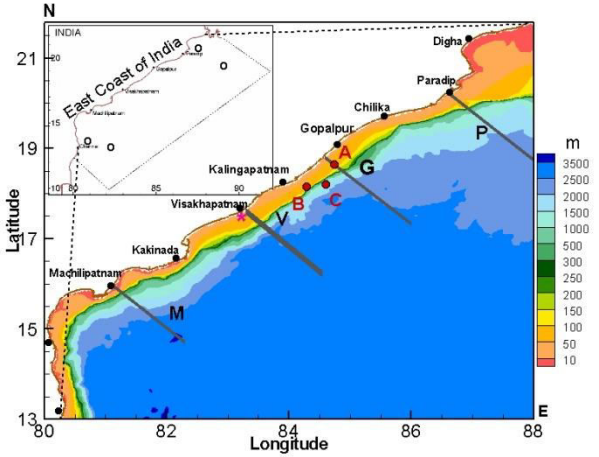


Figure: Model analysis area shown in the inset map; Red dots depict the locations of *in-situ* observations during 19-21 February 2012 at Stn A, B and C. Tide gauge location is marked by star. The locations of TPXO are marked in circles in the inset.

In-situ temperature data and MODEL simulation

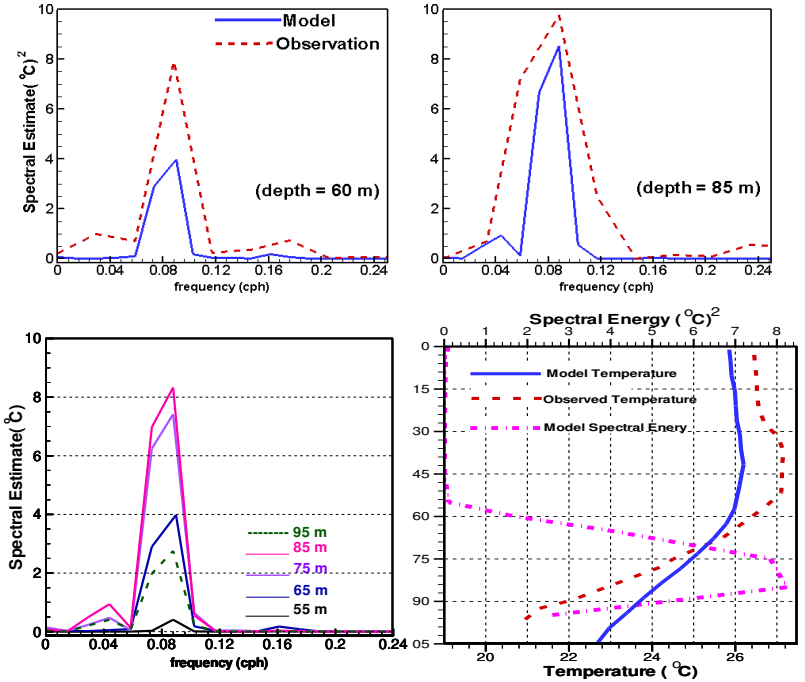


Figure : Estimates of spectral energies during 19-21 Feb 2012 at Stn A; (a, b) comparison at depths 60m 85m; (c) IW spectral energy at different depths; (d) vertical temperature & associated energy due to semidiurnal tide

Satellite imageries showing IWs over the shelf-slope region in western Bay of Bengal

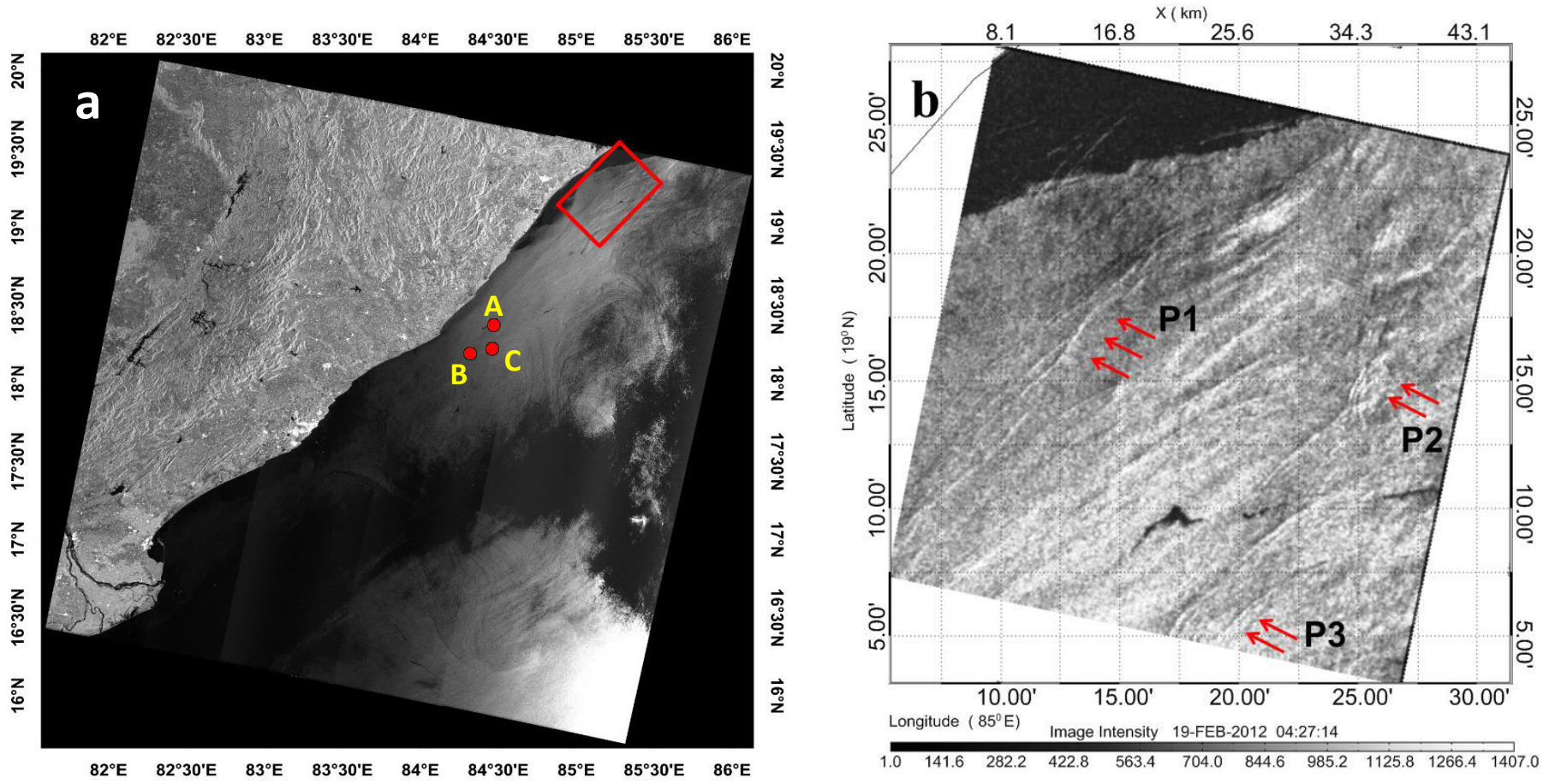
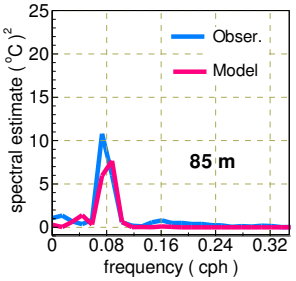


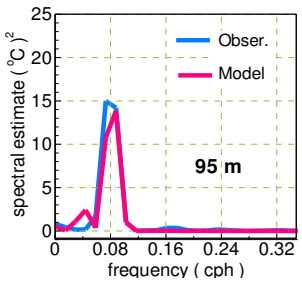
Figure : Surface signatures of internal waves on 19 Feb 2012 (b) Closer look of three groups of rank ordered internal wave packets.

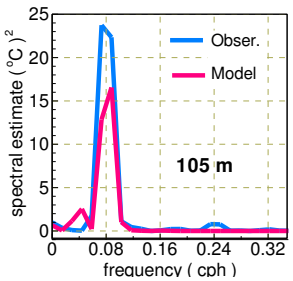
Model Validation:

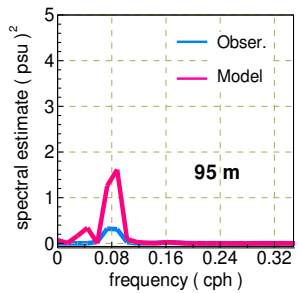
For 20-23 Dec 2013

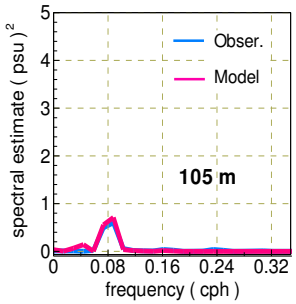
Station A (18˚36.54' N, 84˚47.24' E, Station depth 113m)

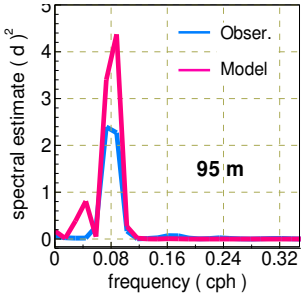


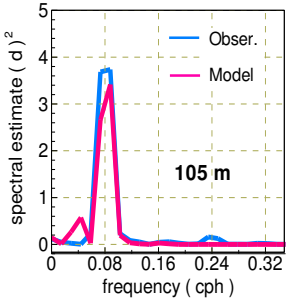




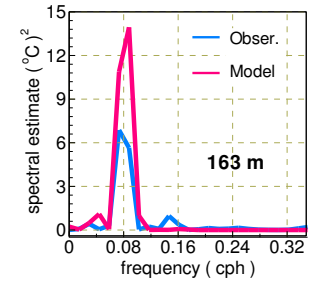


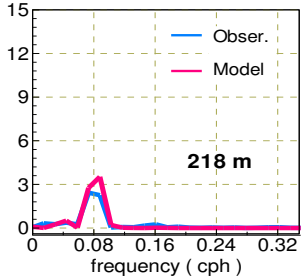


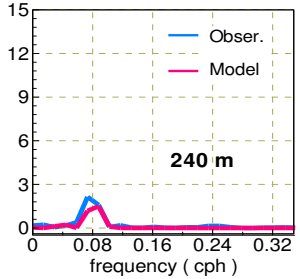




Station C (18˚15.58' N, 84˚30.51' E, Station depth 265m)







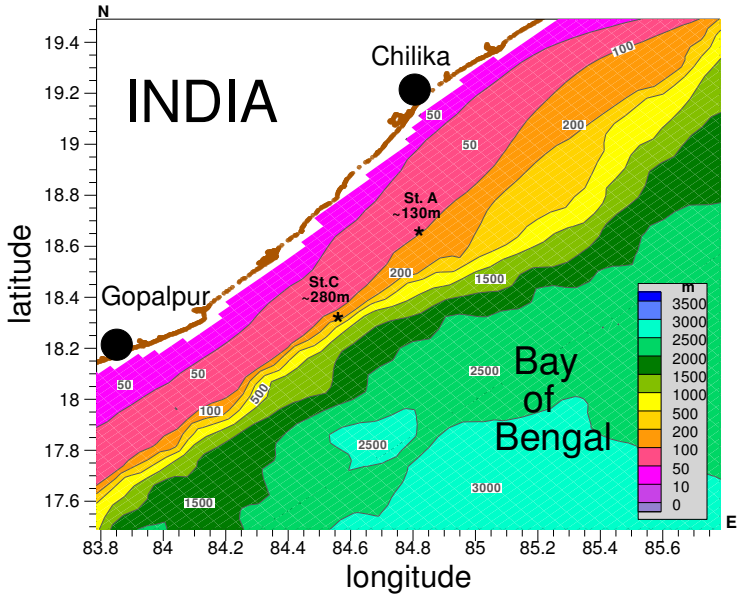
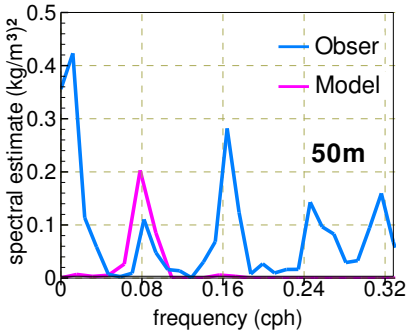
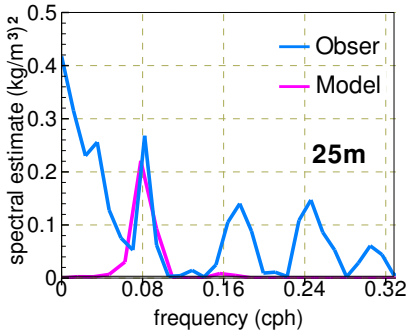


Fig: Bathymetry of the model domain

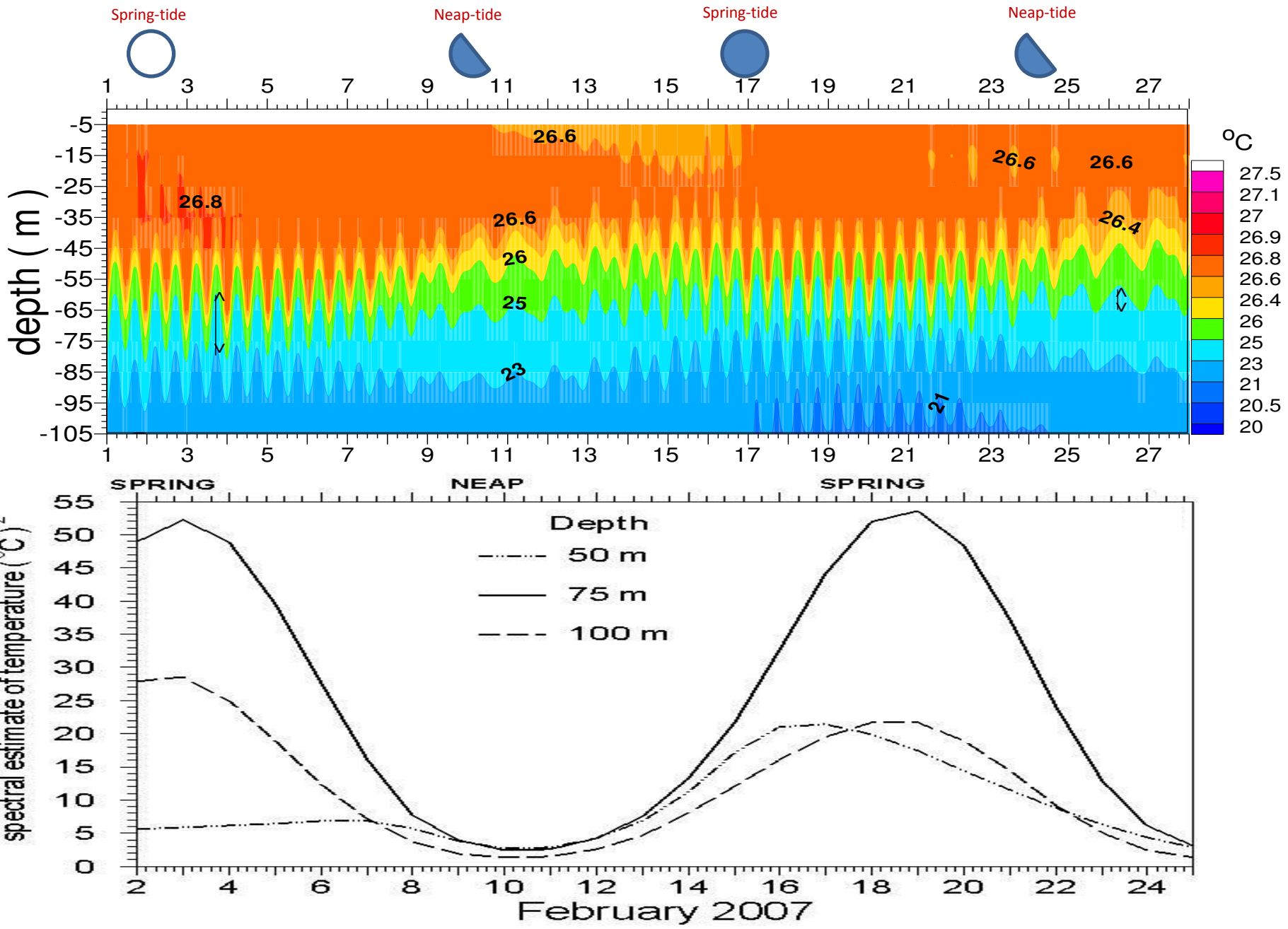
For 27-30 August 2013

Station A

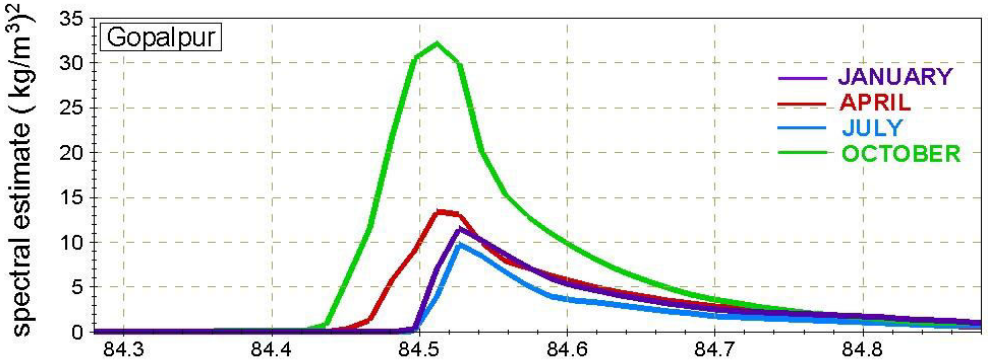


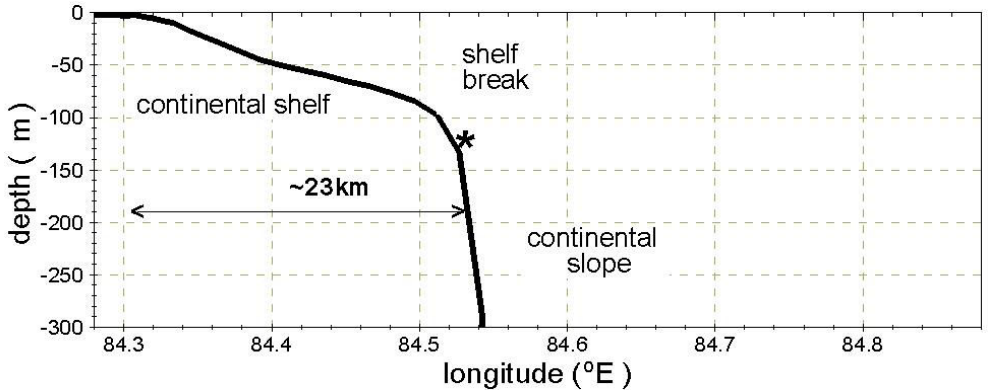


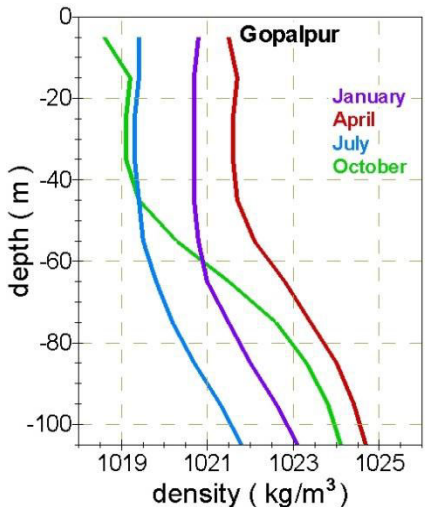
Intra-tidal variability of IWs off Gopalpur

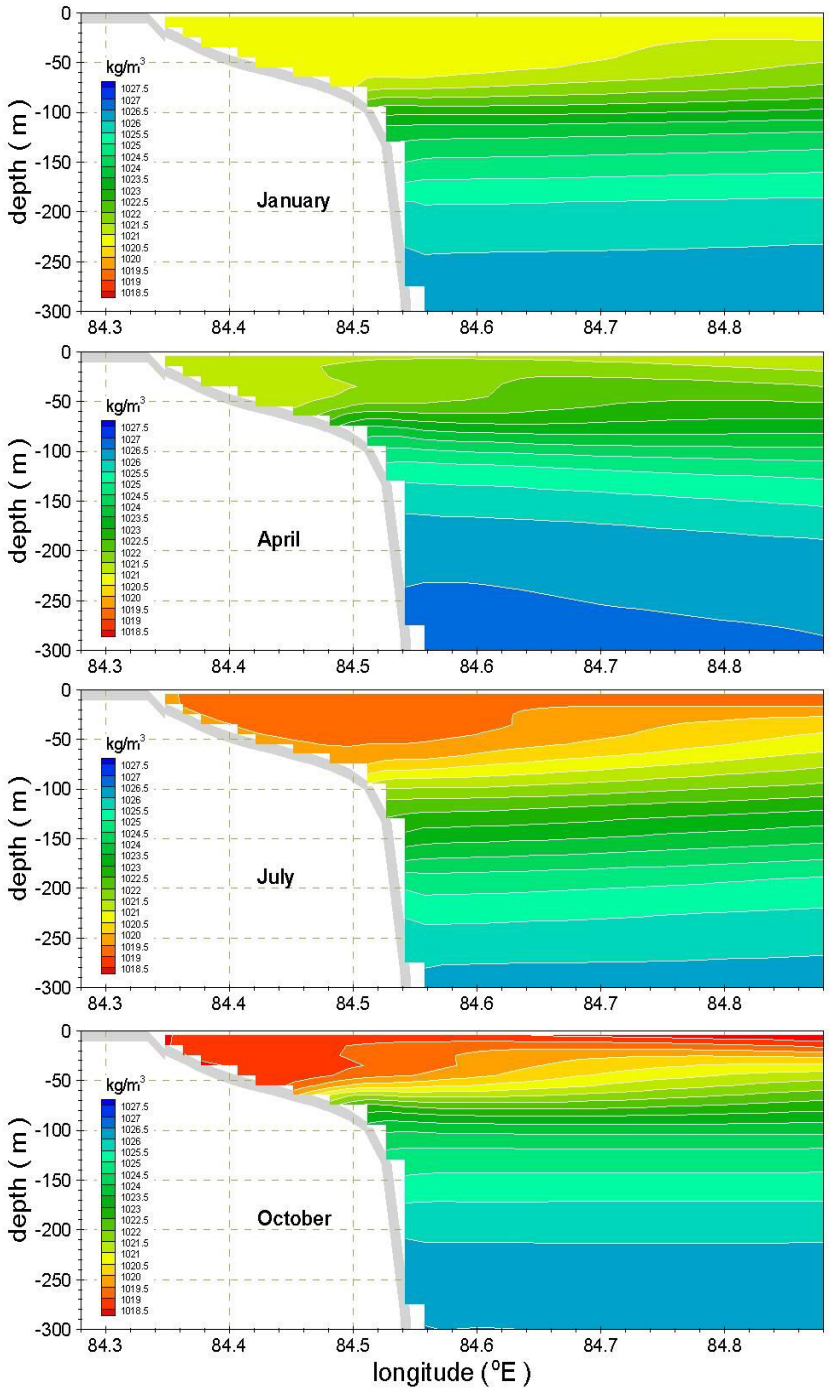


Inter-seasonal variability of Internal tides off Gopalpur

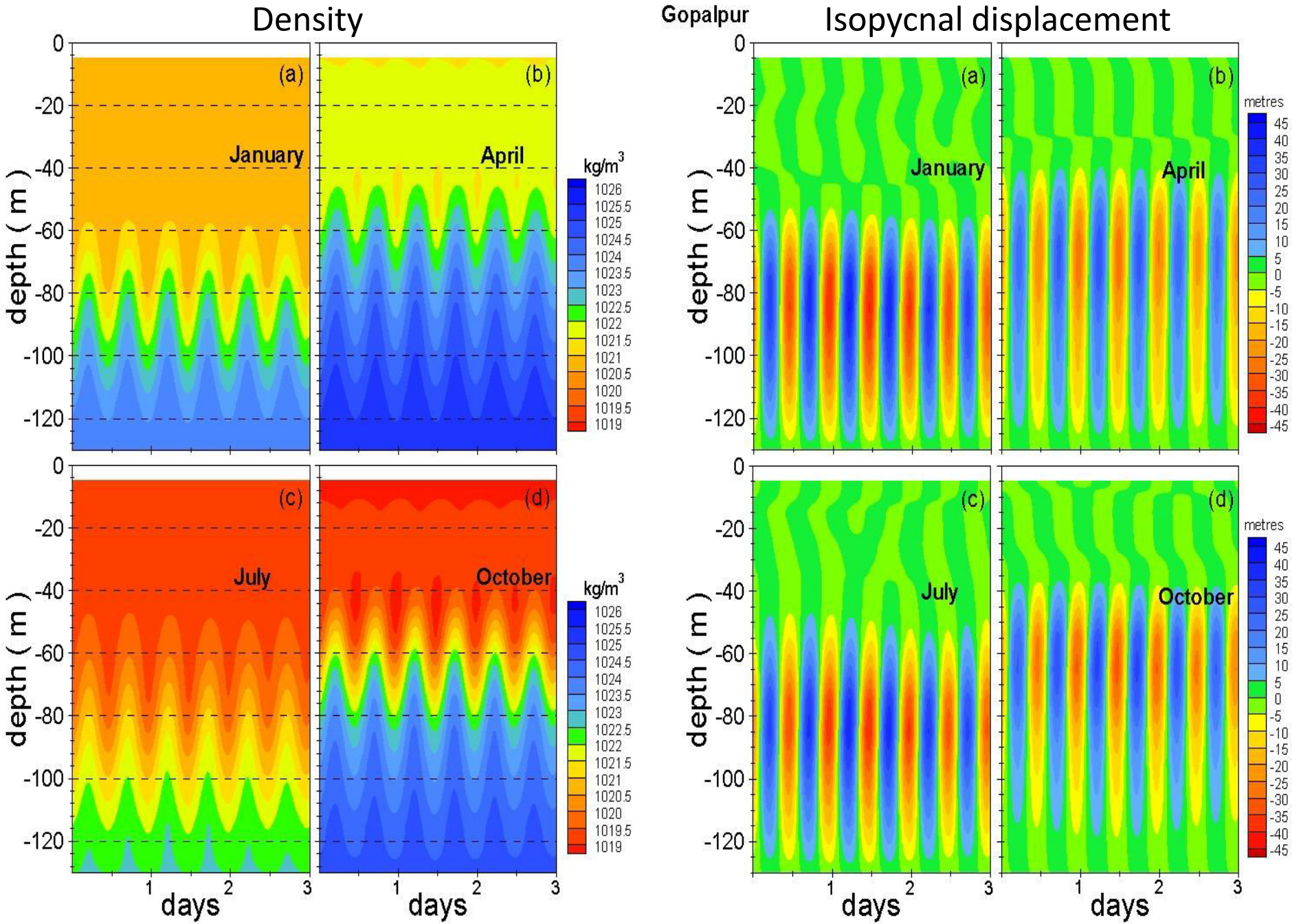








Density oscillations and isopycnal displacement at shelf break off Gopalpur



Snapshots of vertical velocity off Gopalpur

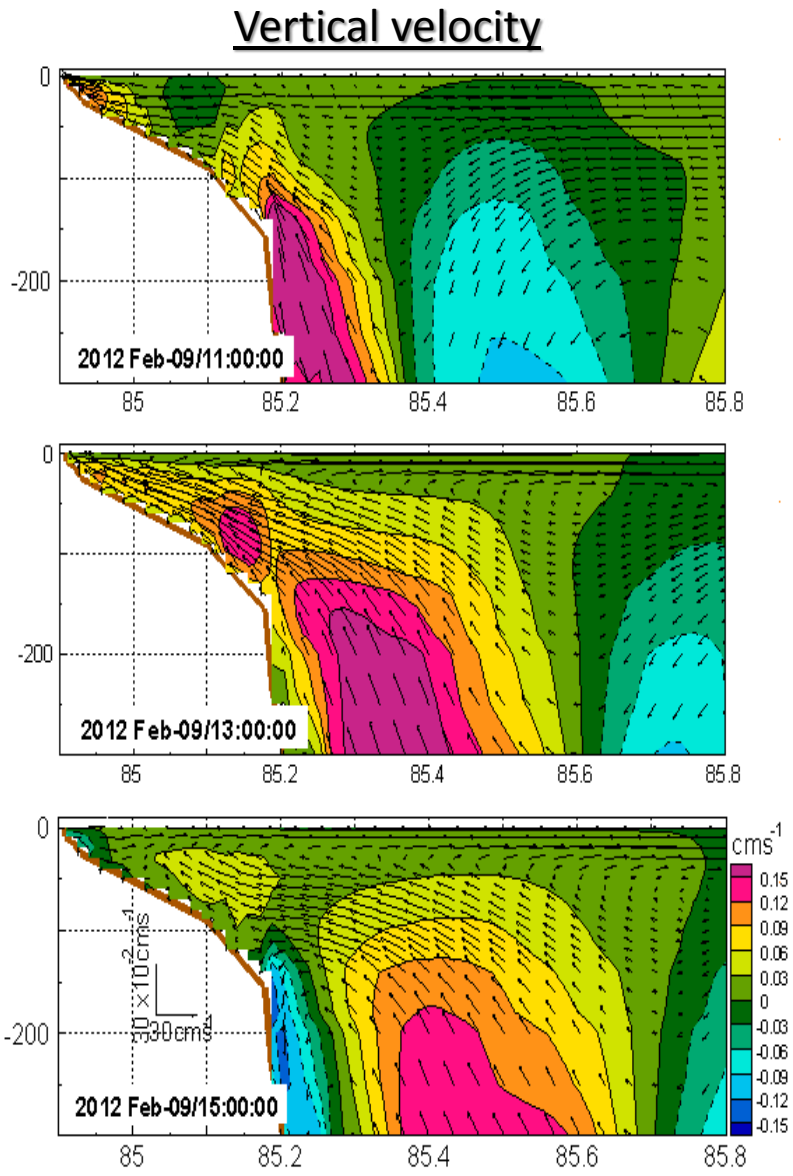
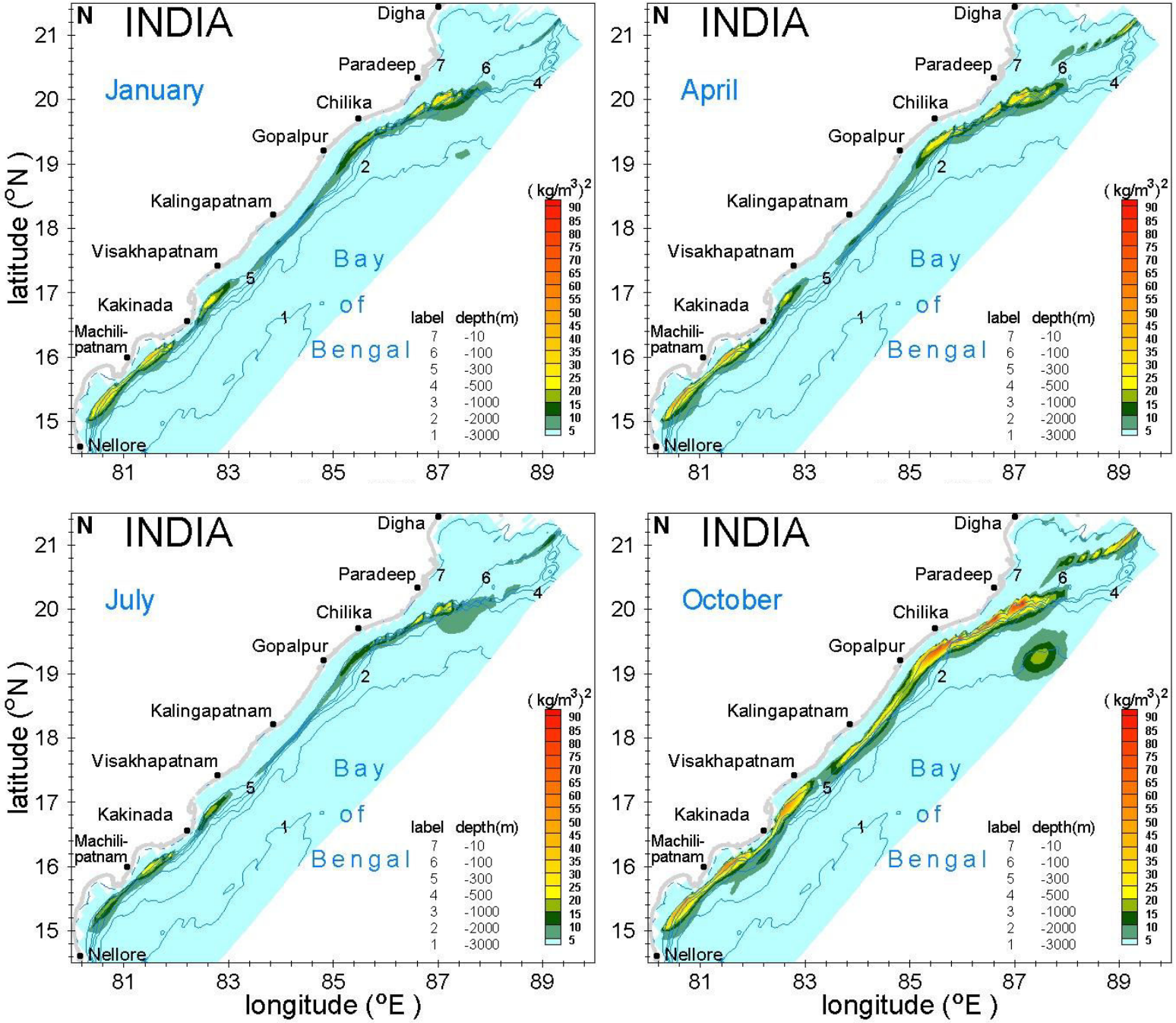


Figure: Snapshots of vertical velocity (shaded) and currents (vectors) at 2-hour interval off Gopalpur.

Inter-seasonal variability of Internal tides in the domain



Experiments with shelf width & shelf break depth

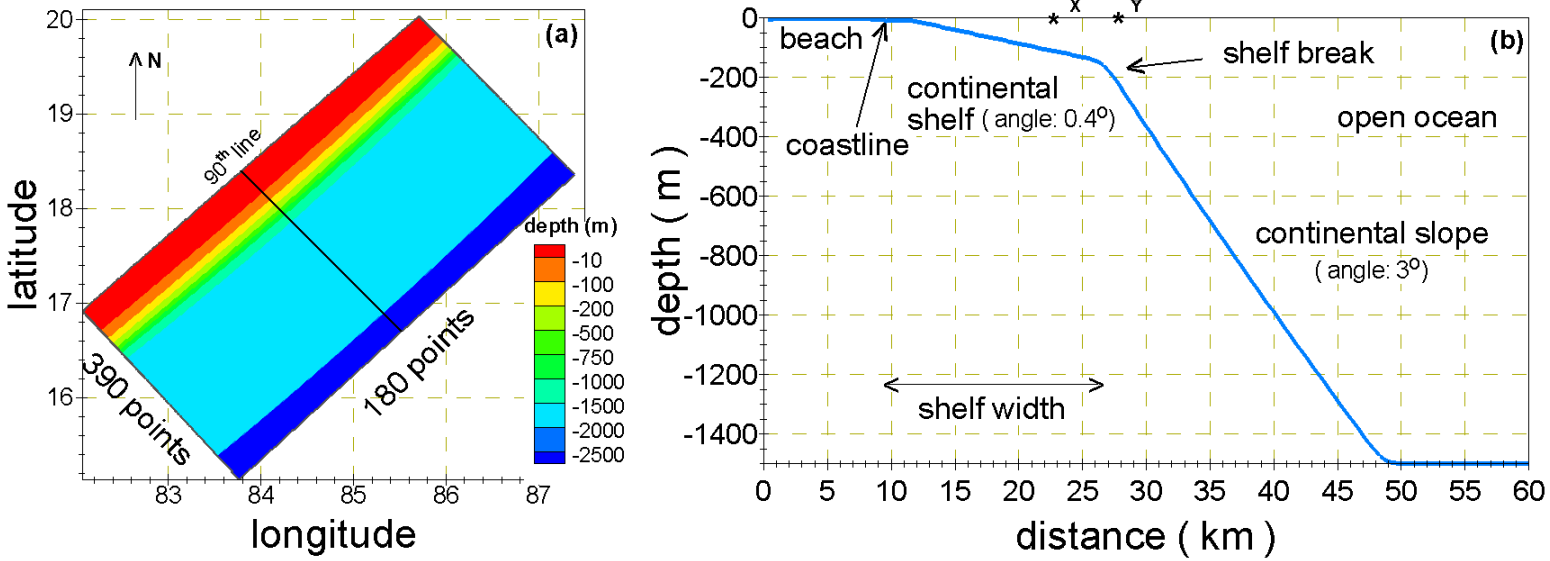


Figure: (a) Schematic representation of model domain along with bathymetry, (b) representative bottom topography showing continental shelf, shelf break and continental slope.

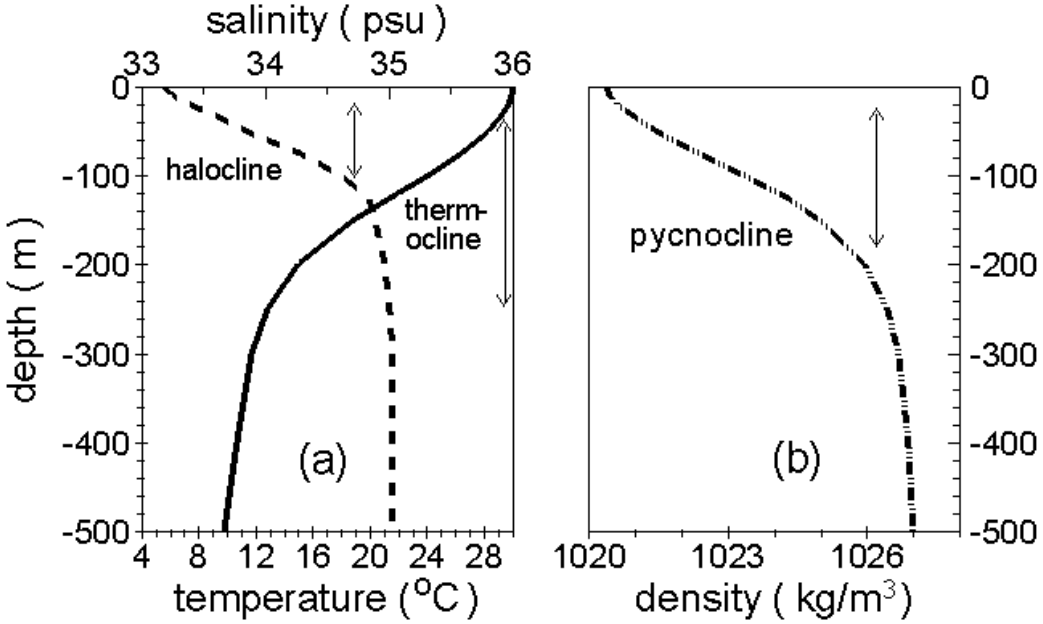


Figure: Vertical profile representative of May (a) Temperature and Salinity, (b) Density.

Idealized experiments :

Experiments with continental shelf angle and stratification

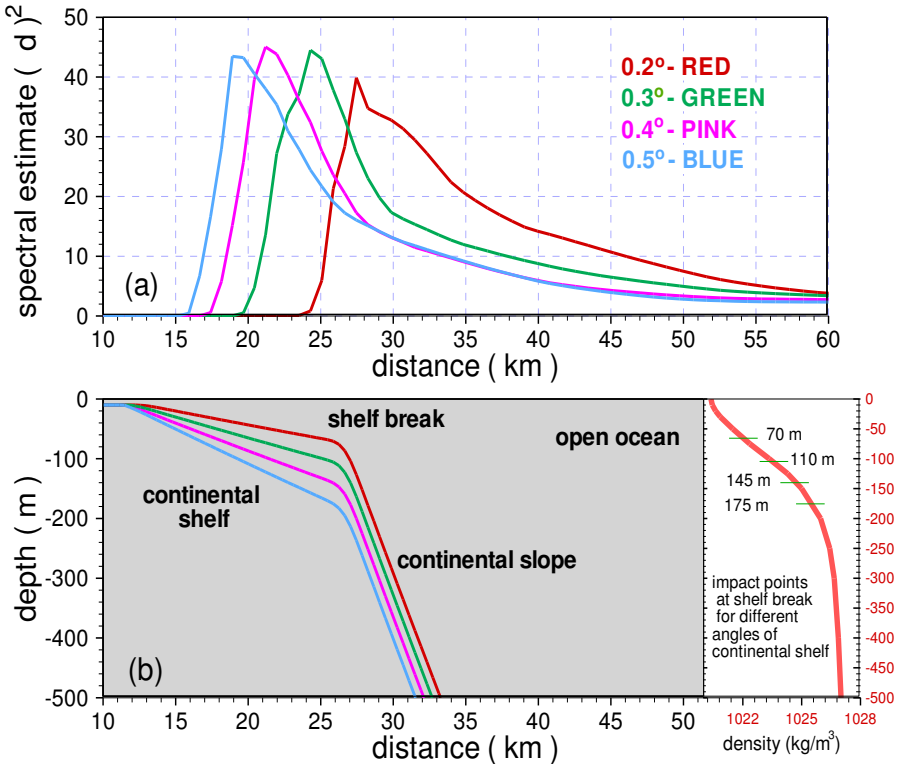


Figure: Spectral estimate of density across all cross-sections. (b) Bottom topography normal to the shelf for all angles (left) and vertical density profile (right).

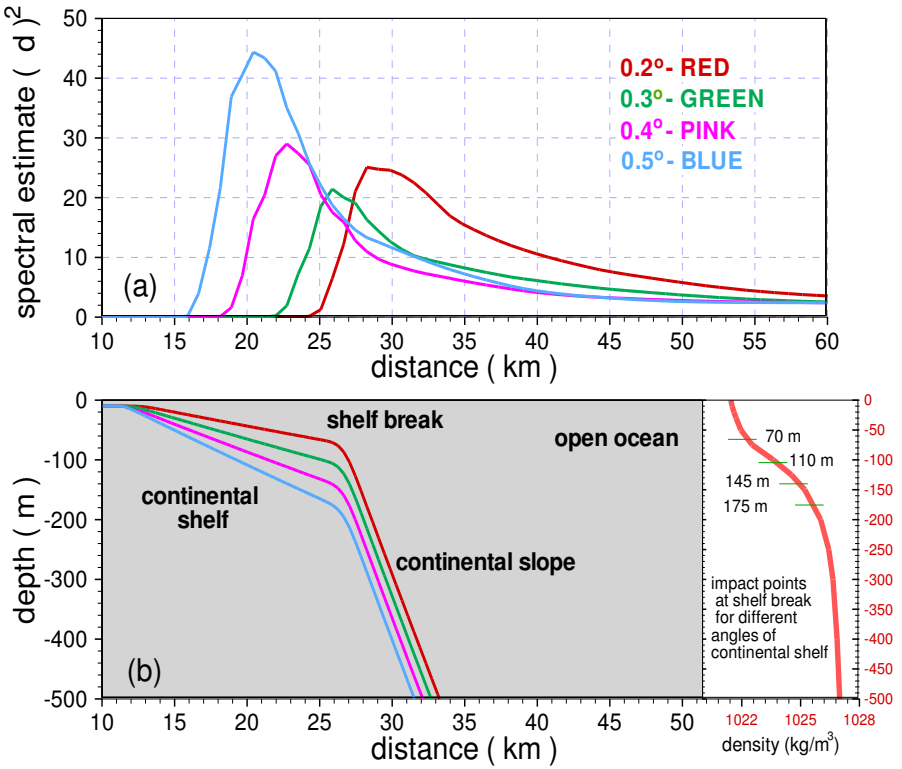
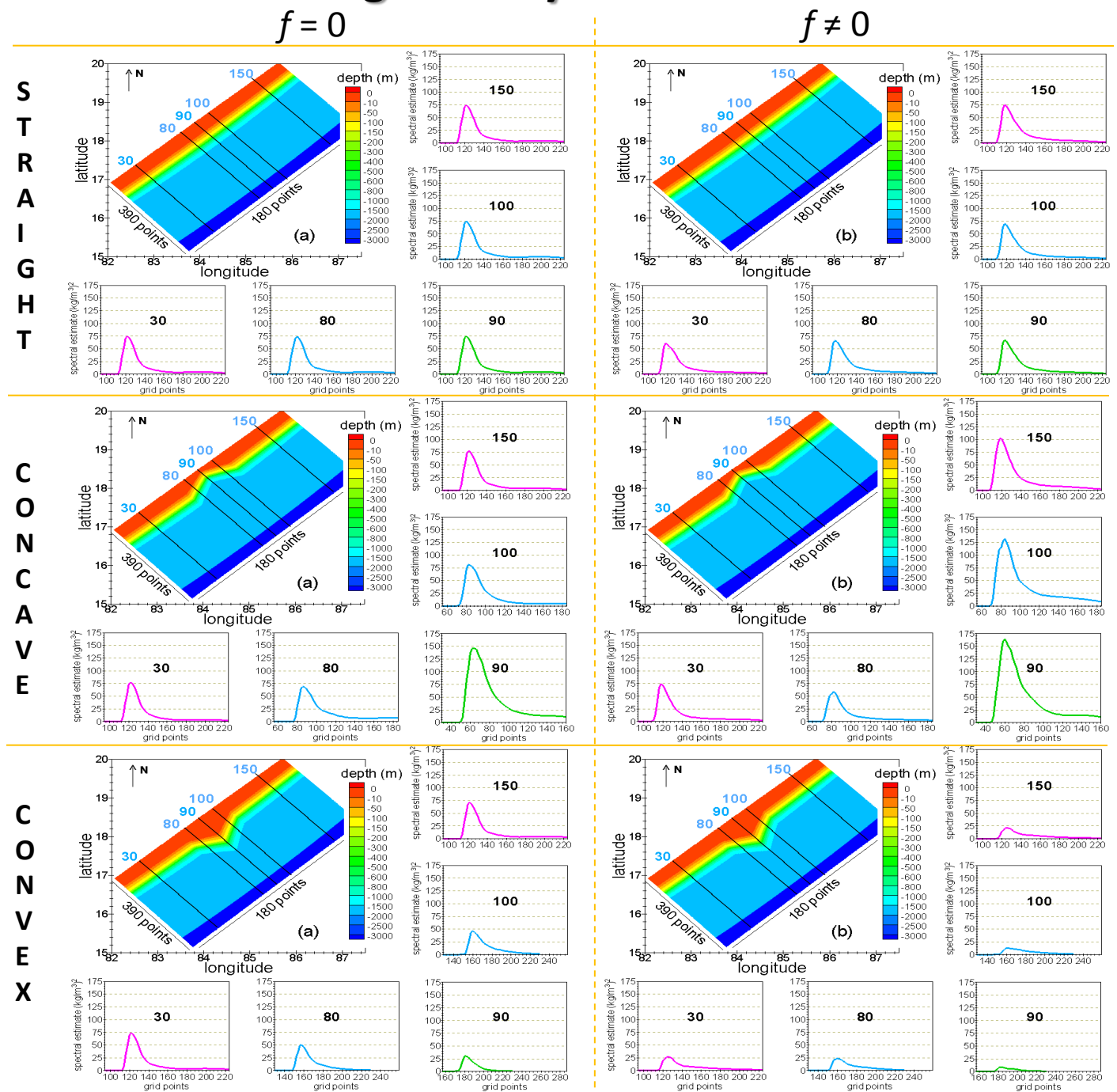


Figure: (a) Spectral estimate of density across all cross-sections. (b) Bottom topography normal to the shelf (left) for all angles and vertical density profile (right).

Effect of Coastal geometry with and without rotation :



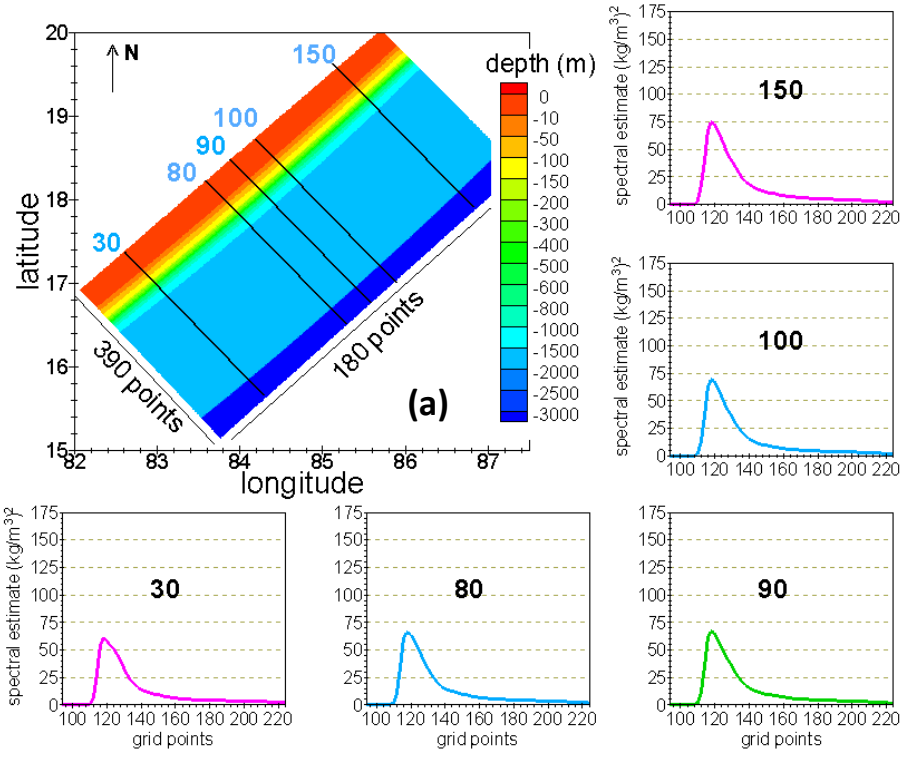
- ✓ The estimate remains the same for $f = 0$.
- ✓ The estimate increases towards the right for $f \neq 0$.

- ✓ The estimate is symmetric with maximum in the concave region for $f = 0$.
- ✓ The estimate increases towards the right but have maxima in the concave part for $f \neq 0$.

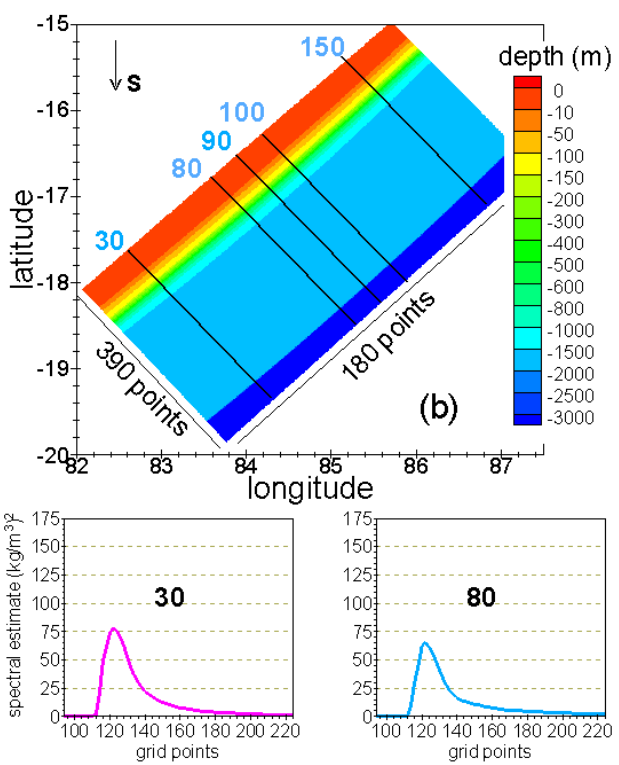
- ✓ The estimate is symmetric with a minima in the convex portion for $f = 0$.
- ✓ The estimate is minimum in the convex portion and the values are less for $f \neq 0$.

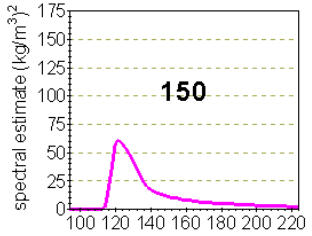
Internal tides in both the hemisphere

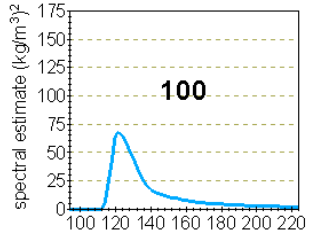
Northern hemisphere

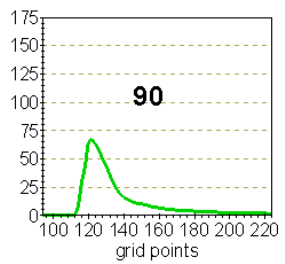


Southern hemisphere





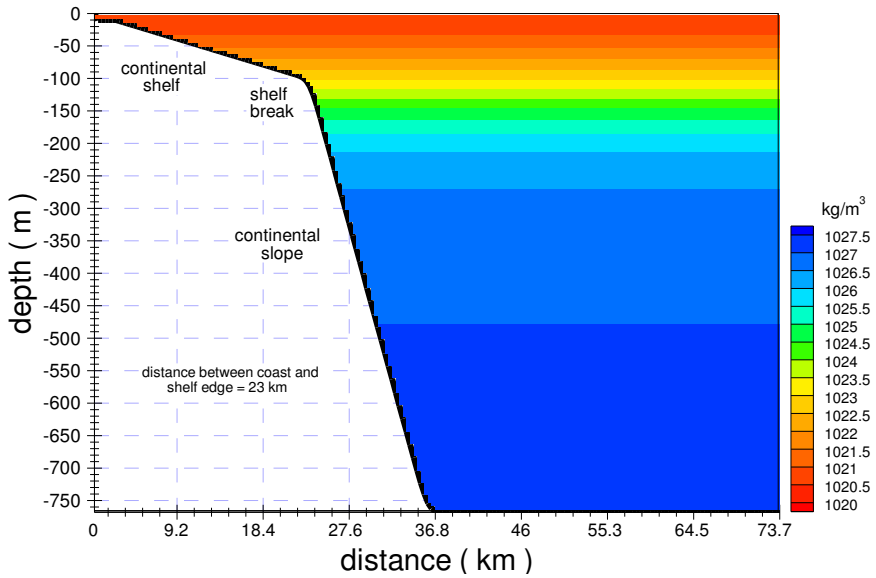


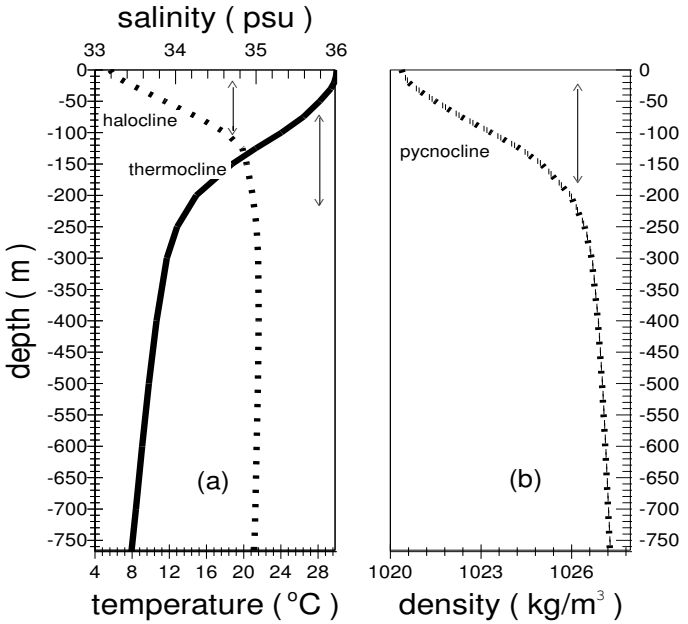


Summary:
The estimate increases from south to north in the northern hemisphere while it increases from north to south in the southern hemisphere.

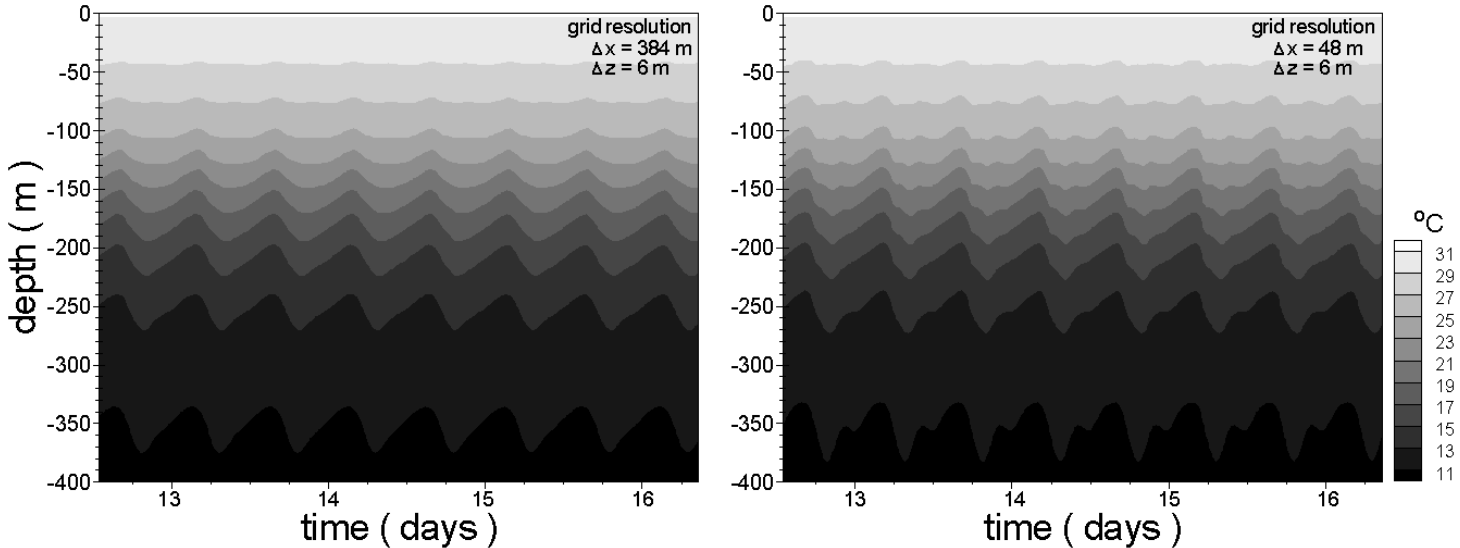
Higher frequency and High resolution modelling : simulations for different model resolutions (semi-diurnal tidal forcing)

Initial state of the 2D-model: bathymetry and density





Time-series of temperature for two different model resolutions

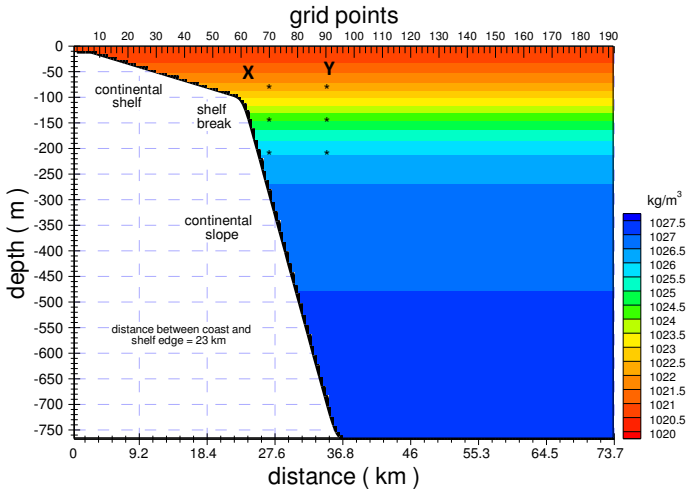


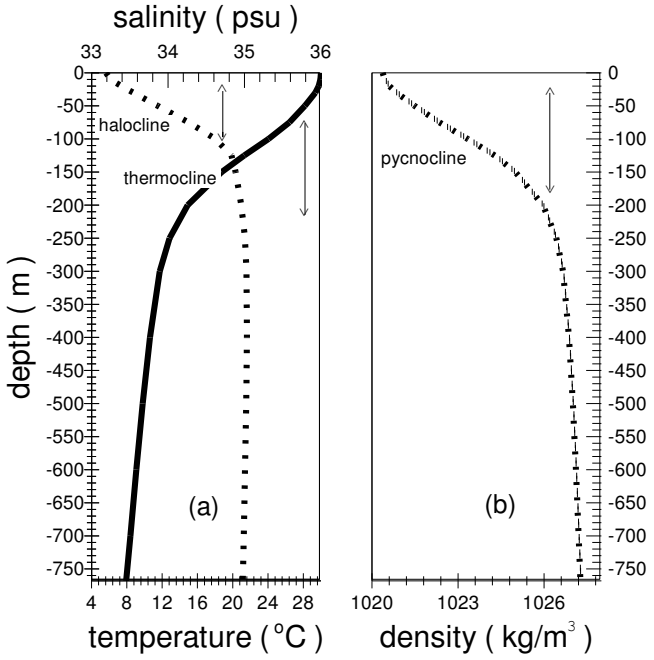
- Computational time (for 30 days simulation) and matrix size:

Δ x = 384m is 12 hours
Matrix size: 192 x 128

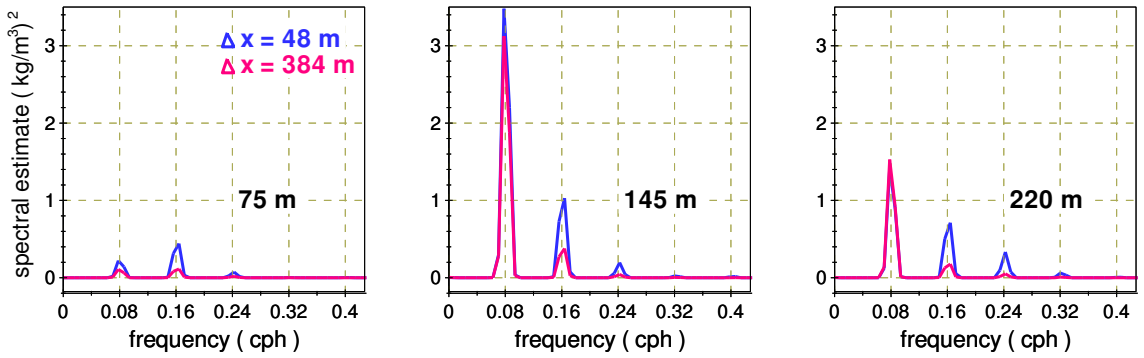
Δ x = 48m is 1.5 days
Matrix size: 1536 x 128

Spectral analysis for density with different model resolutions

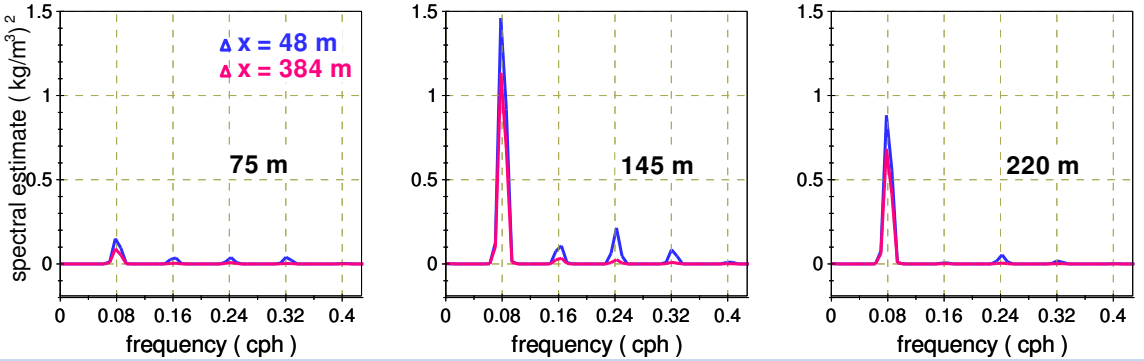




Stn. X



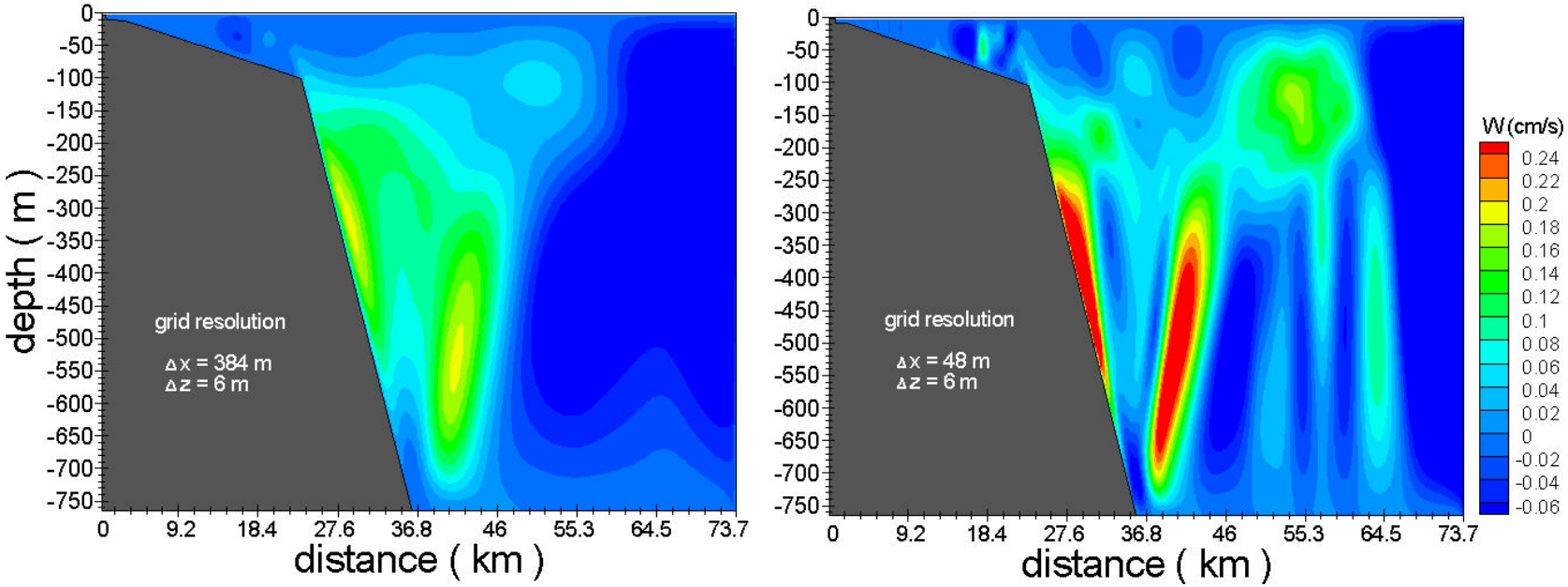
Stn. Y



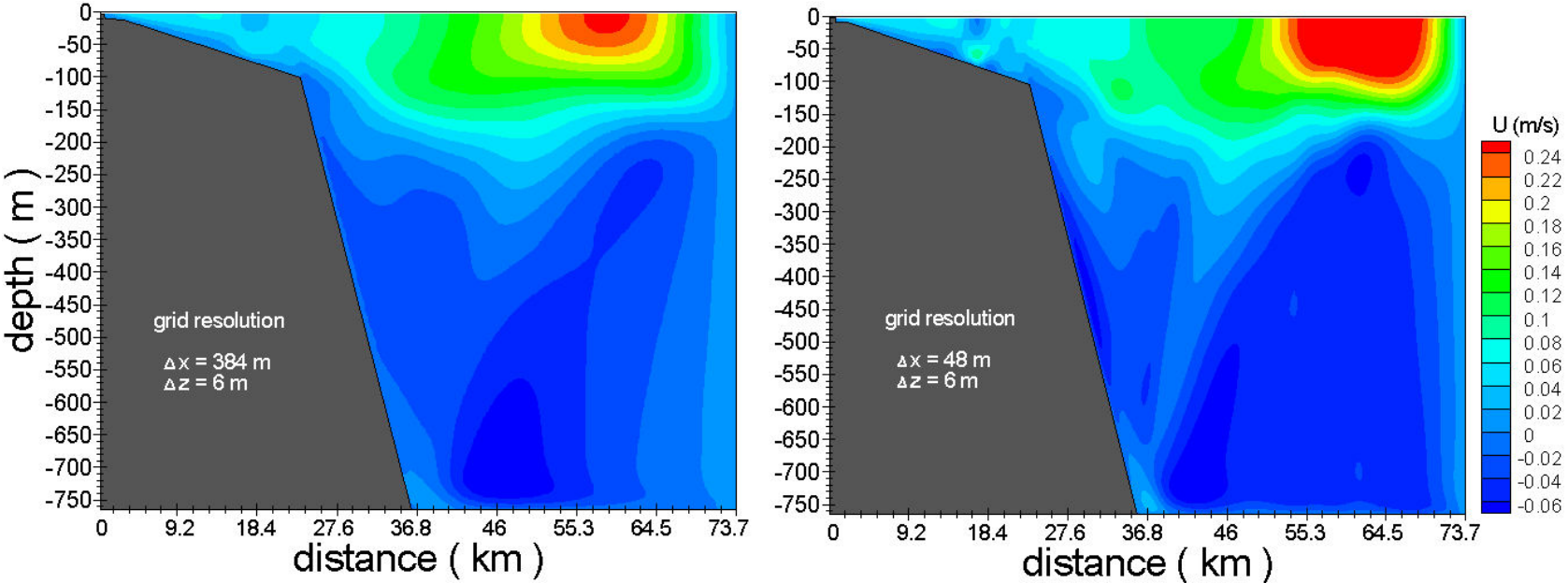
Summary:

- High-frequency (HF) IWs are captured well **with high -resolution** model, i.e. **when Δ x : 48 m**
- Semi-diurnal estimate remains almost same while the estimate of HF IWs are large with high-resolution model.
- The estimate are **higher near the shelf-slope** topography. i.e. Stn. X as compared to Stn. Y.
- **12, 6, 4.12, 3.12, 2.5 hrs : : 0.08, 0.16, 0.24, 0.32, 0.4 cph**

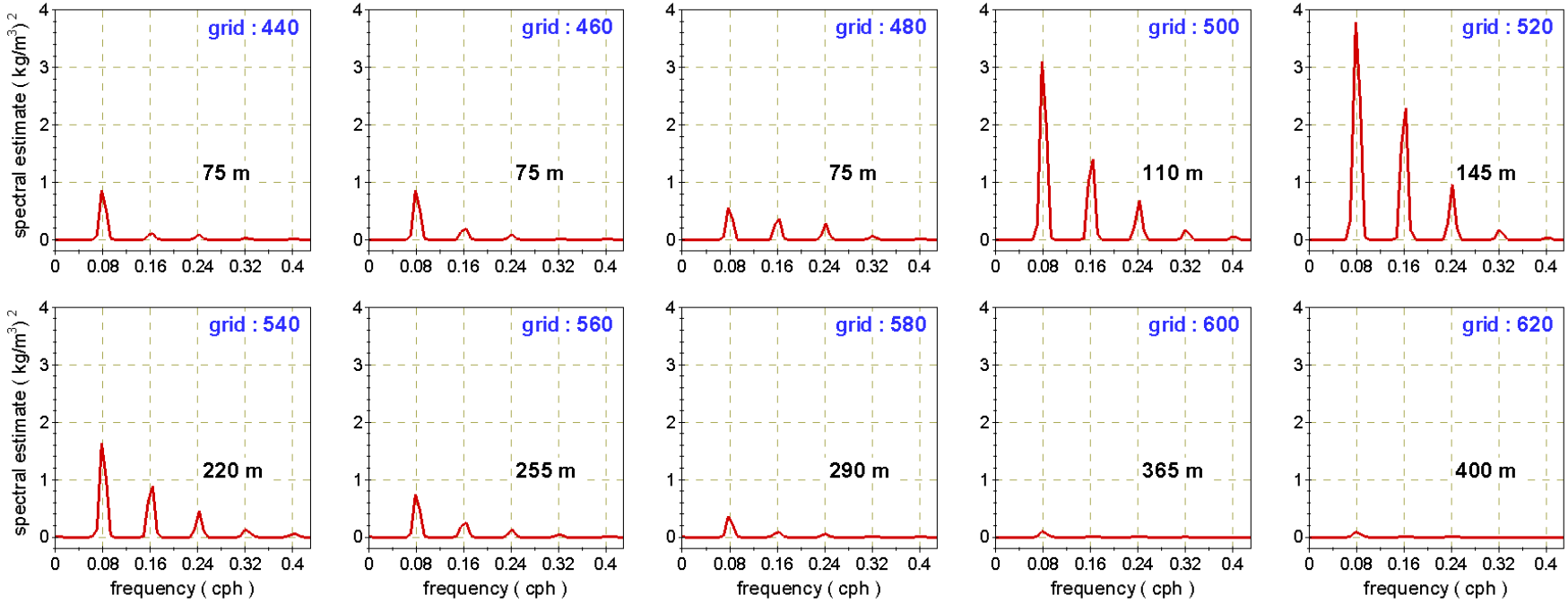
Vertical velocity for different model resolutions (snap-shot)

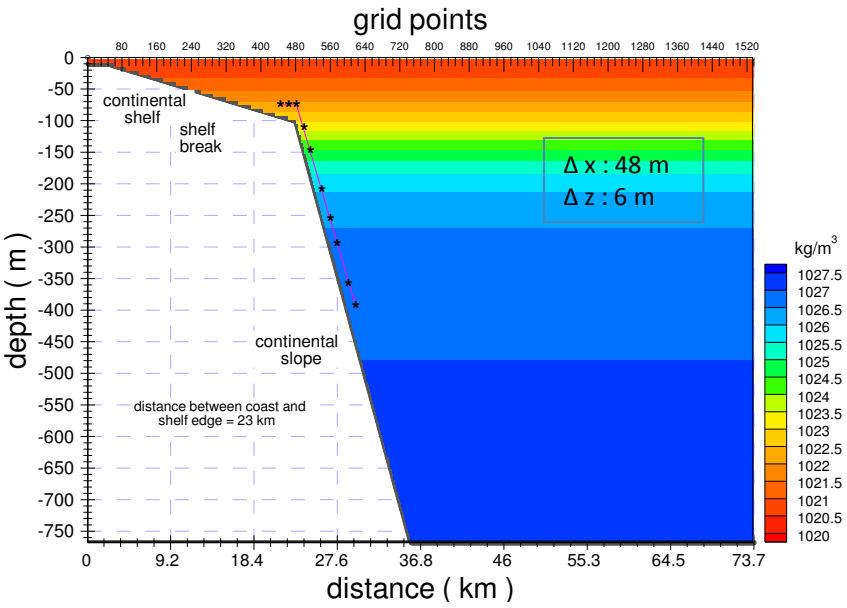


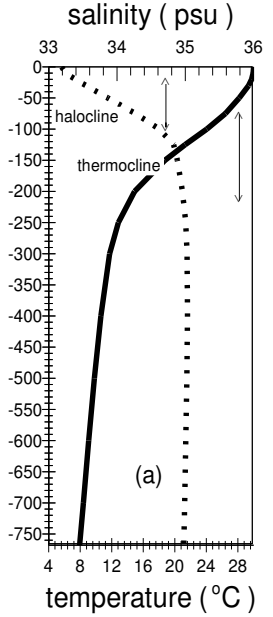
Horizontal velocity for different model resolutions (snap-shot)

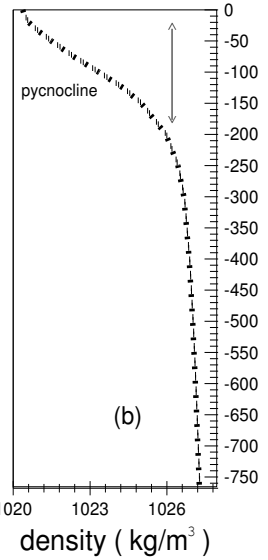


High-frequency zone in the shelf-slope region







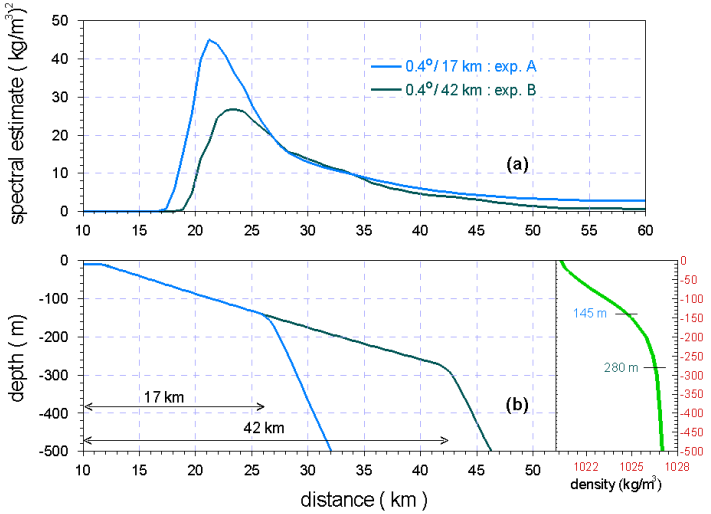


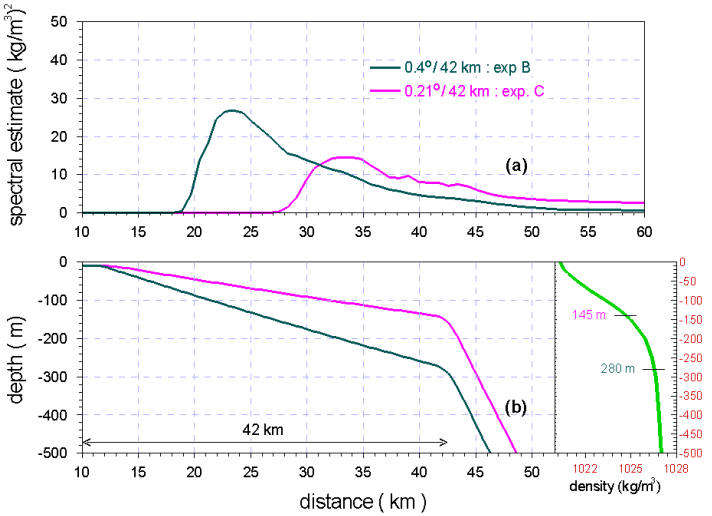
Summary:

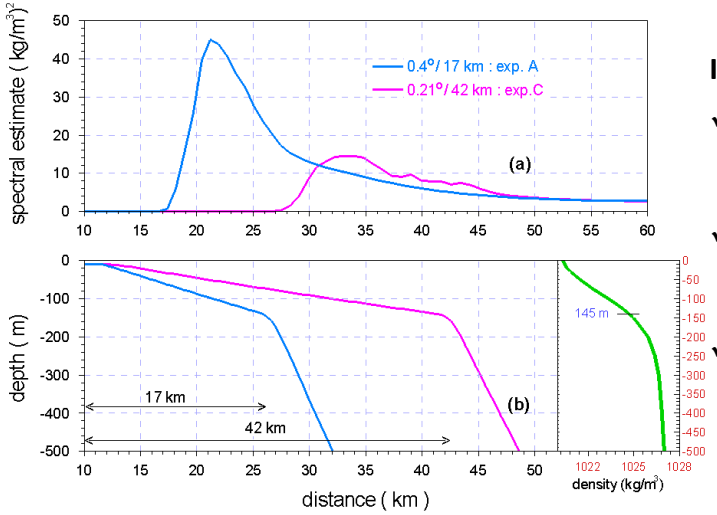
- Low-frequency (LF) IWs of 12 hr period and High-frequency (HF) IWs of **6 hrs, 4.12 hrs, 3.12 hrs, 2.5 hrs** are detected in the density spectra.
- HF IWs are more evident from **75m to 220m** depth. i.e. in the **pycnocline** and very near to the **shelf-slope topography**.

Thank You

Experiments with shelf width & shelf break depth (conti….)



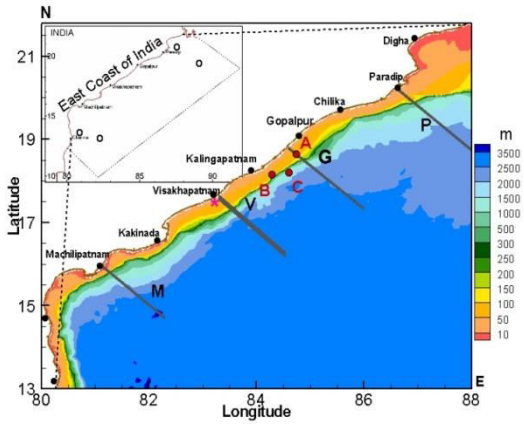




Inferences:

- ✓ Both the shelf break depths falls in the pycnocline.
- ✓ The smaller width induces larger estimates.
- ✓ Propagation over smaller width is 7km and larger width is 15km.

Vertical temperature with and without tide at different cross-sections



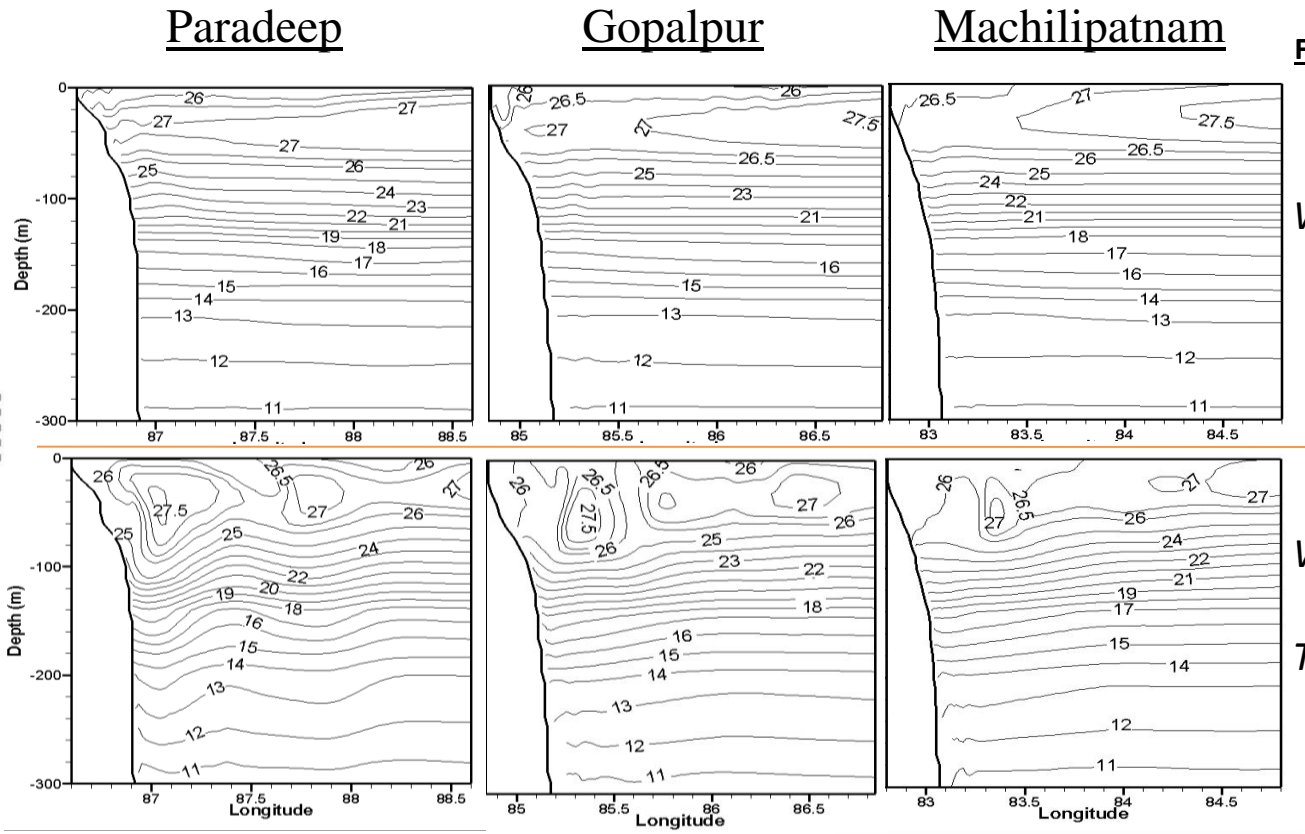


Figure: Model analysis area shown in the inset map; Bathymetry (m) of the area of interest along the coast with the cross-shelf sections Paradeep:P, Gopalpur:G, Visakhapatnam:V and Machilipatnam:M; Red dots depict the locations of *in-situ* observations during 19-21 February 2012 at Stn A, B and C.

Influence of local coastal geometry and continental shelf on IWs

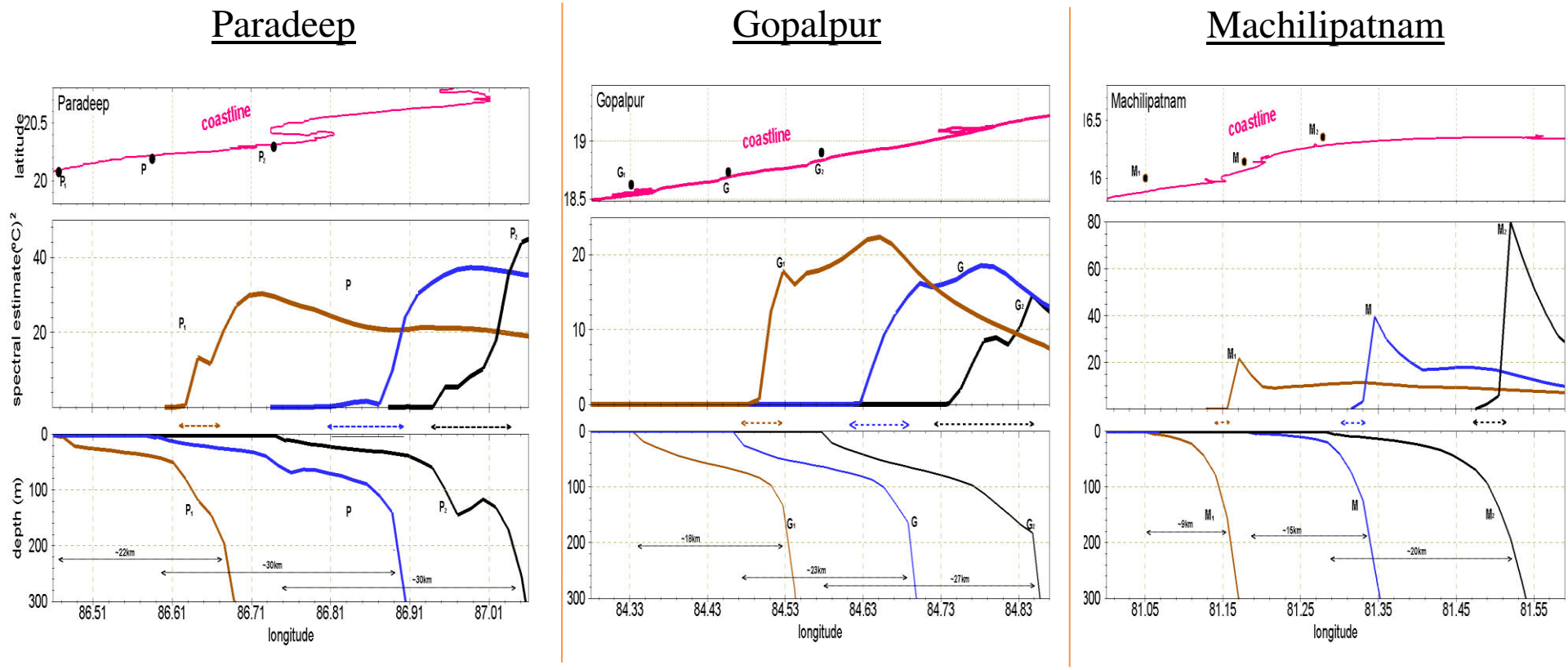
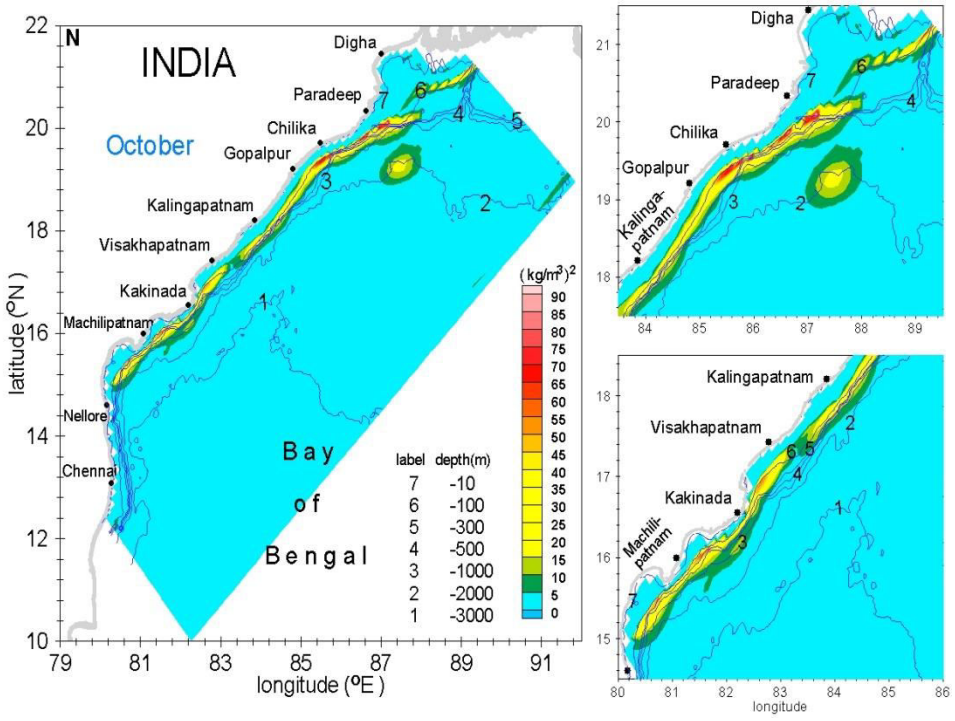
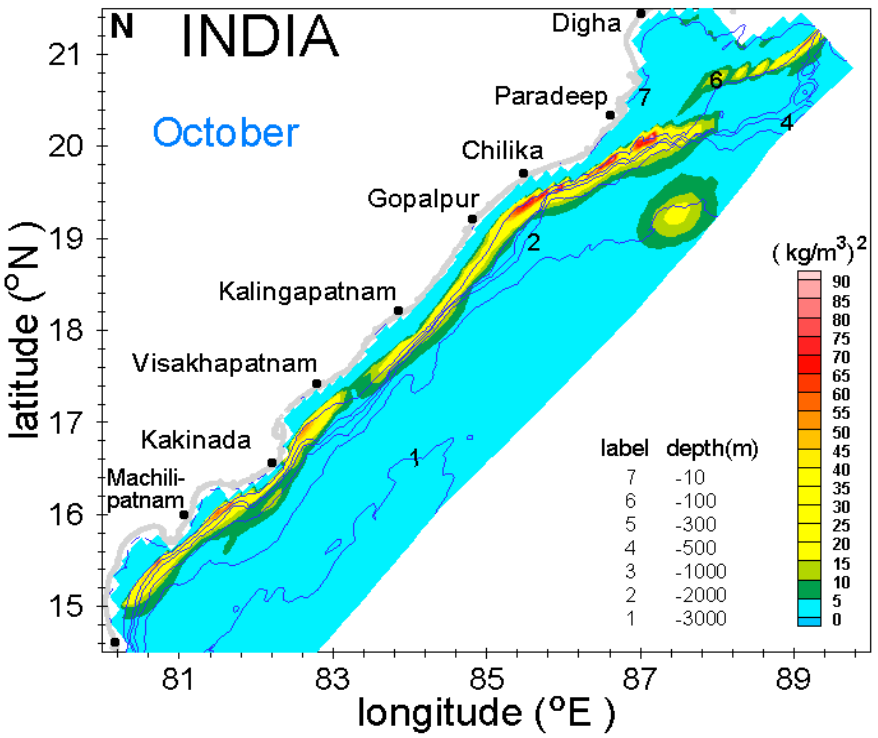
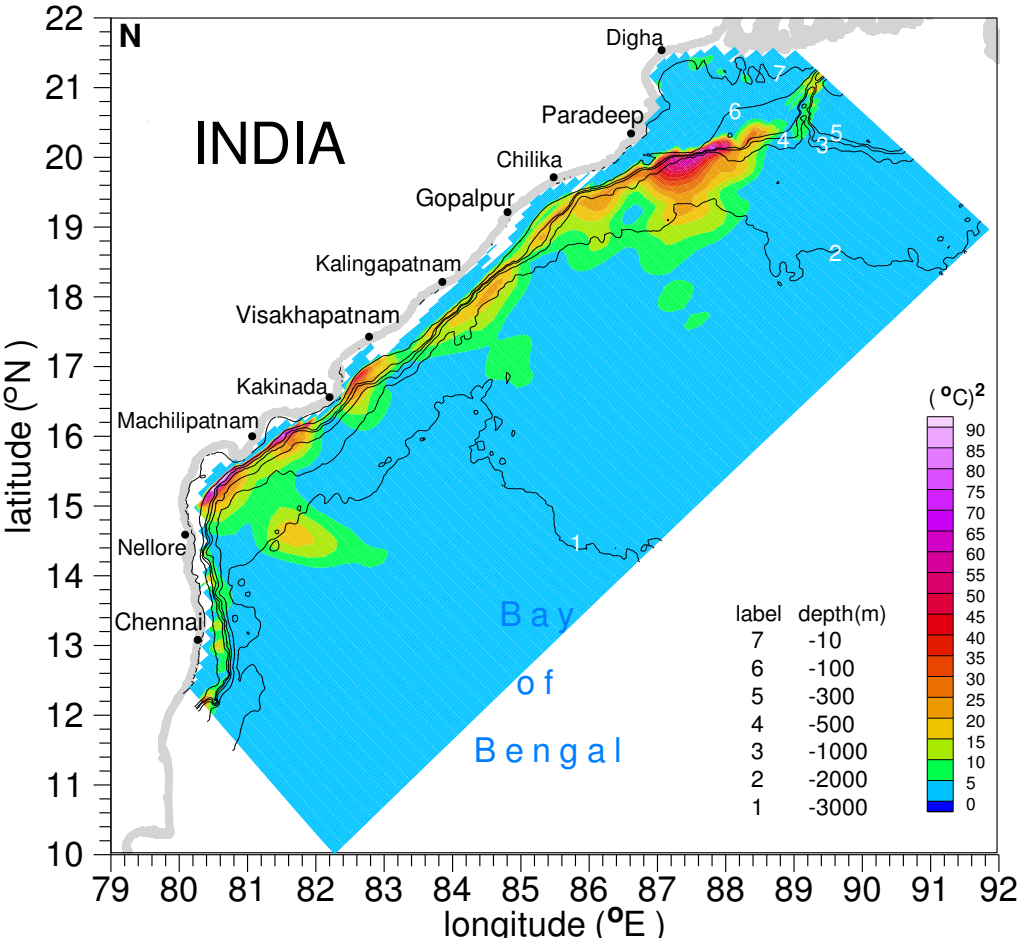


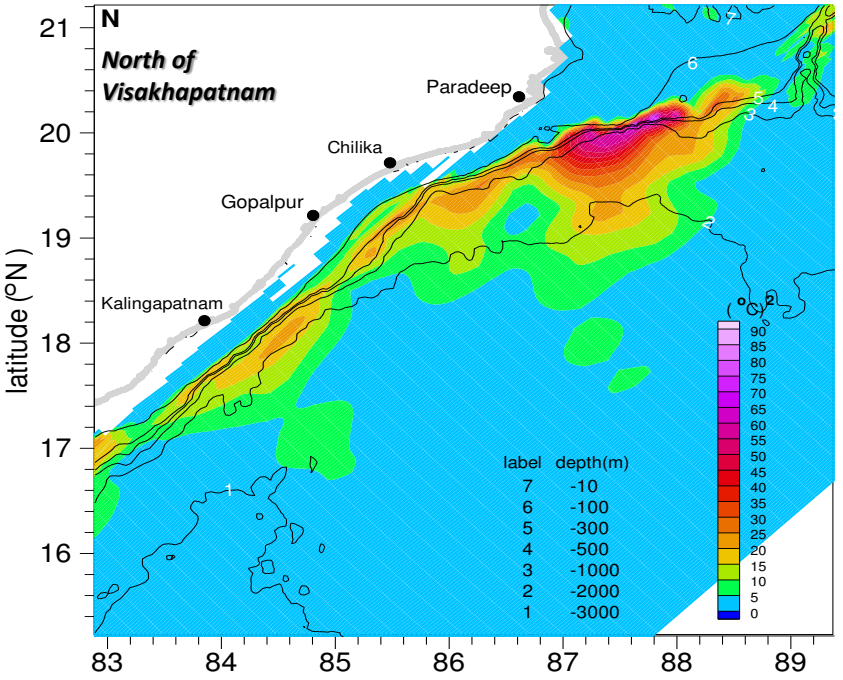
Figure: Upper panel - Local coastline off Paradeep(P_1,P,P_2), Gopalpur(G_1,G,G_2) and Machilipatnam(M_1,M,M_2).
Middle panel - Spectral estimate of temperature (^{o} C)^2 at these cross-sections.
Lower panel - Bathymetry of these cross-sections.

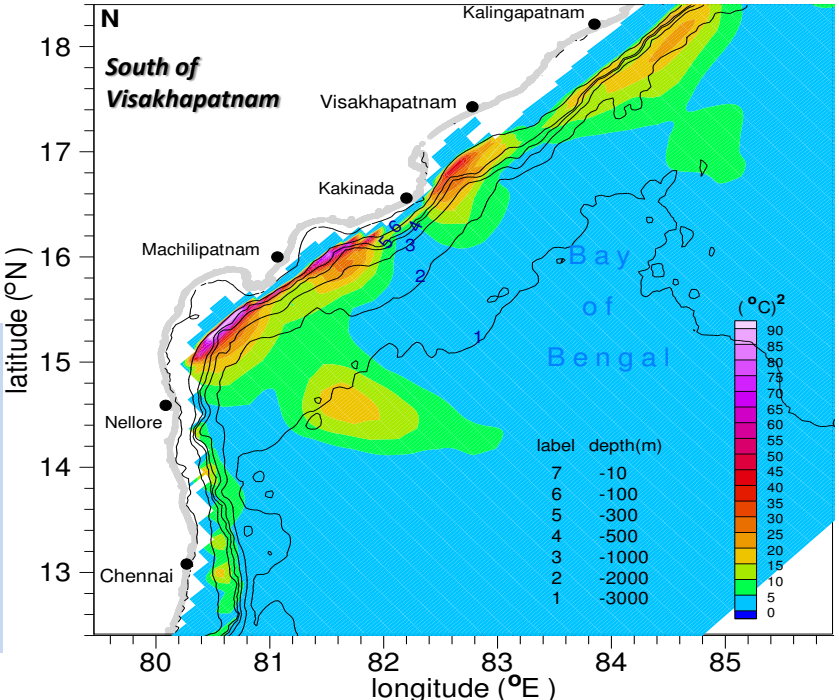

N
INDIA
October
Bay
of
Bengal
Digha
Paradeep
Chilika
Gopalpur
Kalingapatnam
Visakhapatnam
Kakinada
Machilipatnam
Nellore
Chennai
label depth(m)
7 -10
6 -100
5 -300
4 -500
3 -1000
2 -2000
1 -3000
(kg/m3)2
latitude (°N)
longitude (°E)
Kalinga-patnam
Machili-patnam
longitude


N
INDIA
October
Digha
Paradeep
Chilika
Gopalpur
Kalingapatnam
Visakhapatnam
Kakinada
Machili-patnam
label depth(m)
7 -10
6 -100
5 -300
4 -500
3 -1000
2 -2000
1 -3000
(kg/m3)2
latitude (°N)
longitude (°E)

Spatial distribution of spectral estimates during February 2012







- ✓ The estimates south of Machilipatnam, Kakinada and Visakhapatnam has larger estimates due to their concave coastline and steep slopes.
- ✓ In the northern Bay off Paradeep the higher estimates are seen over a broader region due to a combined effect of higher tidal amplitudes and a steeper slope.
- ✓ The maximum estimate of ~90 $^{o}C^{2}$ is found in the Machilipatnam region.

Snapshots of vertical velocity and temperature off Gopalpur

Vertical velocity

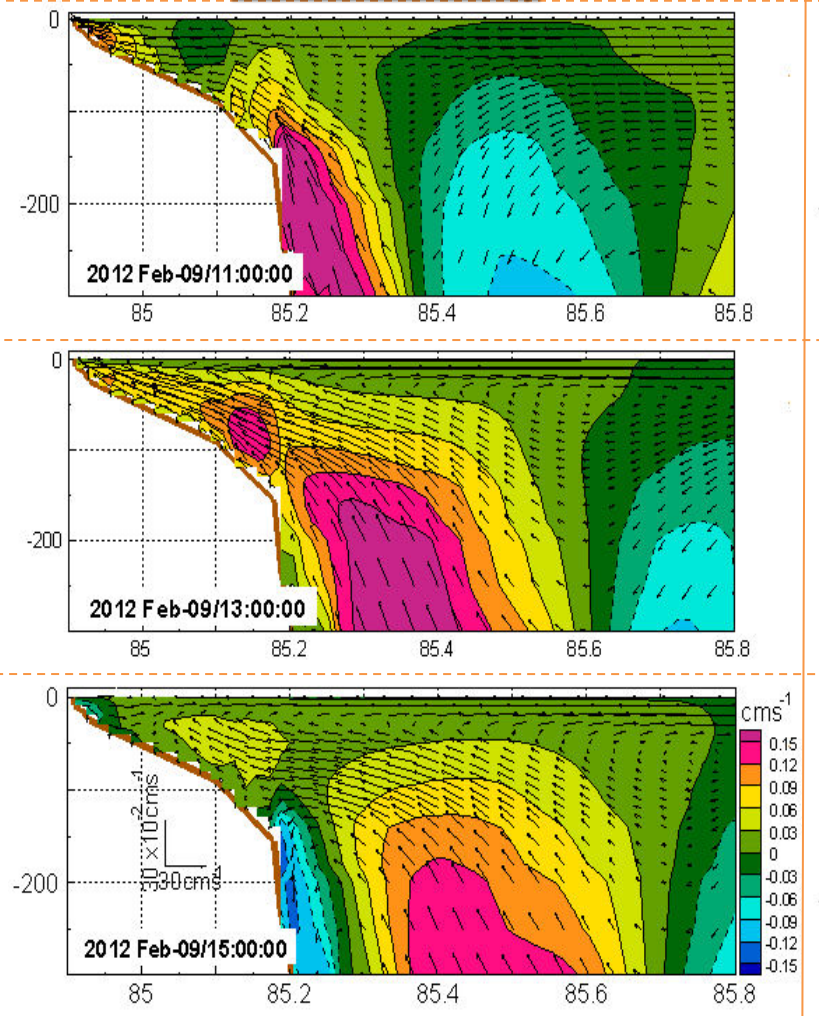


Figure: Snapshots of vertical velocity (shaded) and currents (vectors) at 2-hour interval off Gopalpur.

Density

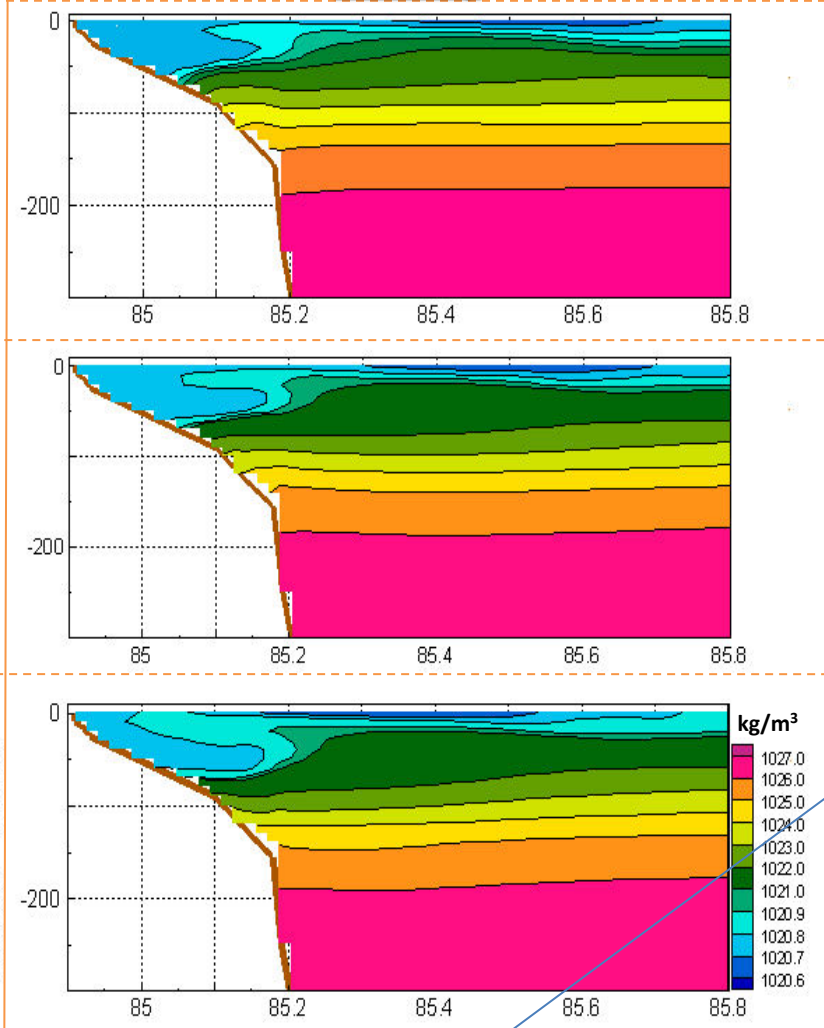
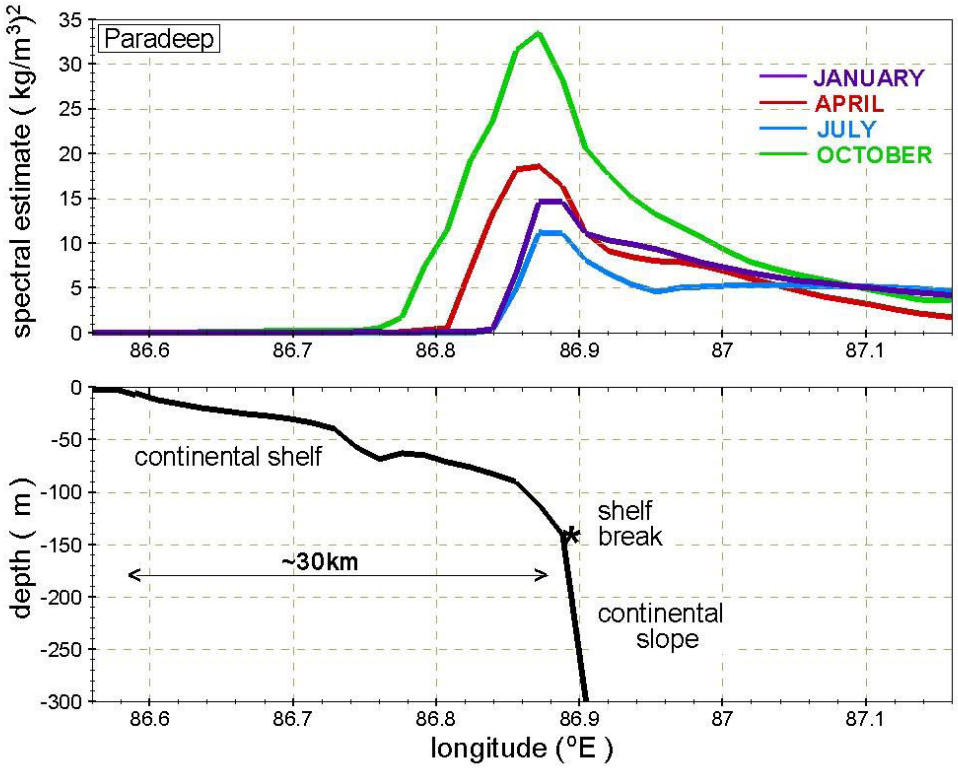
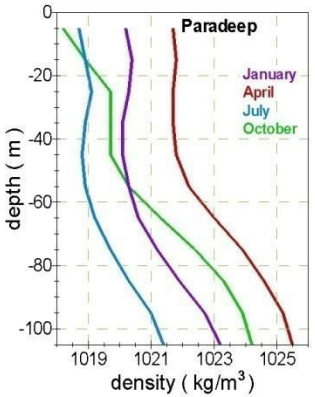
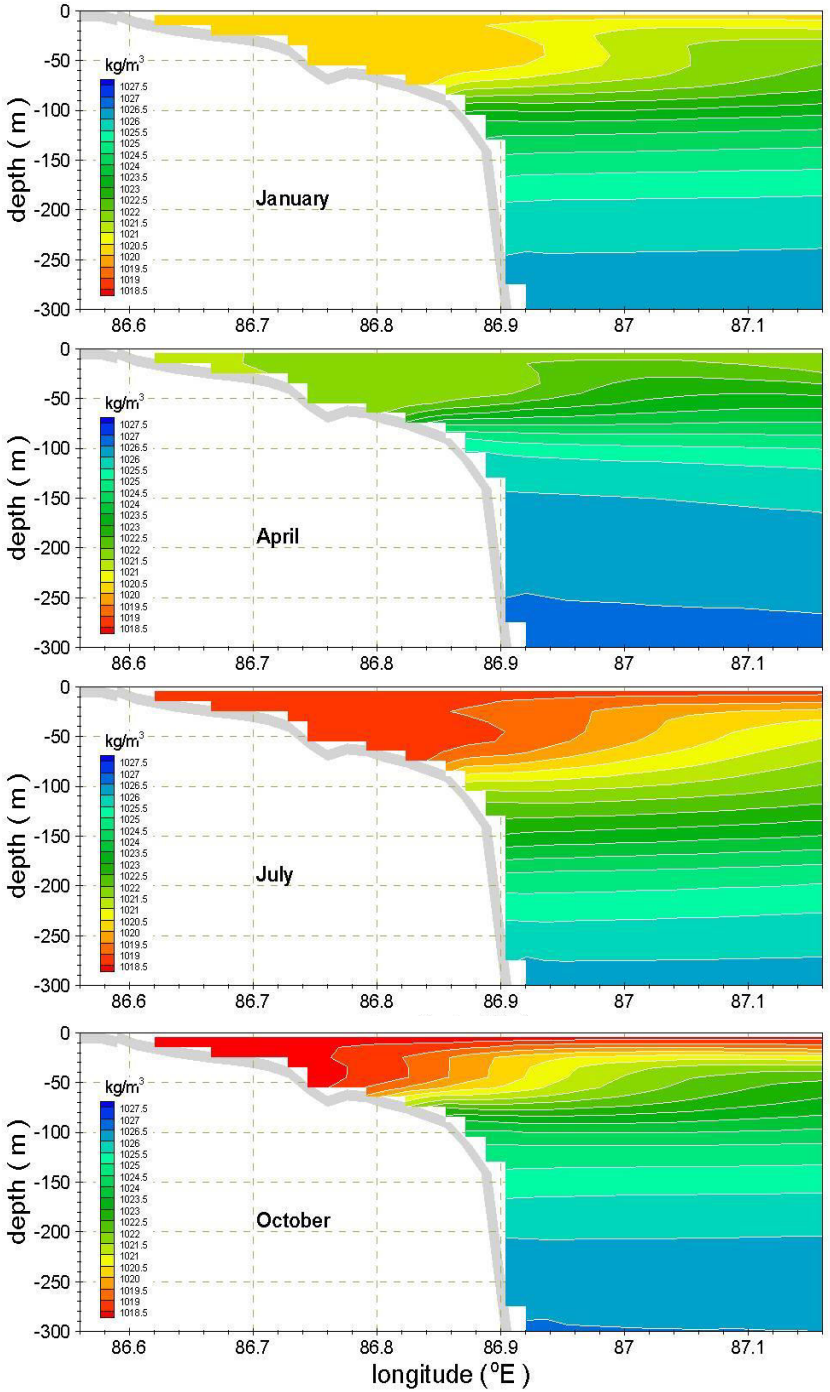


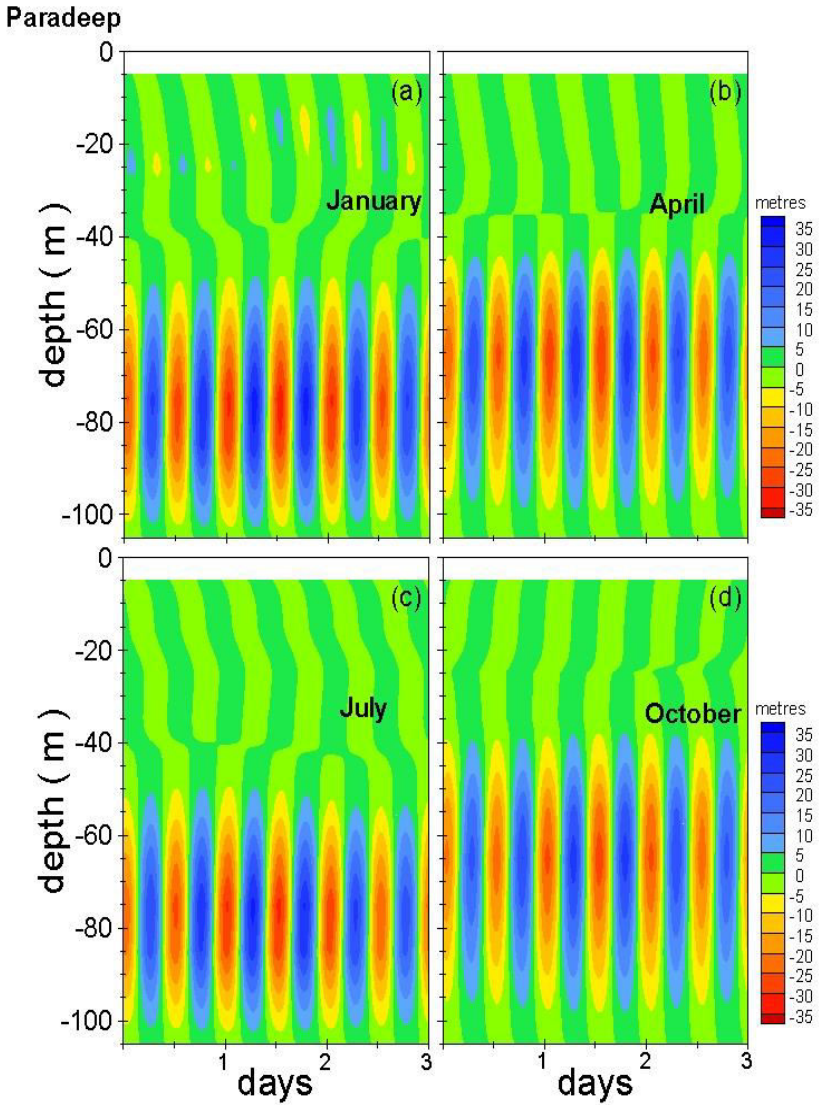
Figure: Snapshots of temperature at 2-hour interval off Gopalpur.

Inter-seasonal variability of Internal tides off Paradeep








Paradeep
(a)
January
(b)
April
(c)
July
(d)
October
depth (m)
0
-20
-40
-60
-80
-100
1
2
3
days
metres
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35