Effect of cyclone's approach angle and cyclone induced precipitation on costal inundation

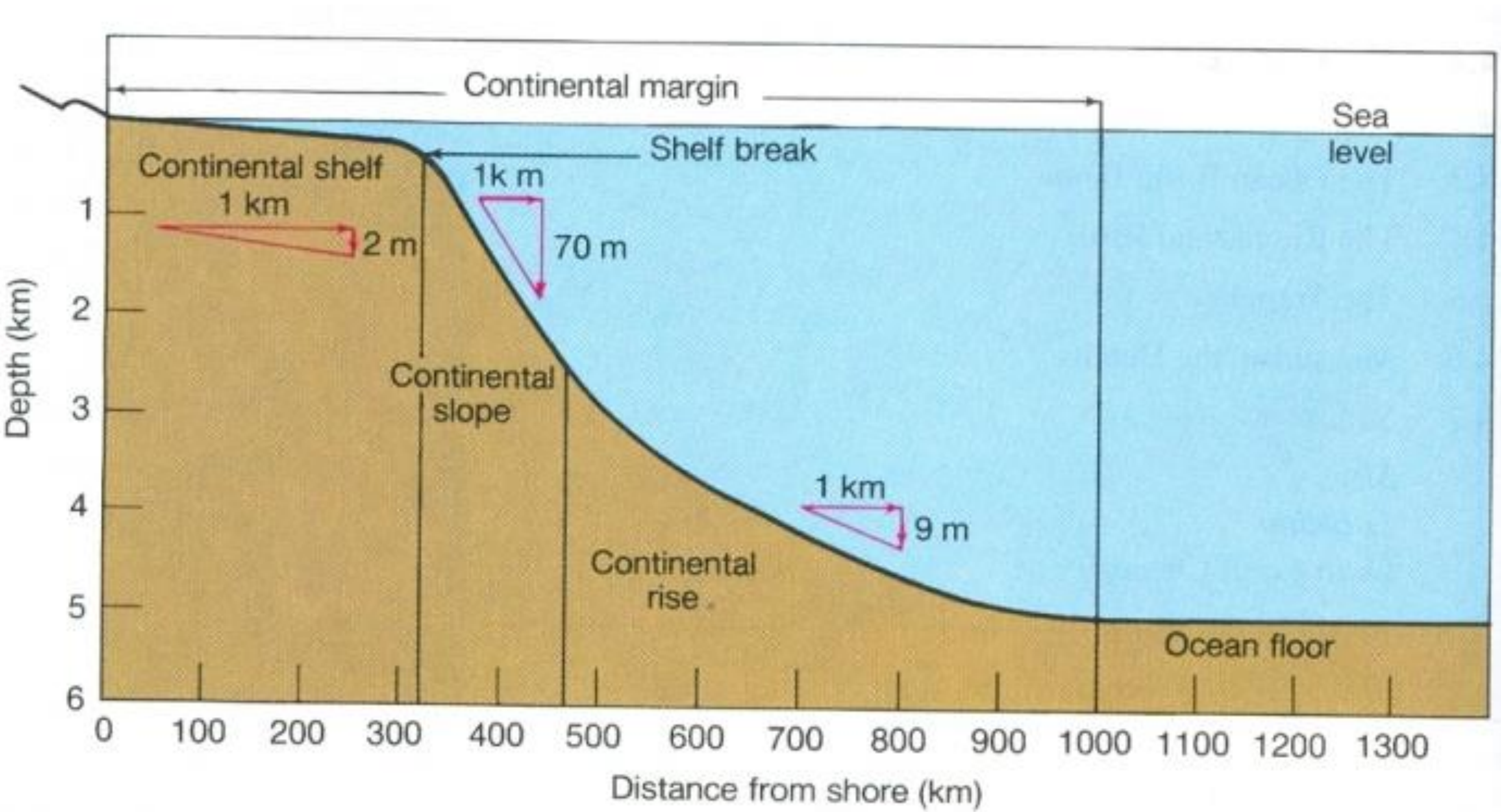
Prof. A D Rao
Centre for Atmospheric Sciences
Indian Institute of Technology Delhi
New Delhi-110016

Factors responsible for generation of storm surges

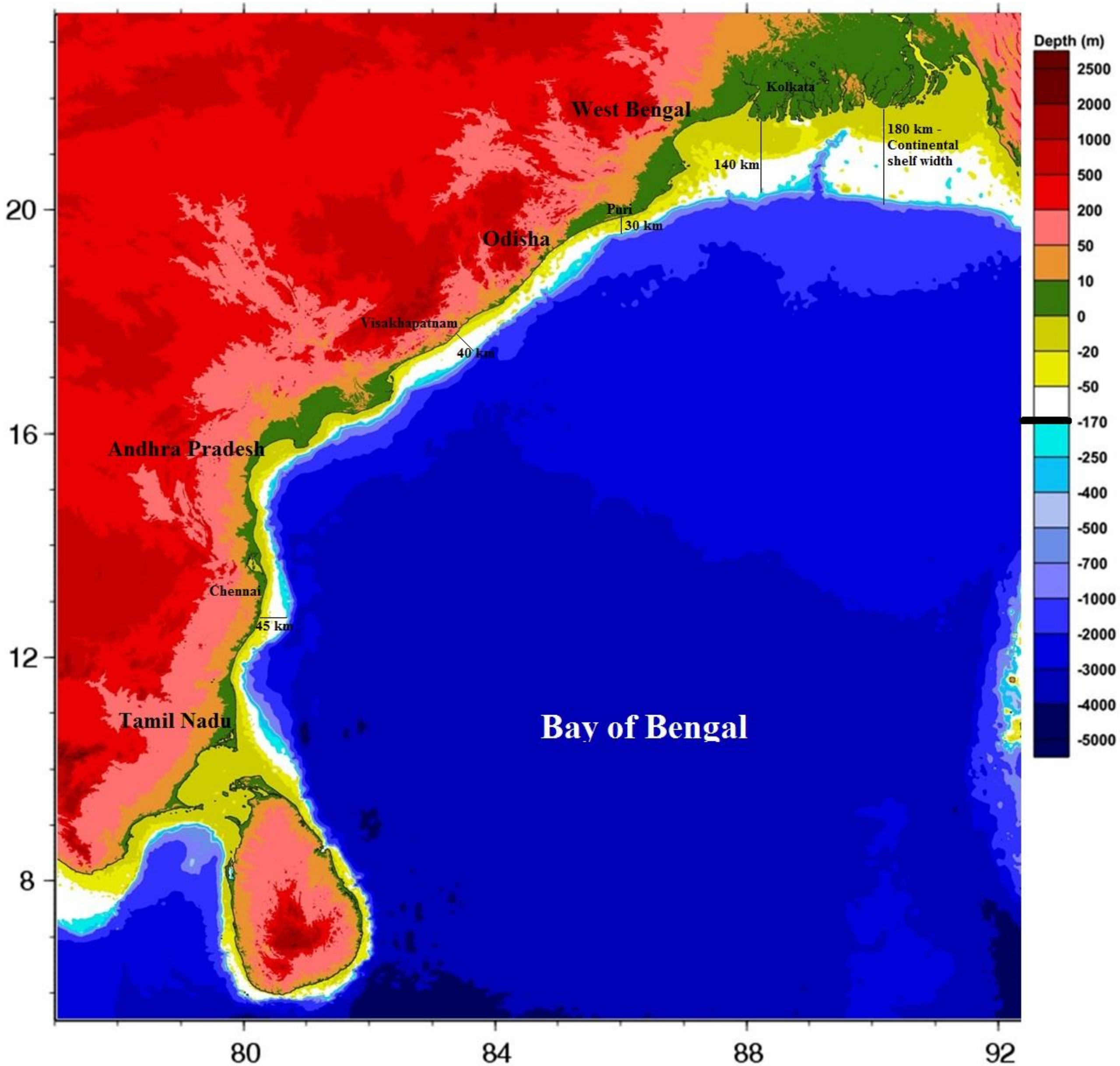
- Convergence of the bay
- Shallow coastal waters
- Continental shelf width
- Translation speed of the storm
- Innumerable number of inlets joining the bay
- Angle at which the onshore cyclonic winds cross the coast

Factors responsible for coastal inundation due to storm tides

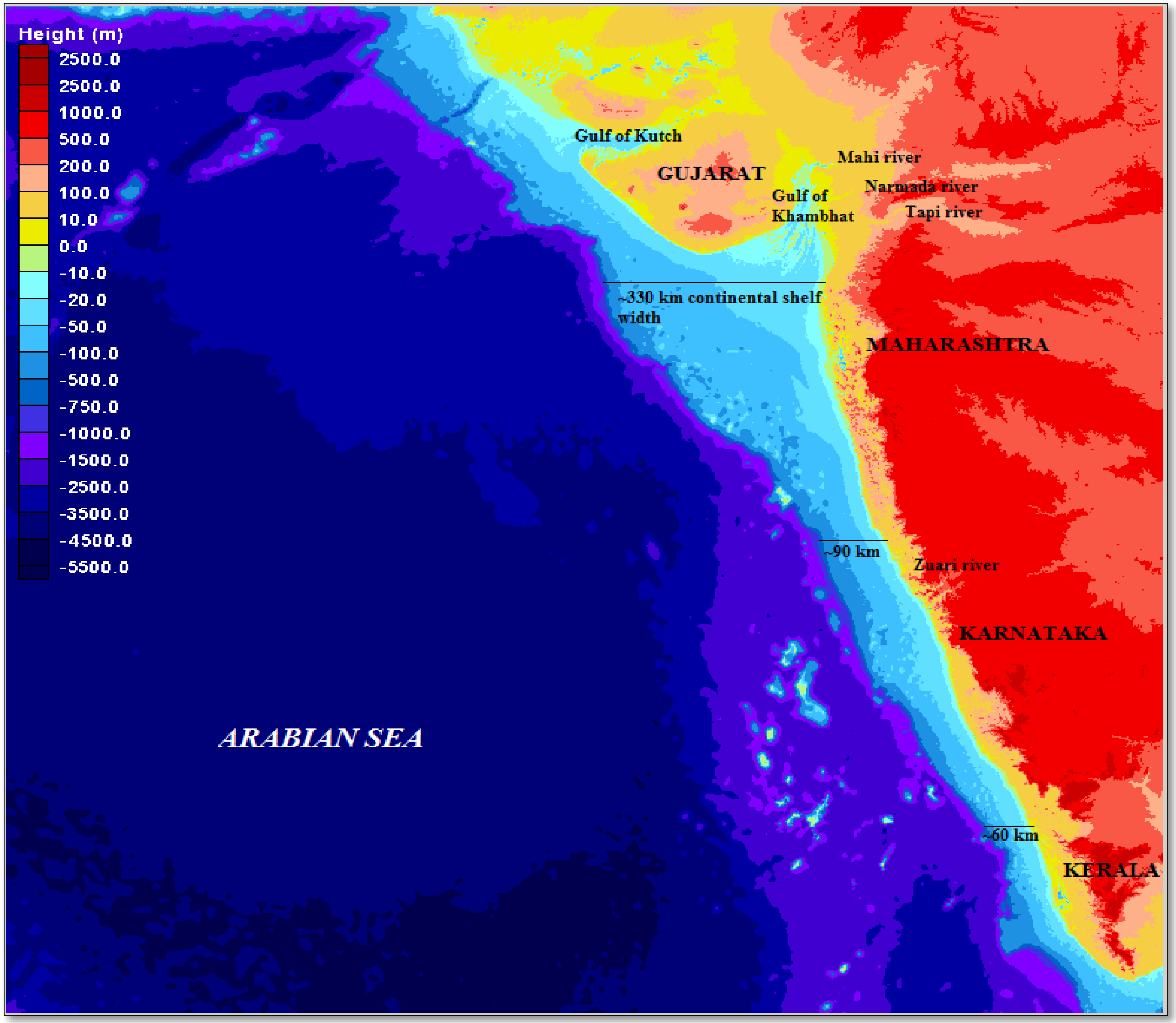
- High astronomical tides
- Regions of low-topography
- LULC
- Cyclone induced precipitation
- Low-lying river deltaic regions
- Number of river inlets joining the bay



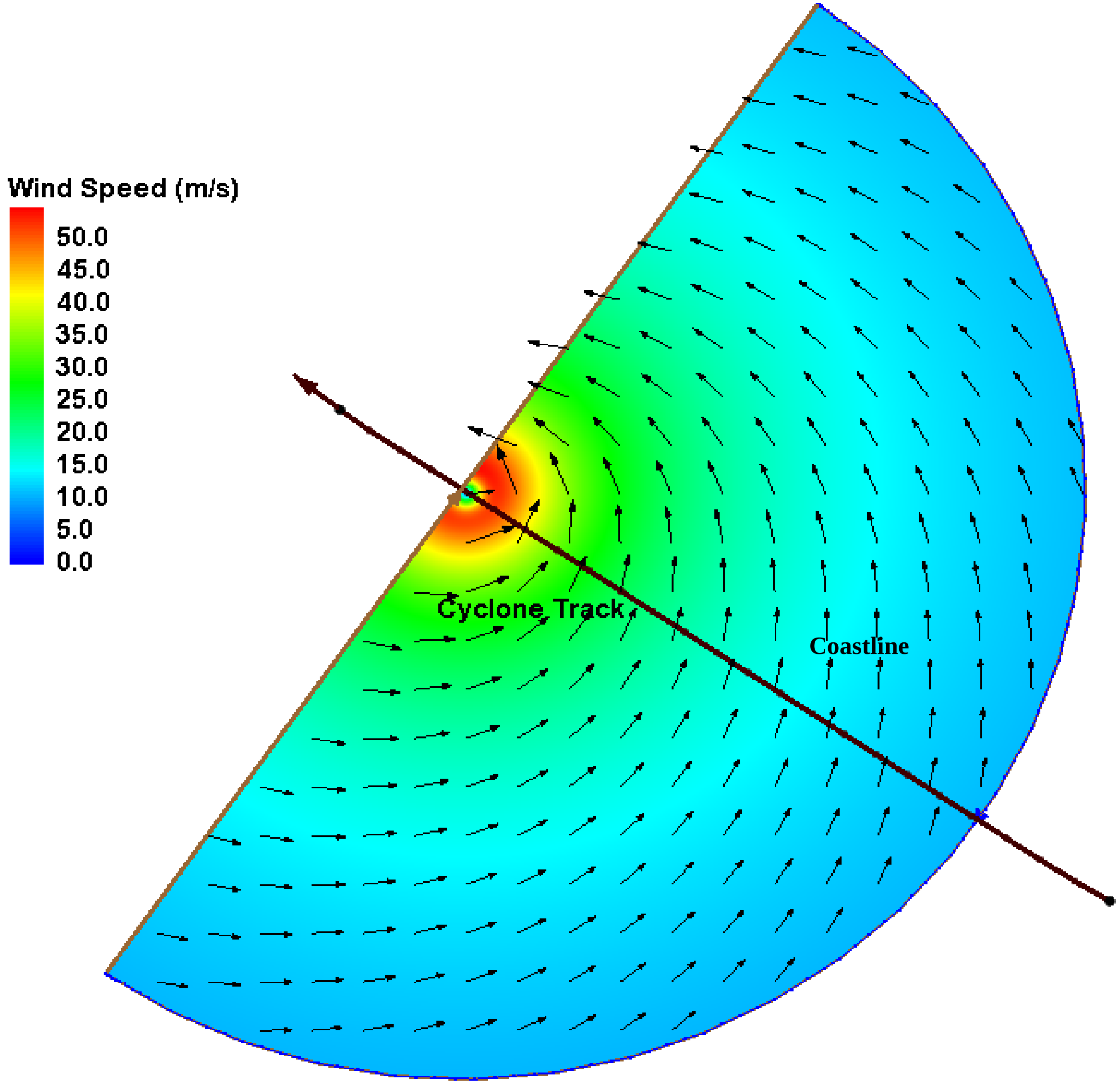
Typical ocean bottom topography



Continental shelf width along the east coast of India



Continental shelf width along the west coast of India



Cyclonic wind distribution at the time of landfall

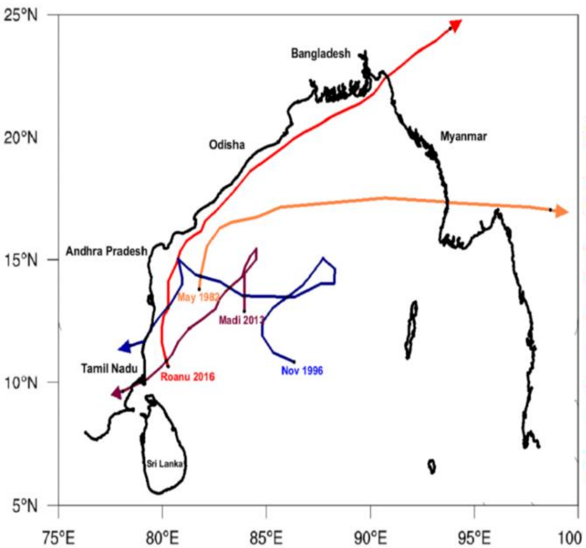
Impact of approach angle of an impinging cyclone on generation of storm surges and its interaction with tides and wind waves

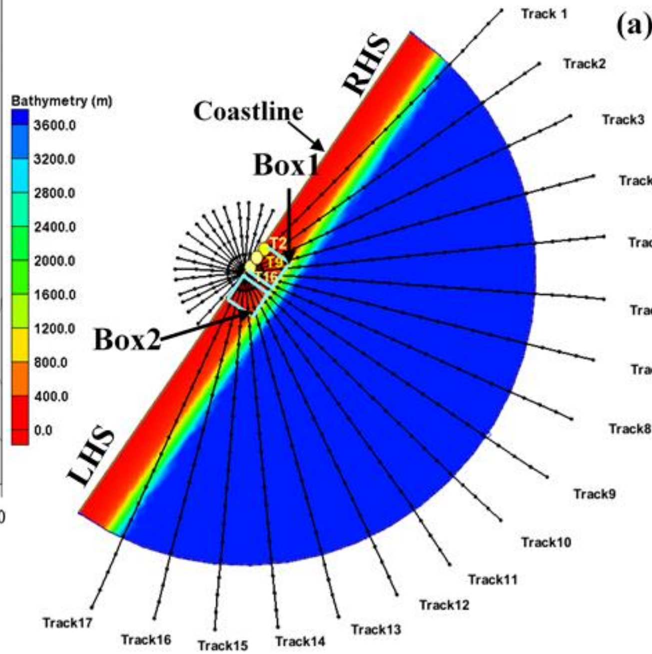
Smita Pandey and A D Rao (2019): JGR Oceans

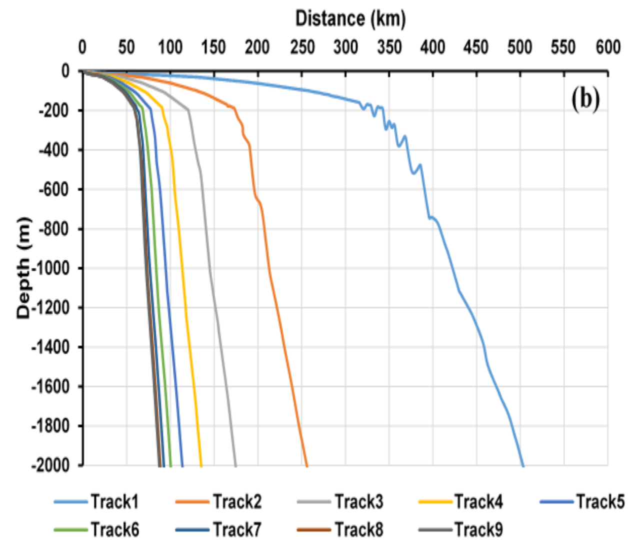
Some cyclone tracks of the recent past in the Bay of Bengal having unusual track directions.

(a) Idealized computational domain along with cyclone tracks at different approach angles starting from north at 10° interval. Yellow dot indicates the location of peak surge for tracks 2, 9 & 16,

(b) Idealized local bathymetry along the tracks 1-9



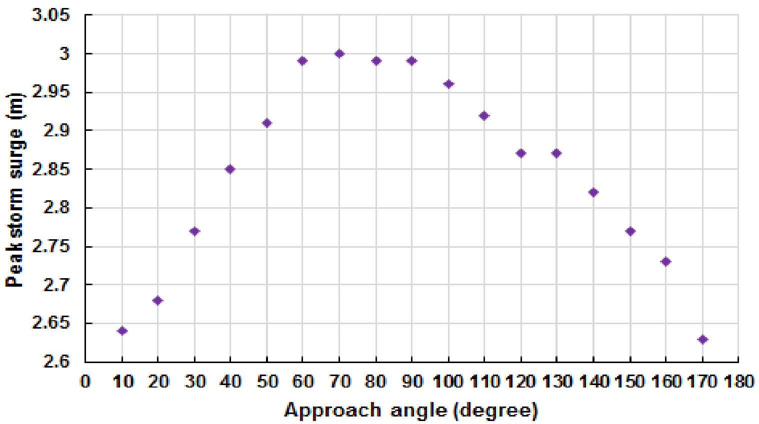


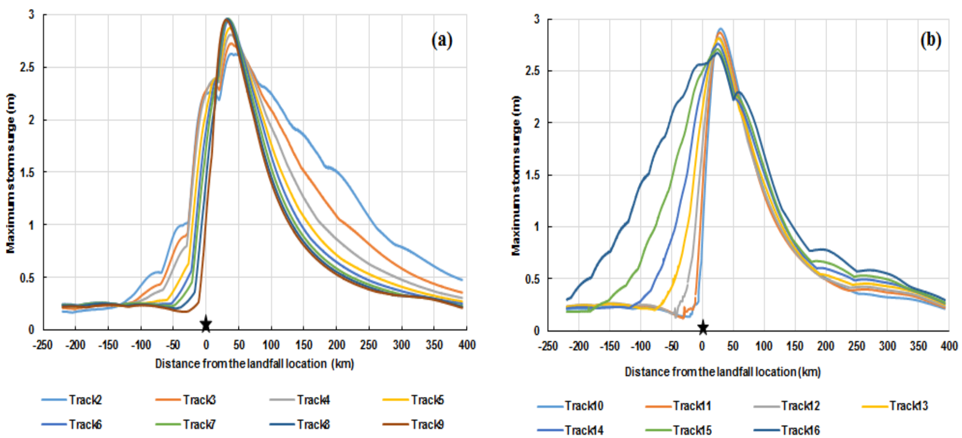


Experiment details

- Straight coastline with constant continental shelf width.
- 17 idealized tracks are considered from 10° to 170° with 10° intervals, making landfall at the same location.
- There are 44072 nodes and 81700 triangular elements.
- The grid resolution is about 200m near the coast and about 19km near the open ocean.

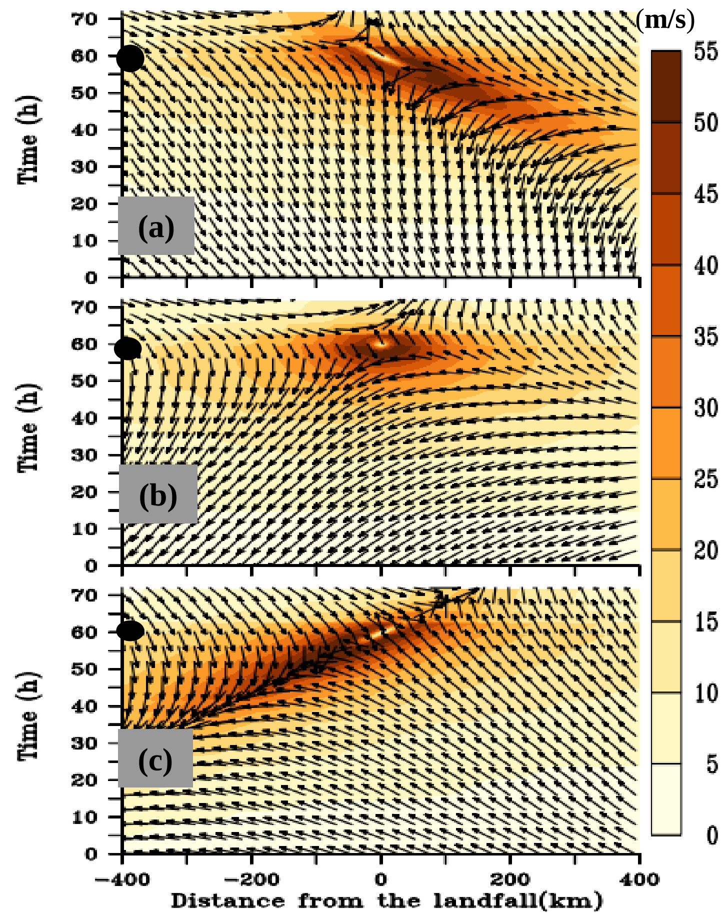
Computed peak storm surge for different approach angles of a cyclone.



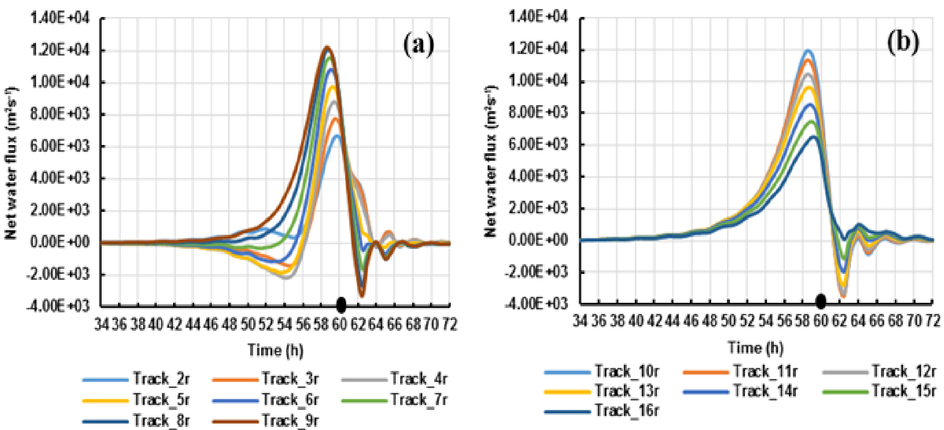


Maximum storm surge envelope along the coast (a) tracks 2-9, (b) tracks 10-16..

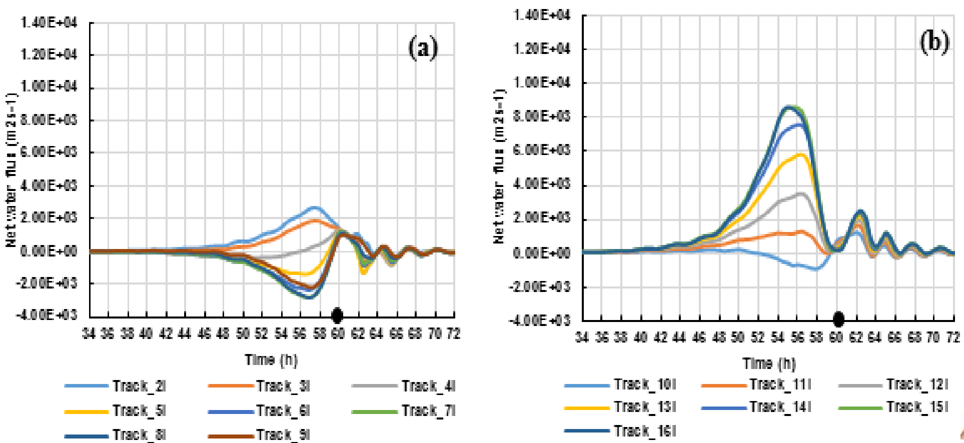
Hovmöller diagram of wind speed in contour and its direction by vector (a-c) along the coast for tracks 2, 9 & 16. The black dot indicates the landfall time.



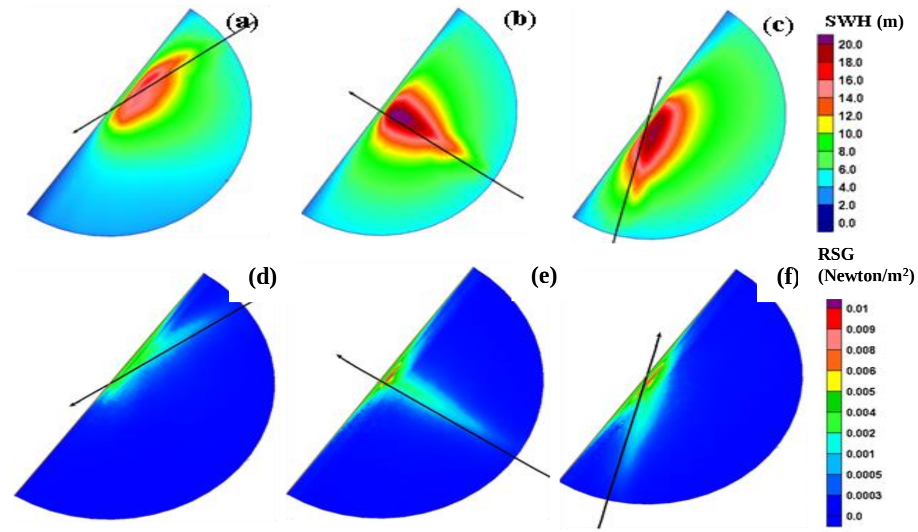
Temporal depiction of net water flux averaged over the box1 for (a) tracks 2-9, (b) tracks 10-16. The black dot represents the landfall time.



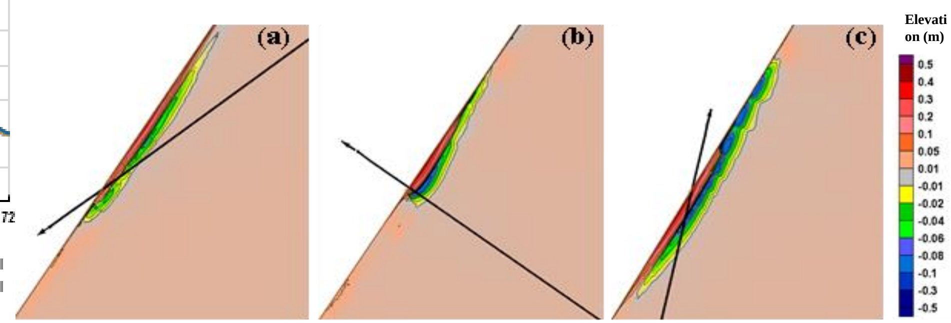
box2 for (a) tracks 2-9, (b) tracks 10-16.



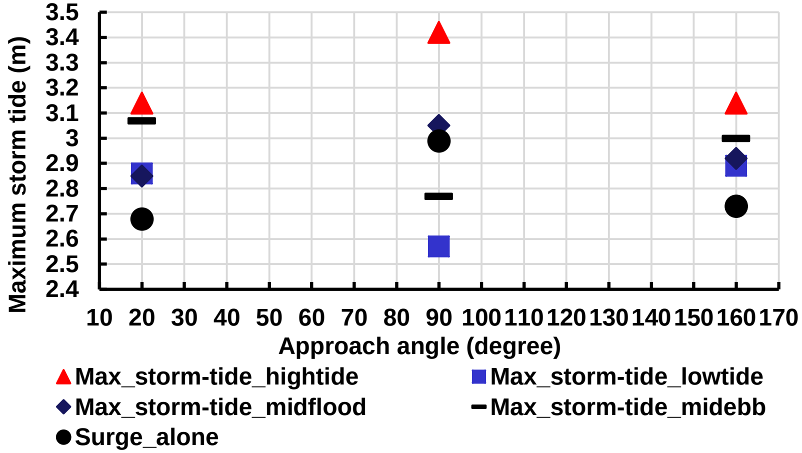
Distribution of maximum SWH over the domain for tracks 2, 9 & 16 (a-c) and distribution of maximum radiation stress gradient (RSG) over the domain for tracks 2, 9 & 16(d- f).



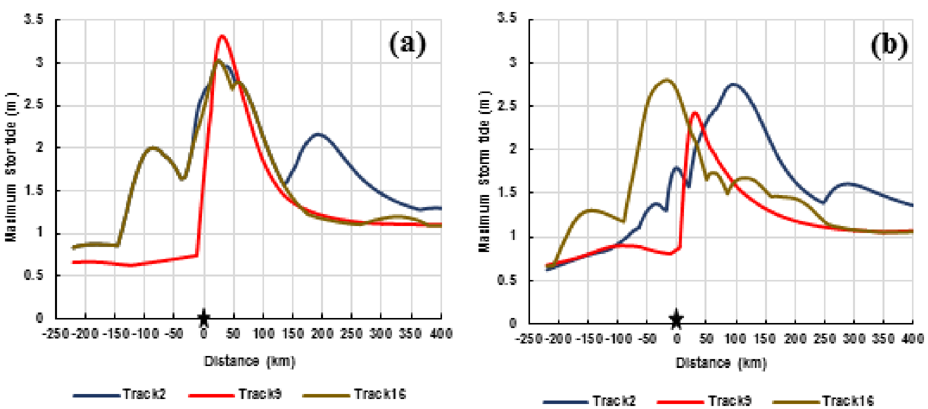
Effect of the wind wave on the maximum water elevation for (a) track2, (b) track 9 & (c) track 16



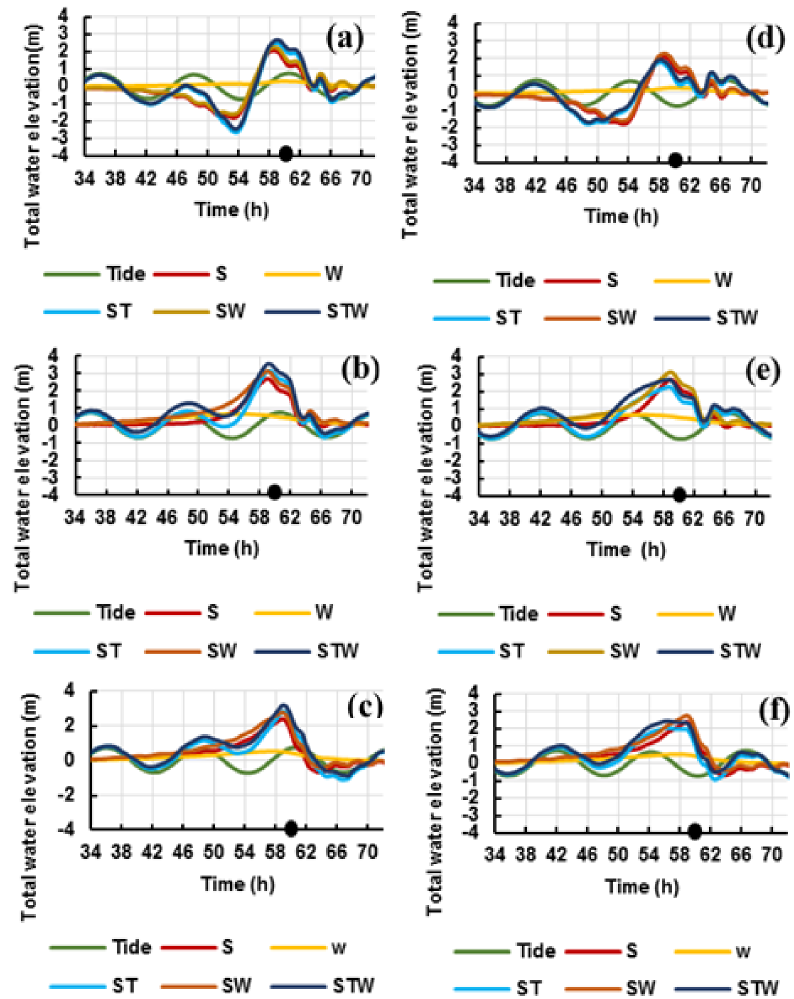
Computed maximum storm tide for track 2 (20°), track 5(50°), track 9 (90°), track 13(130°) and track 16 (160°) at mid-flood, high-tide, mid-ebb and low-tide.



Maximum storm tide envelope along the coast for track 2, track 9 and track 16 at (a) high-tide and (b) low-tide



Temporal depiction of total water elevation of S, W, SW, Tide, ST, STW for tracks 2, 9 & 16 at high-tide (a-c) and low-tide (d-f).



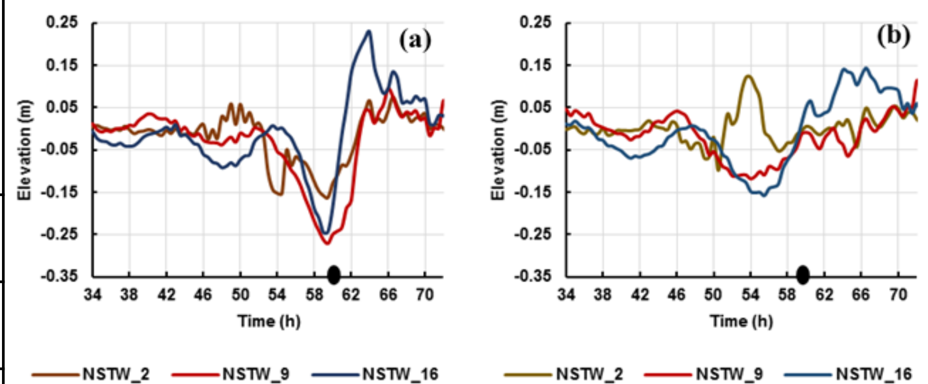
Change of water level in % between surge and SW/ST/STW at high and low-tide.

	High-tide			Low-tide		
Track	Max. increase in ST over S	Max. increase in SW over S	Max. increase in STW over S	Max. decrease in ST over S	Max. increase in SW over S	Max. decrease in STW over S
Track2	20%	8.6%	29.9%	14.5%	8.6%	6.7%
Track9	15.9%	15.5%	31.4%	16.6%	15.5%	1%
Track16	20.9%	15%	33.4%	14.6%	15%	4.2%

Range of interaction
Track 2: 0.6-5%
Track9: 0.4-7%
Track16: 0.38-6%

Temporal depiction of non-linear interaction of surge-tide-wave (NSTW) for tracks 2, 9 &16 at (a) high-tide, (b) low-tide.

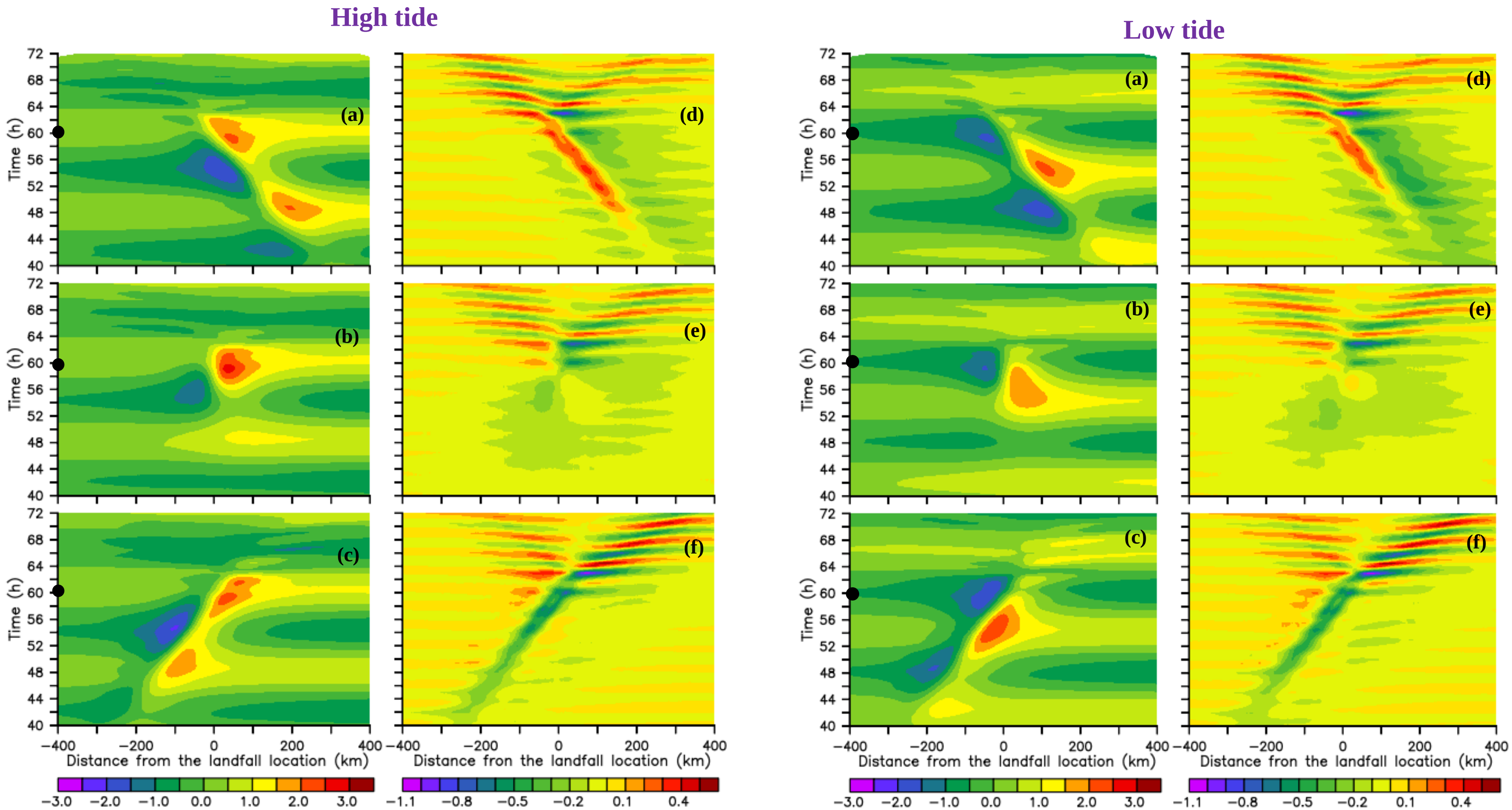
NSTW = STW-(S+T+W)



Percentage of NSTW with respect to the linear addition of S, T and W
At high-tide is about 5-7% for track2, 16 & 9

At low-tide it is about 0.4-0.6% for track 9, 16 & 2.

Hovmöller diagram for STW (a, b & c) and NSTW (d, e & f) along the coast for tracks 2, 9 & 16 at high-tide and low-tide, respectively. The black dot indicates the landfall time.



Conclusions:

- Storm surge simulations conducted using the ADCIRC model suggest that the maximum surge is computed for tracks 9 (90^o), while the minimum surge occurs for tracks 1 (10^o) and 17 (170^o).

- It is noticed that the increase in peak storm surge from tracks 1-6 is about 15%, while the decrease from tracks 9-17 is about 13%.

- The distribution of surge above 1m along the coast infers that the coastal stretch on the RHS of the landfall is maximum affected by track 2, which reduces to about 50% when the cyclone travels from tracks 2-9. Furthermore, affected area along the coast due to track 16 is noticed on both LHS and RHS of the landfall location equally.

- The storm surge and wind wave simulations show that the contribution of wind waves on surges varies with cyclone's approach angle. The increase in water level is about 21-26% as the cyclone direction changes from tracks 2-16 with maximum wave contribution for track 9.

- At the peak storm surge location percentage of NSTW with respect to the linear addition of S, W and tide is about 5-7% for tracks 2,16 & 9 at high-tide and 0.4-0.6% at low-tide for tracks 9,16 & 2.

- The spatial and temporal distribution of NSTW along the coast at both high and low-tide shows that maximum positive interaction for all the tracks occurs 2-4hrs after the landfall.

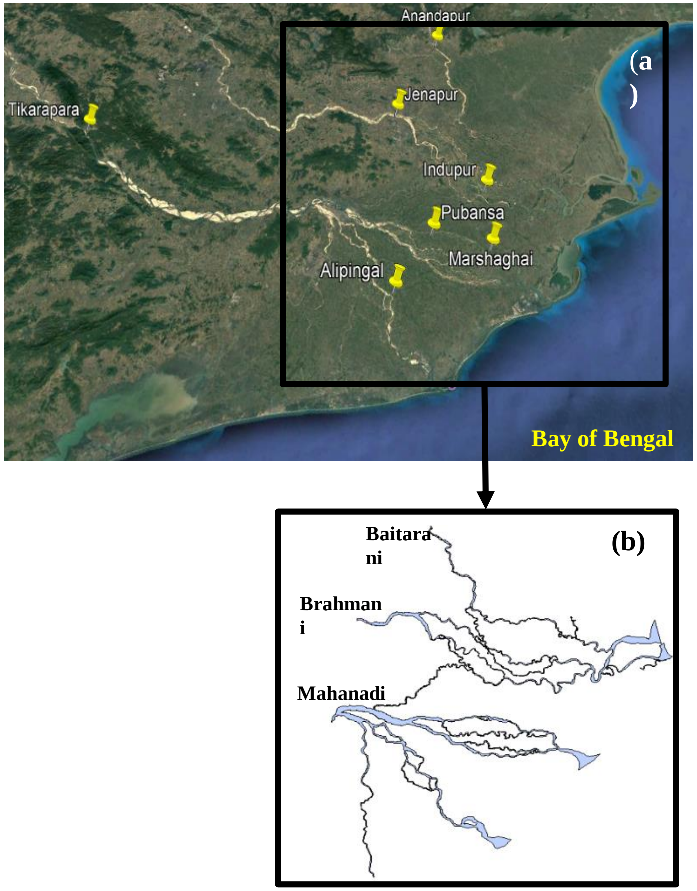
Modeling of coastal inundation in response to a tropical cyclone using a coupled hydraulic HEC-RAS and ADCIRC model

Smita Pandey and A D Rao (2021): JGR Oceans

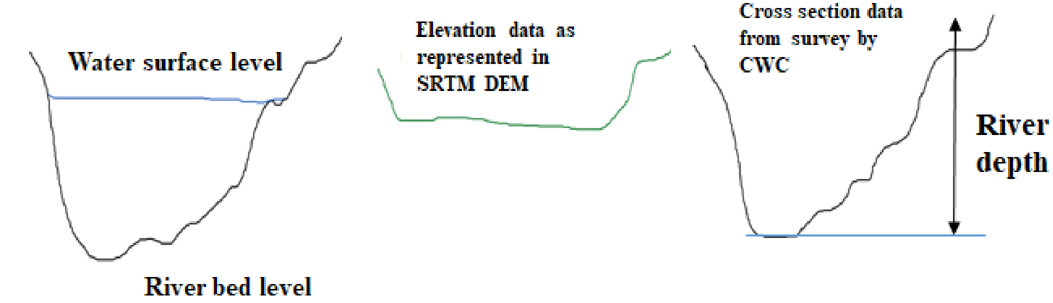
Objectives

- To configure ADCIRC model for the Odisha coast by incorporating three rivers: the Mahanadi, the Brahmani and the Baitarani.
- To quantify the contribution of upstream river discharge on coastal inundation using 1999 Super cyclone
- To assess the role of LULC data on coastal inundation.
- Configure HEC-RAS model for the Mahanadi delta region.
- Compute coastal inundation as a combined effect of storm-tides, river discharge and cyclone induced precipitation.

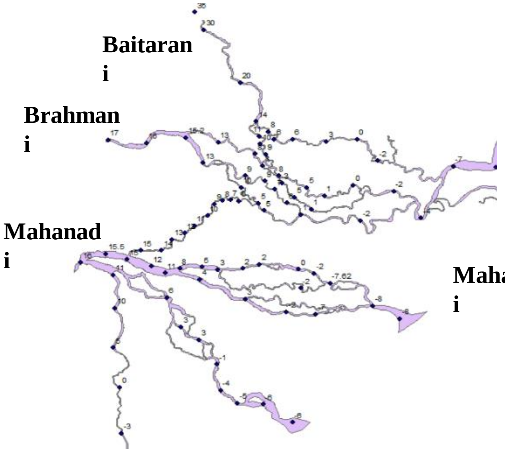
Depiction of (a) Mahanadi deltaic region along with river cross-sections and discharge observed locations (b) Digitized Mahanadi, Brahmani and Baitarani Rivers along with their tributaries



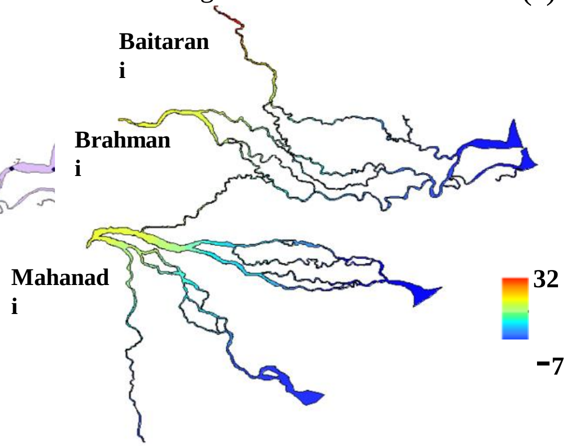
Method of assigning river depth at various locations in all the river polygon



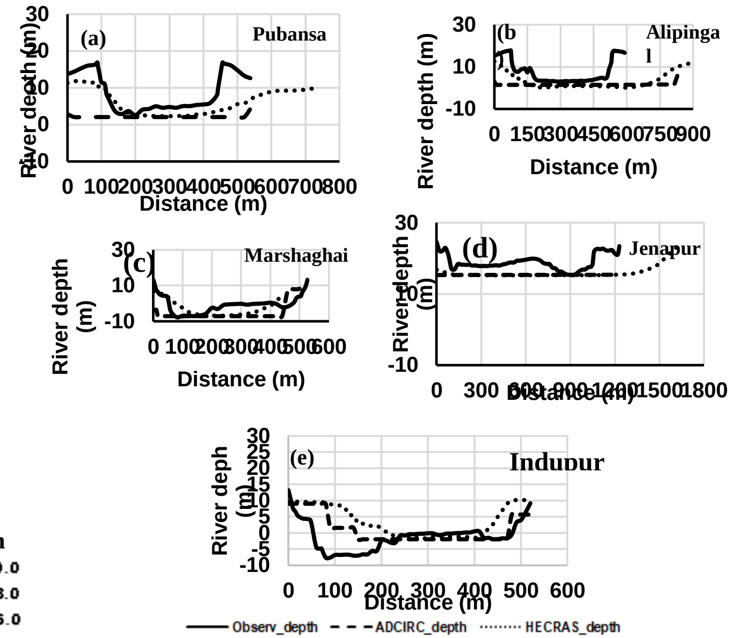
River bed levels are estimated at multiple points along the river.



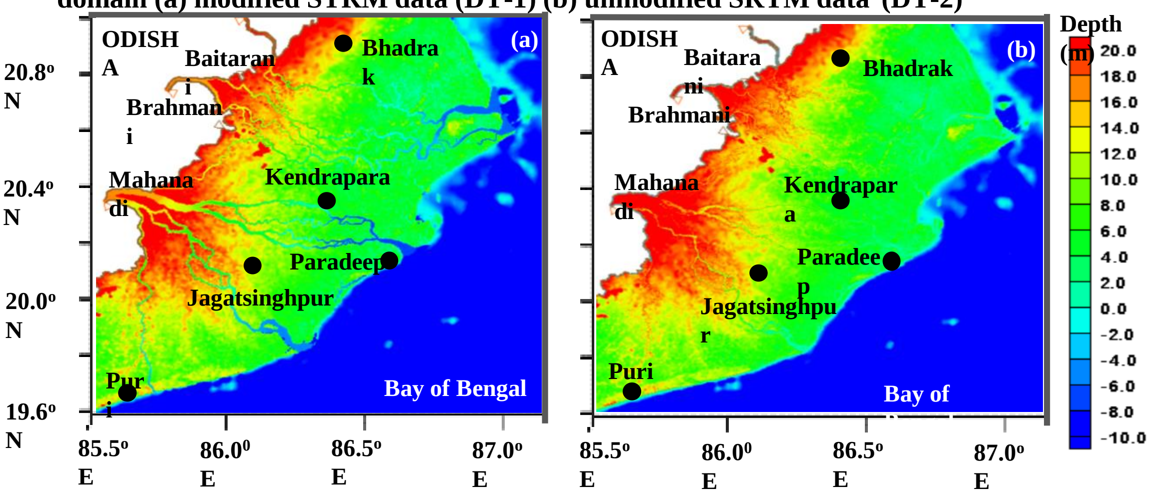
Interpolation is carried using Inverse Distance Weighted method.



Comparison of observed and computed river cross-sectional depth at (a) Pubansa (b) Alipingal (c) Marshaghai (d) Jenapur (e) Indupur



Bathymetry and onshore topography of the Mahanadi deltaic region for the model domain (a) modified STRM data (DT-1) (b) unmodified SRTM data (DT-2)



Data used in the study:

Bathymetry : GEBCO 900m

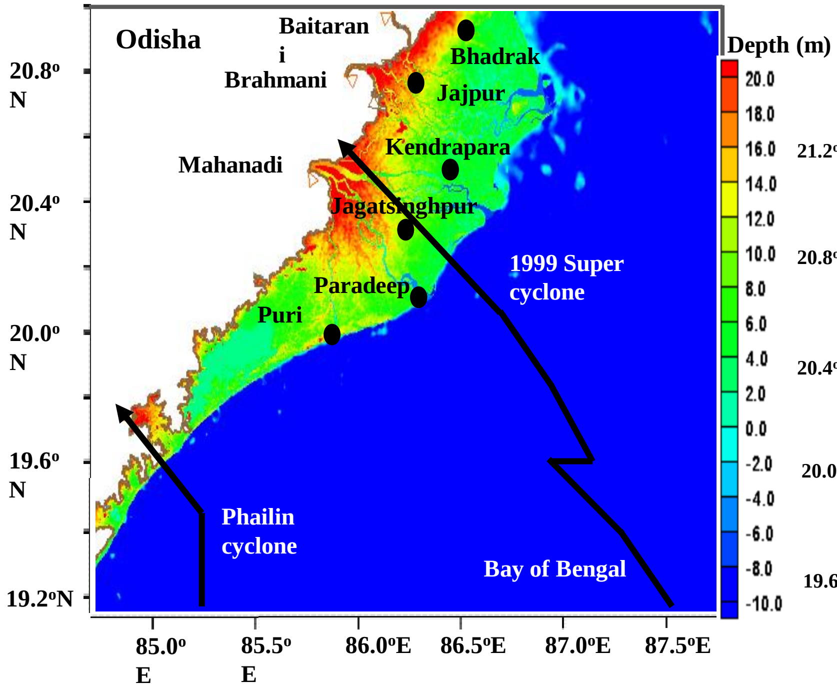
Topography: SRTM 30m

Grid resolution: Within the riverine region :50m

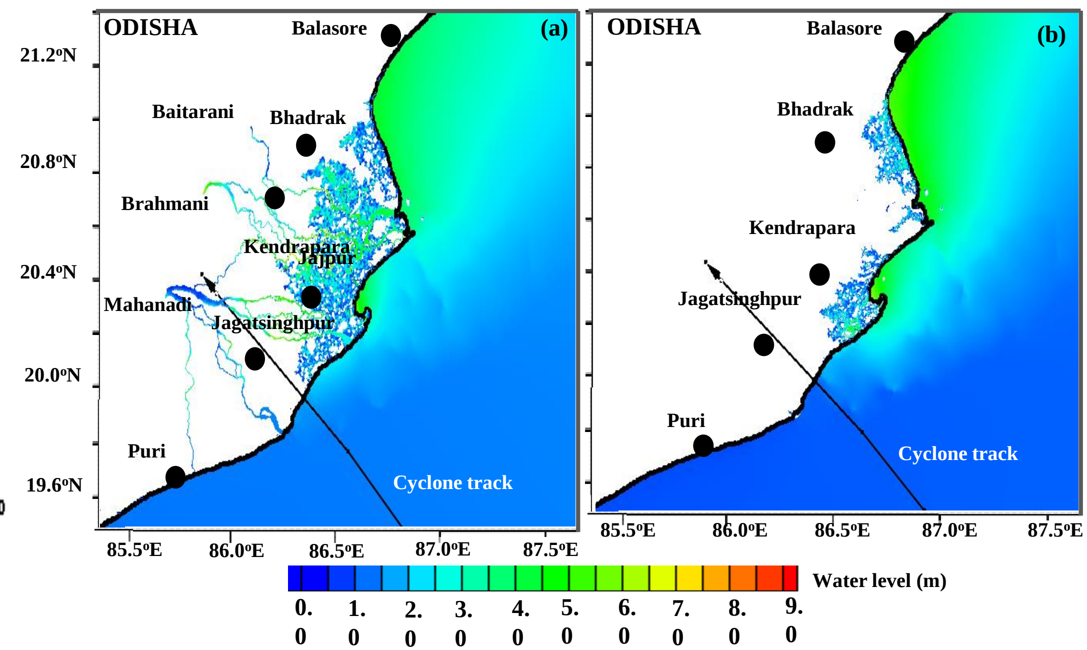
At open boundary: 23km

Computational nodes: 829136

Computational domain (DT-1) along with cyclonic tracks for 1999 Super cyclone and 2013 Phailin cyclone



Spatial coverage of coastal inundation and maximum water level for the 1999 Super cyclone (a) Domain with modified SRTM data (DT-1) (b) Domain with unmodified SRTM data (DT-2)

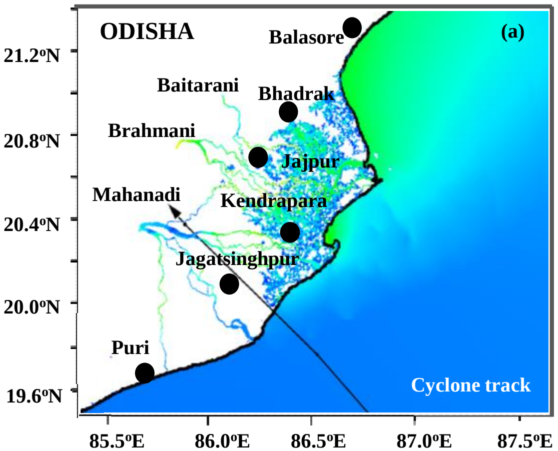


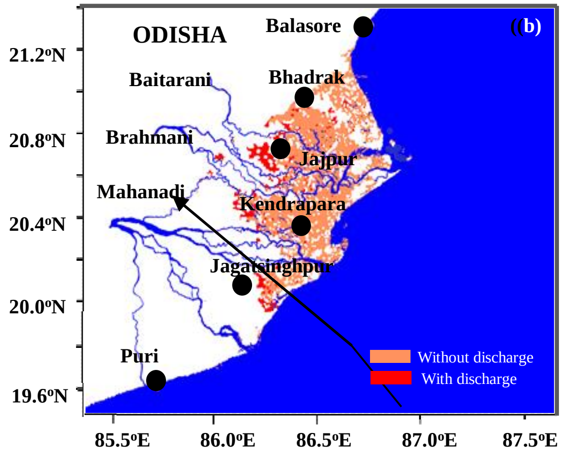
Inundated area with modified SRTM -- 1940km²

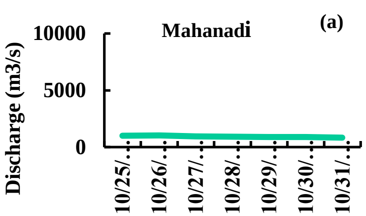
Inundated area with unmodified SRTM – 685km²

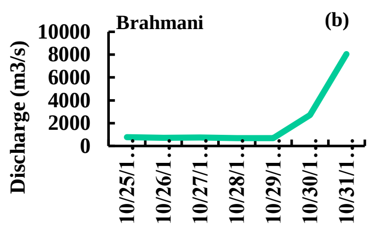
(a) coastal inundation and maximum water level with daily river discharge for the 1999 Super cyclone

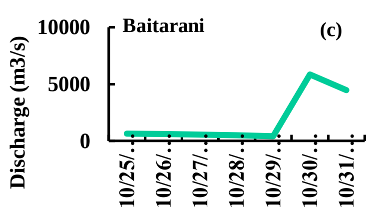
(b) composite depiction of coastal inundation for 1999 Super cyclone as an aggregate response of without and with discharge







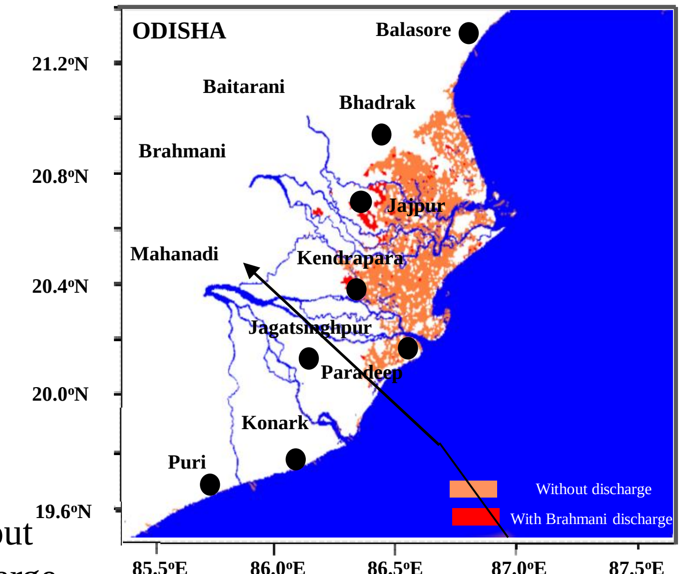




Inundated area without upstream river discharge- **1940km²**

Inundated area with upstream discharge- **2275km²**

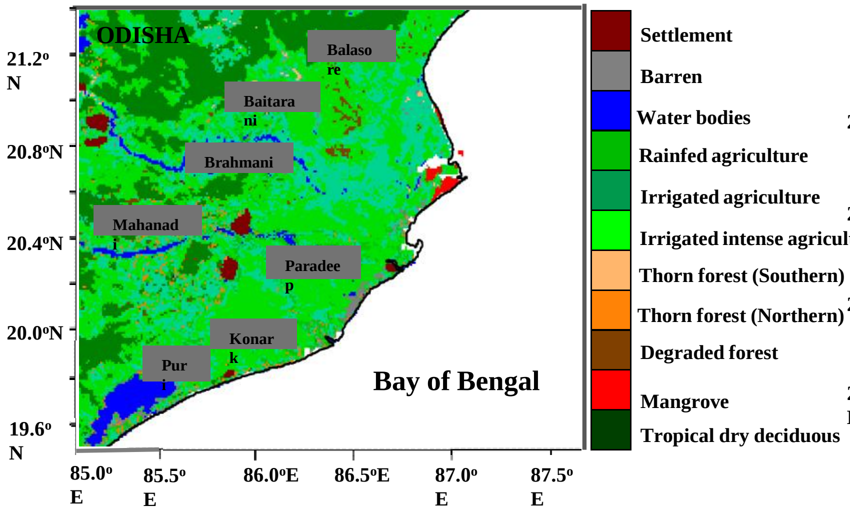
A composite depiction of coastal inundation as an aggregate response of with no-discharge and with discharge only into Brahmani River.



Simulated inundated area with only Brahmani River-**2095km²**

Daily-discharge hydrograph during the 1999 Super cyclone at (a) Mahanadi (b) Brahmani (c) Baitarani

Depiction of LULC data over the Mahanadi delta.

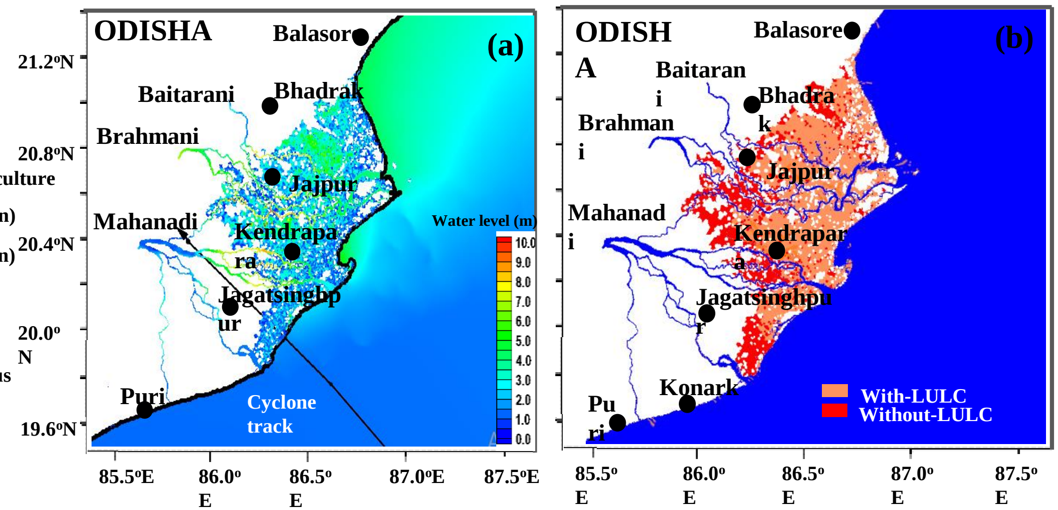


LULC data

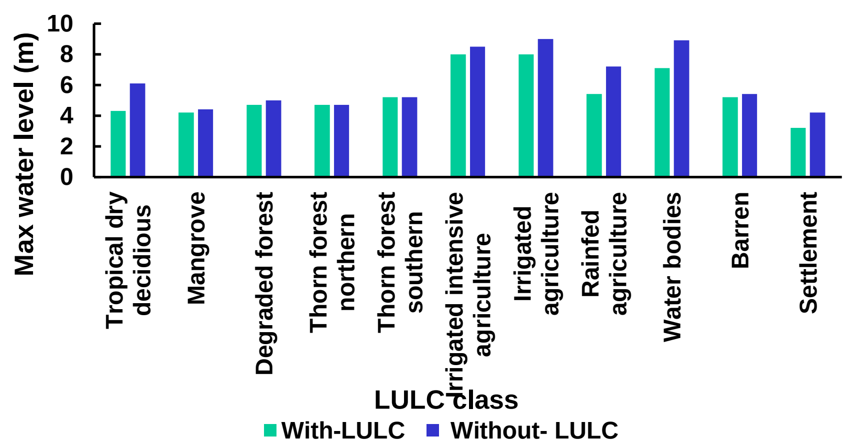
- **For the 1999 Super cyclone: 2000 GLCC**

(a) Spatial coverage of coastal inundation with maximum water level and

(b) composite depiction as an aggregate response with and without including LULC information for 1999 Super cyclone

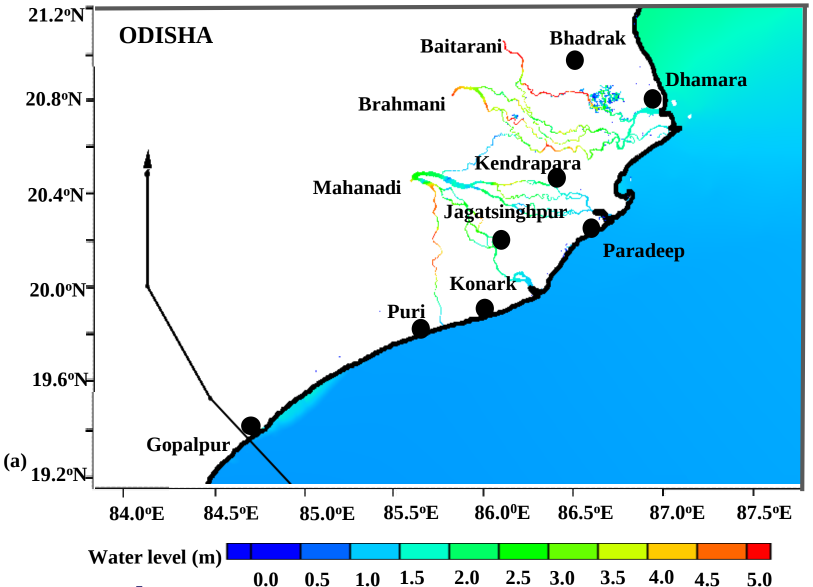


Simulated inundated area without LULC data - 3475km²



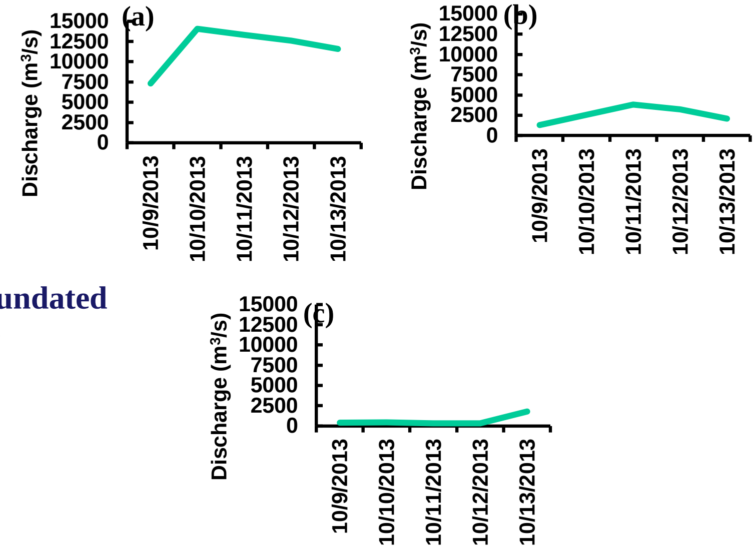
Inundated maximum water level with and without LULC for each classification

Spatial coverage of coastal inundation and maximum water level for Phailin cyclone



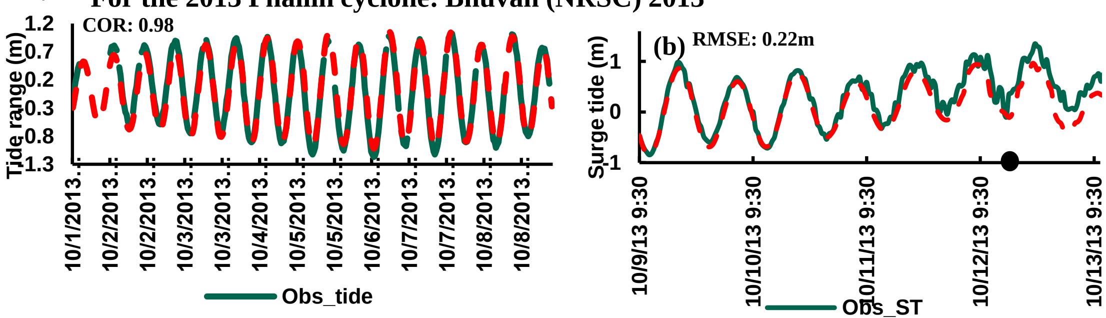
Simulated inundated area – 75km²

Daily-discharge hydrograph during the 2013 Phailin cyclone at (a) Mahanadi (b) Brahmani (c) Baitarani



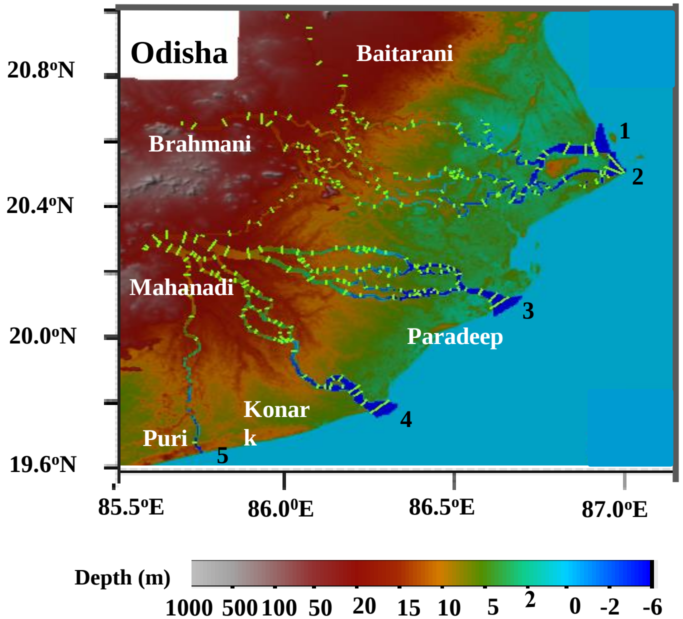
LULC data

- **For the 2013 Phailin cyclone: Bhuvan (NRSC) 2013**



Comparison of modelled tide against the observed tide at Paradeep, (b) Comparison of model simulated storm tide with observations for Phailin cyclone. Black dot shows the landfall time.

Computational domain for HEC-RAS model along with cross-sections. Label 1-5 shows the river coast boundary for Baitarani, Brahmani and the Mahanadi Rivers, respectively



Hydrologic Engineering Center (HEC) – River Analysis System (RAS)

(HEC of US Army Corps of Engineers (USACE))

- **It can be used either as a 1D steady or 1D and 2D unsteady flow model**
- **It can simulate hydraulic flow in river channels and flood plains in a single reach or in a network of reaches.**
- **In the present study the HEC-RAS version 5.0 is used as a 2D unsteady flow model.**

Mass conservation equation

$$\frac{\partial H}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0$$

Momentum equations for current

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-c_f u+fv$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial H}{\partial y}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f v-fu$$

where, $H(x,y,t)=z(x,y)+h(x,y,t)$: Water surface elevation

h : Water depth

z : Bottom surface elevation

u v : Velocity components in the x y directions respectively,

t :Time

q :Source/sink term

g : Gravitational force

v_t : Horizontal eddy viscosity coefficient,

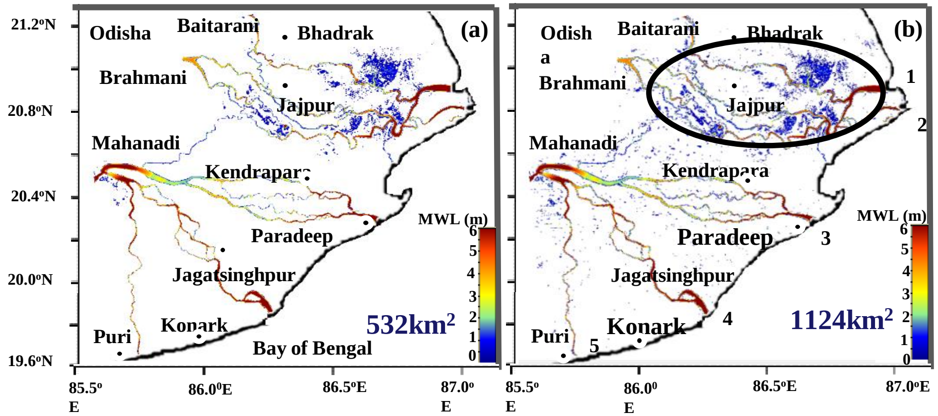
$v_t = Dhu_*$ D : Eddy viscosity transverse mixing coefficient

u_* : Shear velocity, $u_*=\frac{\sqrt{g}}{R^{1/6}}|V|$ R : Hydraulic radius

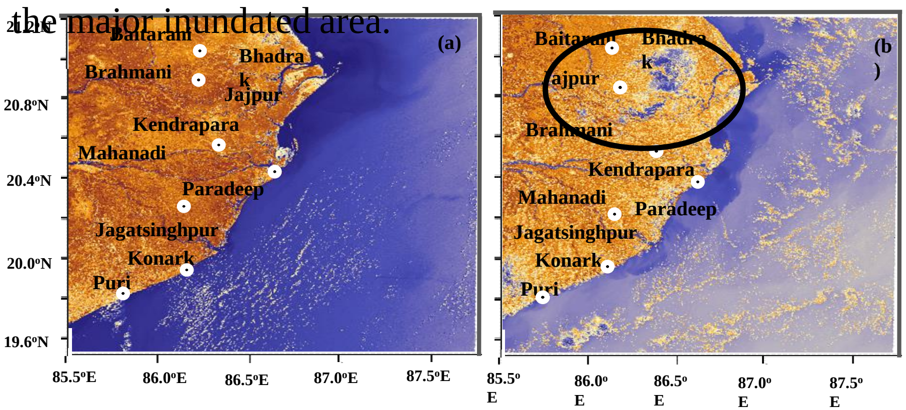
$|V|$: Magnitude of velocity

c_f : is the bottom friction coefficient, $c_f=\frac{n^2 g|V|}{R^{4/3}}$

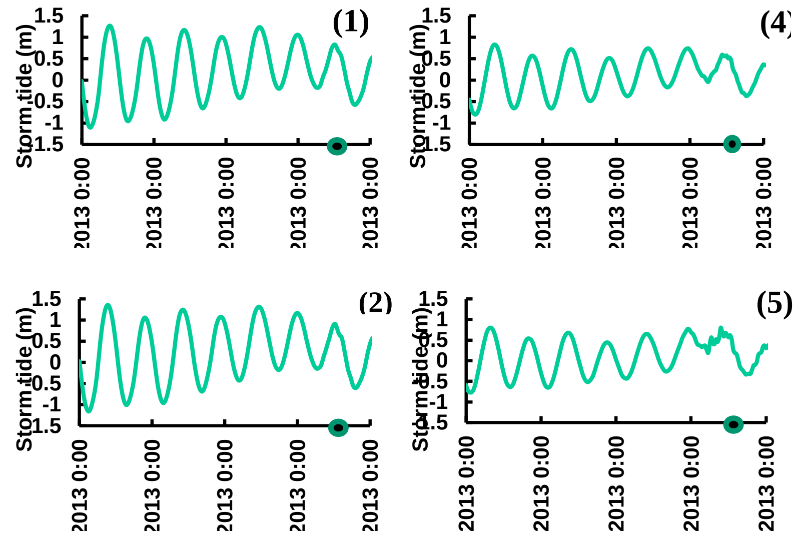
Maximum water level and coastal inundation during Phailin cyclone (a)simulation with storm-tide and river discharge, (b) simulation with storm-tide, river discharge and precipitation. Black oval highlights the major inundated area



(a) Landsat-8 satellite image of 26th April 2013 when there was no weather system (b) Landsat-8 satellite image of 19th October 2013 just after the cyclone. Black oval highlights the major inundated area.

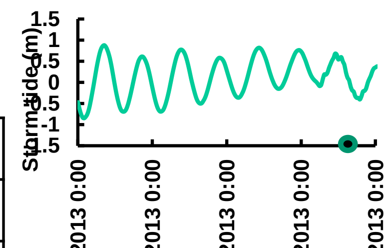


Temporal depiction of storm tide during the Phailin cyclone at river coastal boundary (1)Baitarani (2)Brahmani (3) Mahanadi opening1 (4) Mahanadi opening2 (5) Mahanadi opening3. Black dot represents the landfall time.



Daily area-averaged precipitation over the Mahanadi deltaic region during the Phailin cyclone

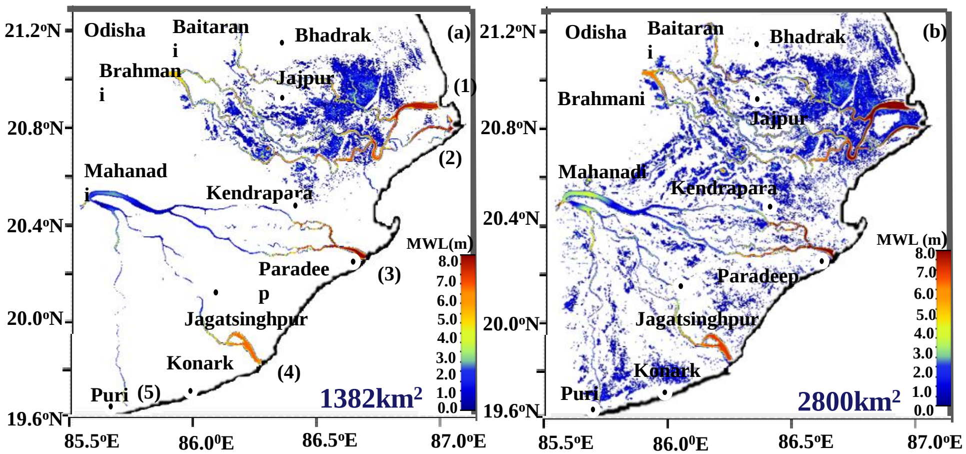
2013 Phailin cyclone	
Day	Area-averaged precipitation (mm)
09 Oct. 2013	16.8
10 Oct. 2013	12
11 Oct. 2013	0.1
12 Oct. 2013	31
13 Oct. 2013	110
14 Oct. 2013	23



Depiction of maximum water level and coastal inundation during 1999 Super cyclone

(a) simulation with storm tide and river discharge

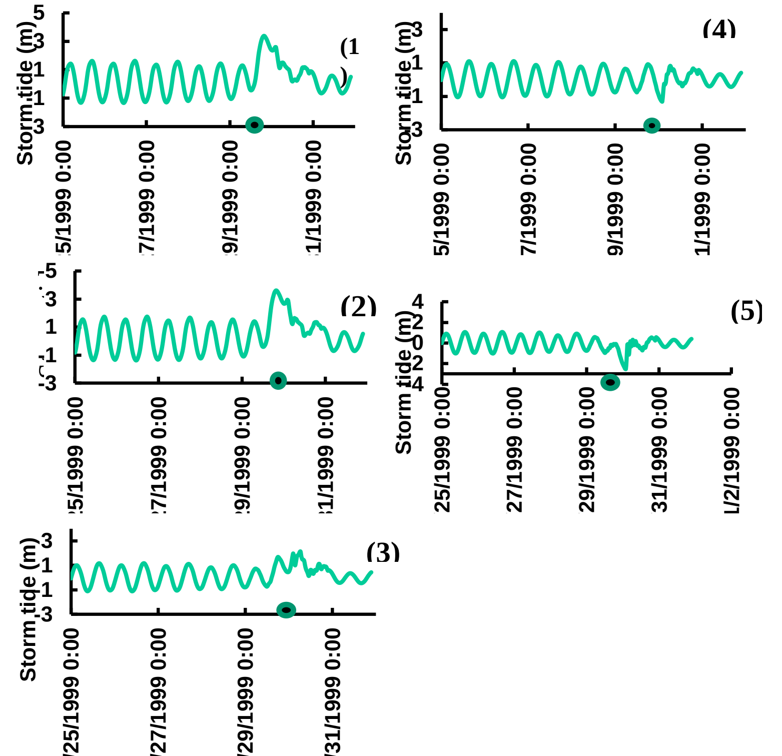
(b) simulation with storm tide, river discharge and precipitation



Temporal depiction of storm tide during the 1999 Super cyclone at river coastal boundary

(1) Baitarani, (2) Brahmani, (3) Mahanadi opening1, (4) Mahanadi opening2, (5) Mahanadi opening3.

Black dot represents the landfall time.



Daily area-averaged precipitation over the Mahanadi deltaic region during the 1999 Super cyclone

1999 Super cyclone	
Day	Area-averaged precipitation (mm)
25 Oct. 1999	2.3
26 Oct. 1999	0
27 Oct. 1999	0.6
28 Oct. 1999	25.6
29 Oct. 1999	216.5
30 Oct. 1999	70.5
31 Oct. 1999	5

Conclusions:

- The inundated area increases by about 64% after incorporating river streams with better representation of depths

- The contribution of freshwater discharge on coastal inundation is computed by using daily data available from CWC at the upstream of the Mahanadi, Brahmani and Baitarani Rivers. The inundated area after incorporating river discharge is expanded by about 14%.

- The coastal inundation is found to reduce by 35% with the LULC, which demonstrates the significance of LULC on the computation of inland inundation.

- The impact of inland precipitation on the computation of inundated area is estimated by using a coupled ADCIRC and HEC-RAS model for the Phailin cyclone and the 1999 Super cyclone. It is observed that the inundated area is almost double with cyclone induced precipitation.

- It is inferred that coupling a ADCIRC and HEC-RAS model helps to achieve more reliable flood mapping in the river delta regions as the coupled system can simulate better fluid flow in the river system.

- Finally, for the accurate prediction and understanding of the flood risk, it is essential to resolve precise river configuration and incorporate hydrological components including river discharge and cyclone induced precipitation in the computational domain.

Recent publications on storm surges

- Smita Pandey, **A D Rao** and Raktim Haldar “Modeling of coastal inundation in response to a tropical cyclone using a coupled hydraulic HEC-RAS and ADCIRC model”, Journal of Geophysical Research: Oceans (2021) 126, https://doi.org/10.1029/2020JC016810.
- Jismy Poulose, **A. D. Rao,** S. K. Dube, "Mapping of cyclone induced extreme water levels along Gujarat and Maharashtra coasts: a climate change perspective", **Climate Dynamics,** https://doi.org/10.1007/s00382-020-05463-4, 2020.
- **A. D. Rao,** Puja Upadhaya, Hyder Ali, Smita Pandey and Vidya Warrier, "Coastal inundation due to tropical cyclones along the east coast of India: an influence of climate change impact", **Natural Hazards,** https://doi.org/10.1007/s11069-020-03861-9, 2020.
- **A. D. Rao**, Puja Upadhaya, Smita Pandey and Jismy Poulose, “Simulation of extreme water levels in response to tropical cyclones along the Indian coast: a climate change perspective", **Natural Hazards,** https://doi.org/10.1007/s11069-019-03804-z., 2020.
- Smita Pandey and **A D Rao** “Impact of approach angle of an impinging cyclone on generation of storm surges and its interaction with tides and wind waves”, **Journal of Geophysical Research: Oceans,** https://doi.org/10.1029/2019JC015433., 2019.
- Smita Pandey, **A.D. Rao** “An improved cyclonic wind distribution for computation of storm surges”, **Natural Hazards.** 92:93-112, 2018. DOI: 10.1007/s11069-018-3193-3., 2018.

Thank You