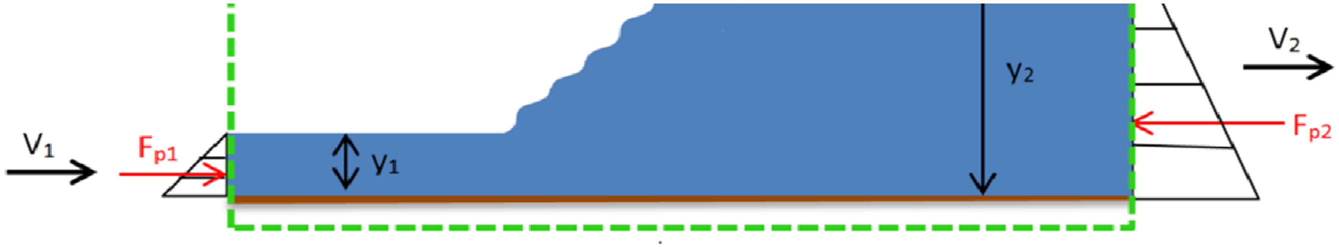
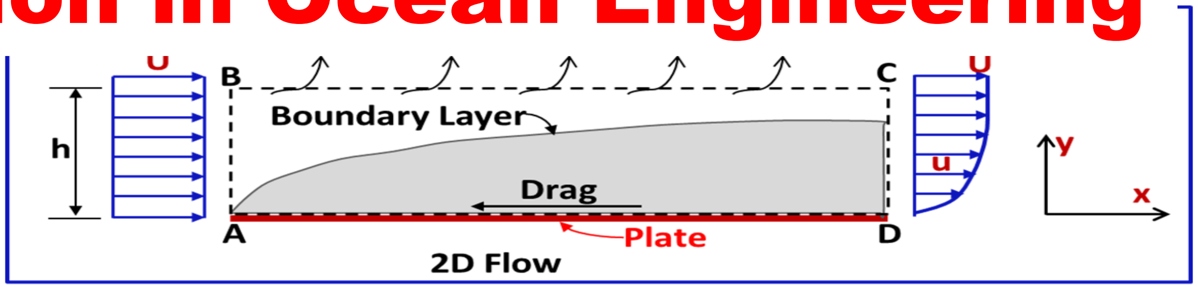
FLUID MECHANICS

Fundamentals and Application in Ocean Engineering





Prof. Manas R. Behera

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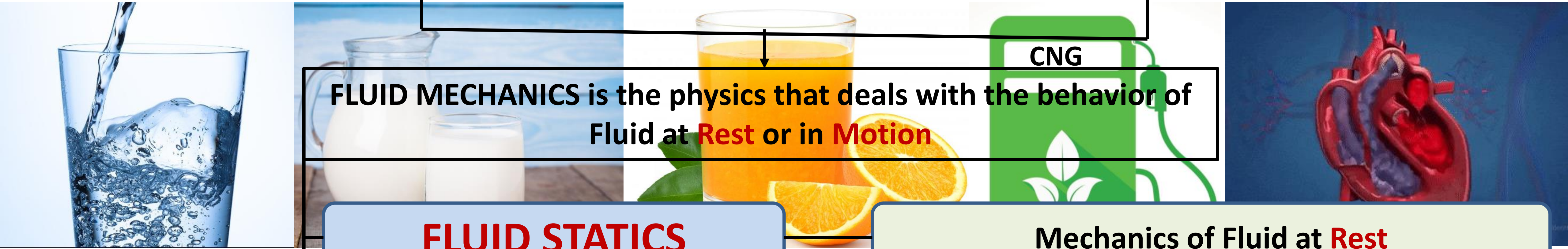
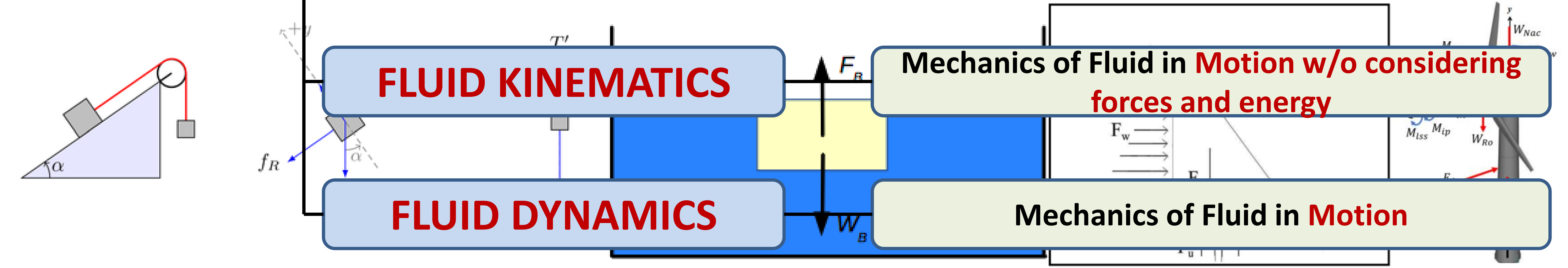
What is FLUID MECHANICS?

A substance in LIQUID or GAS phase is referred as a FLUID

Physics that deals with the behavior of stationary or moving bodies when subjected to Forces



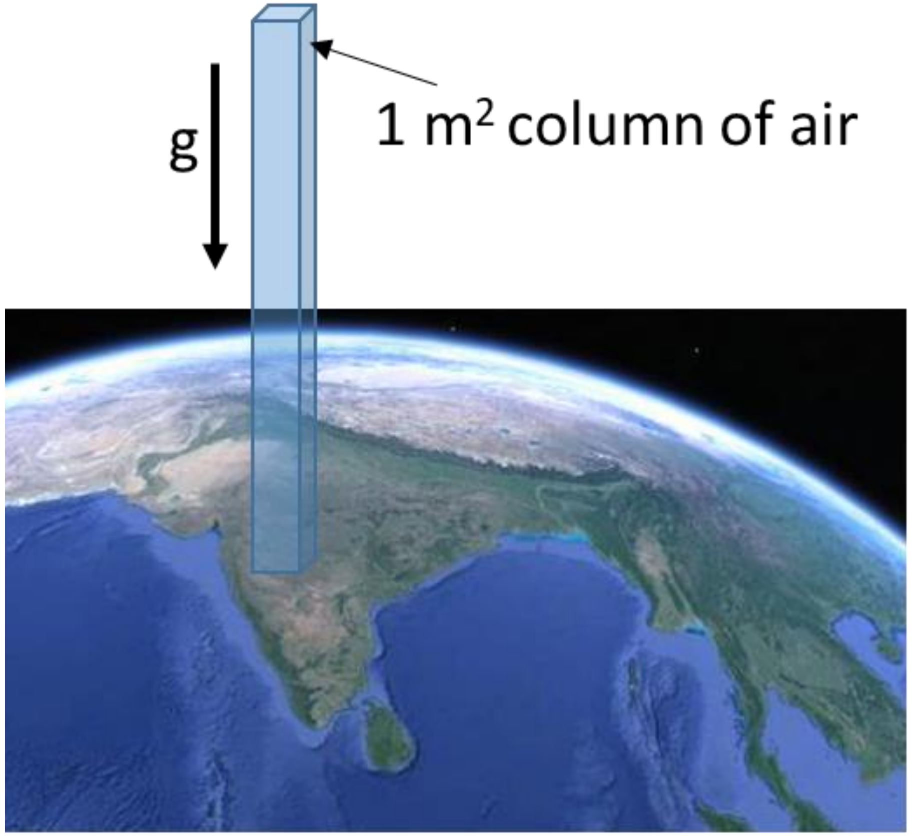
FLUID MECHANICS is the physics that deals with the behavior of Fluid at Rest or in Motion

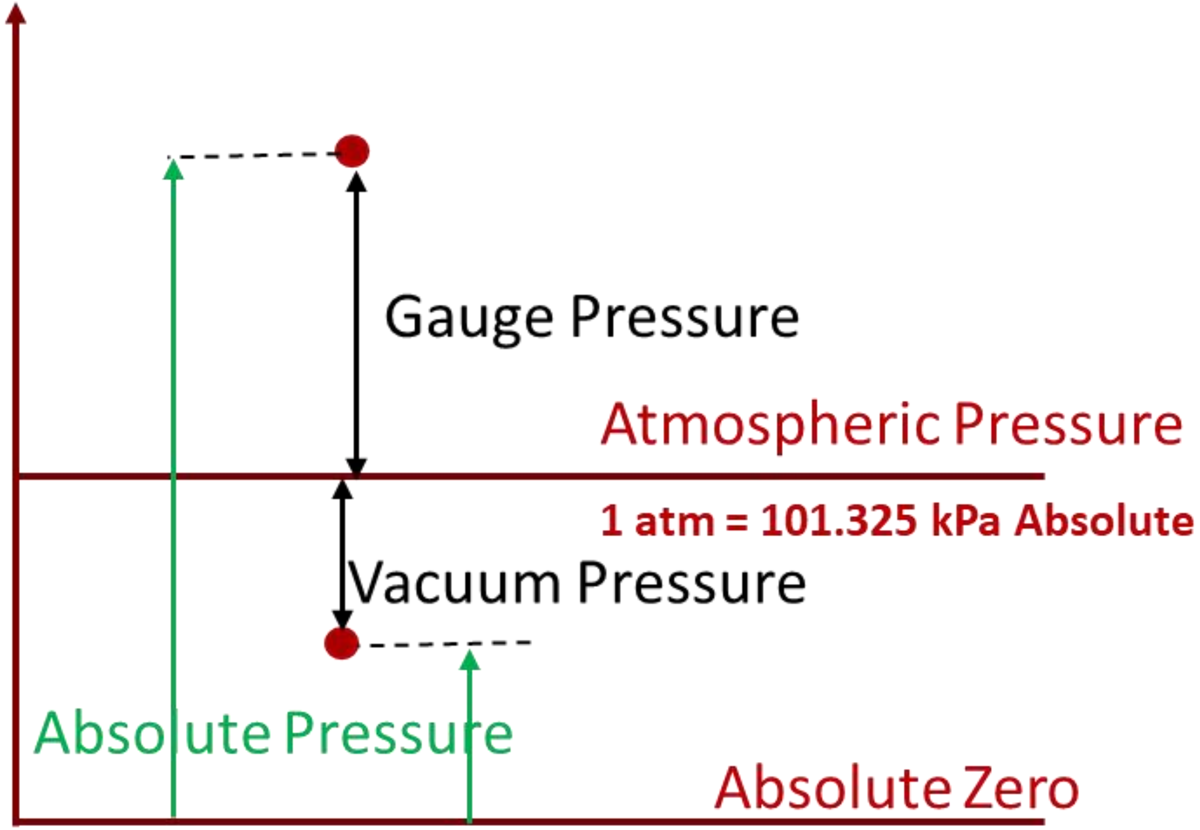


FLUID STATICS	Mechanics of Fluid at Rest
FLUID KINEMATICS	Mechanics of Fluid in Motion w/o considering forces and energy
FLUID DYNAMICS	Mechanics of Fluid in Motion

Fluid Statics

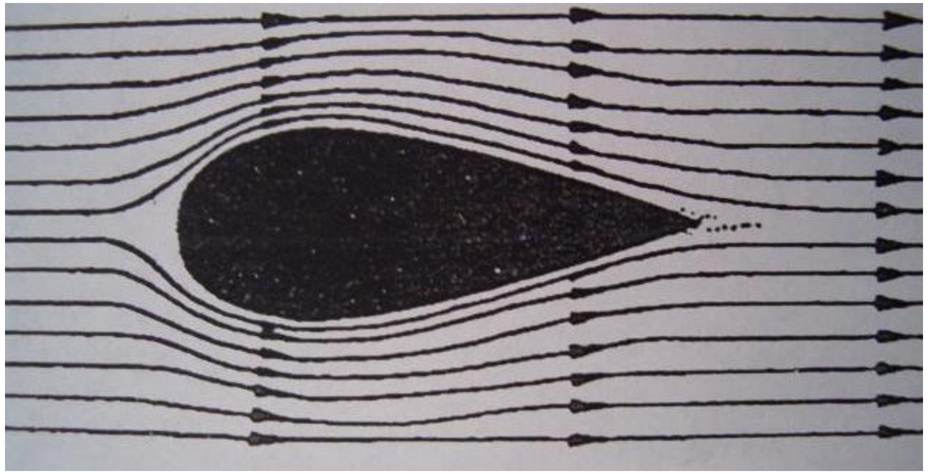
$$p = \gamma h$$

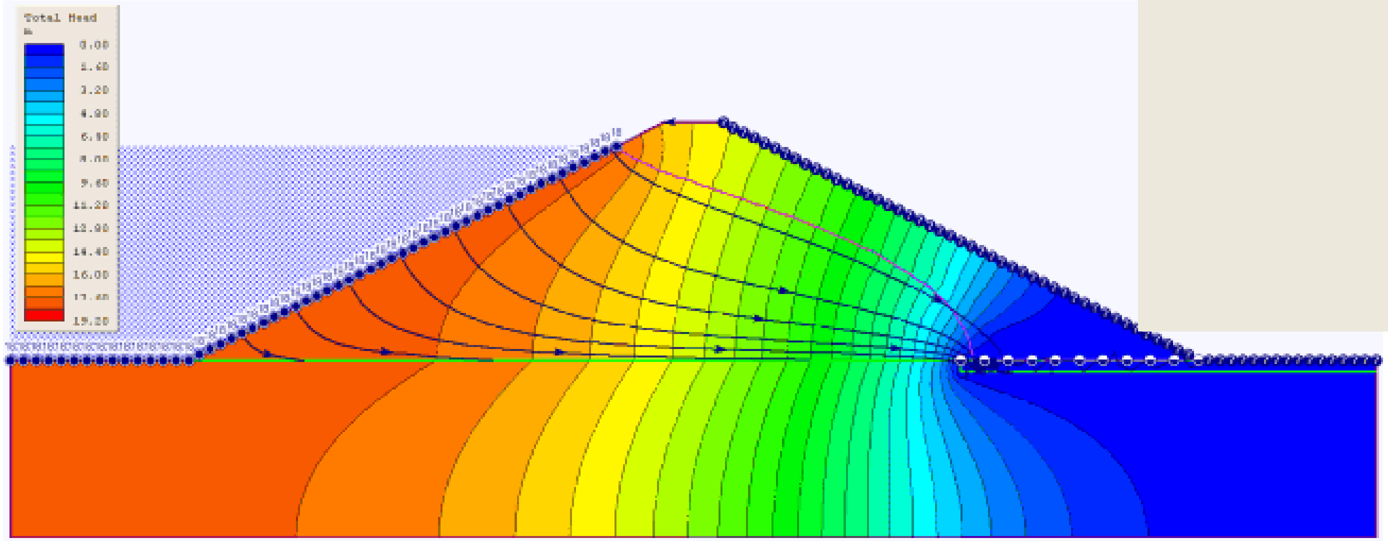




Fluid Kinematics

Streamline, Path line, Streak line





Fluid Dynamics

Navier-Stokes Equations

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

Momentum Equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = g_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = g_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right]$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = g_z - \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right]$$

Solutions of N-S equations

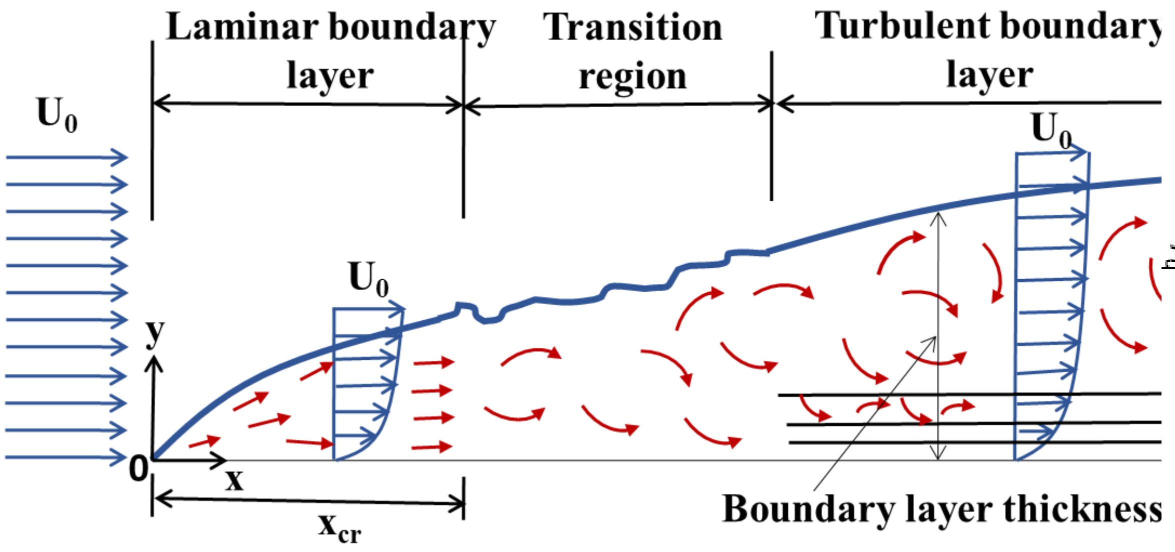
The solutions of N-S equations can be mainly classified into two categories:

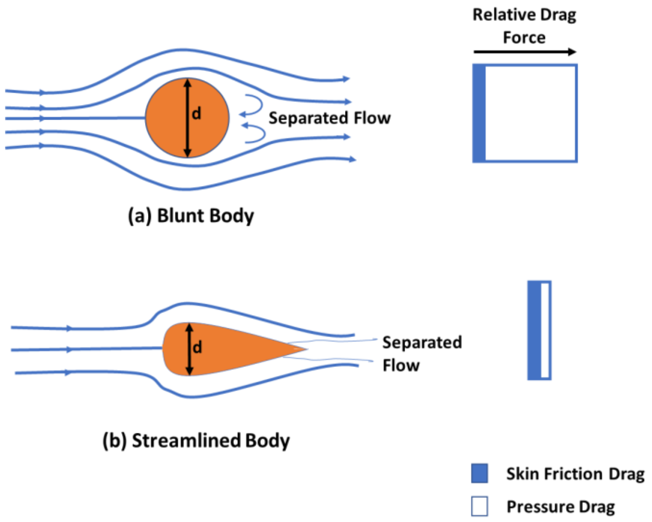
(a)Exact solutions

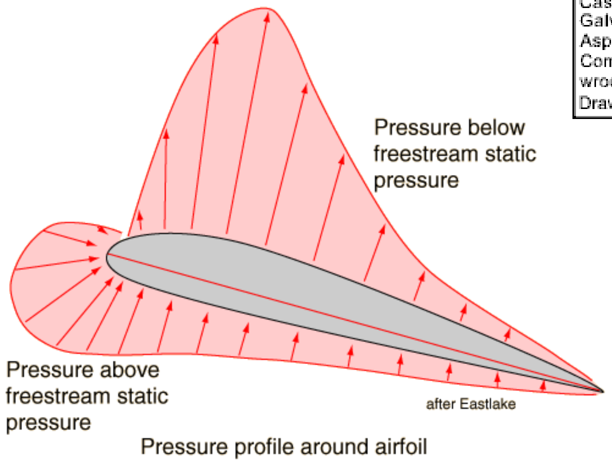
(b)Approximate solutions

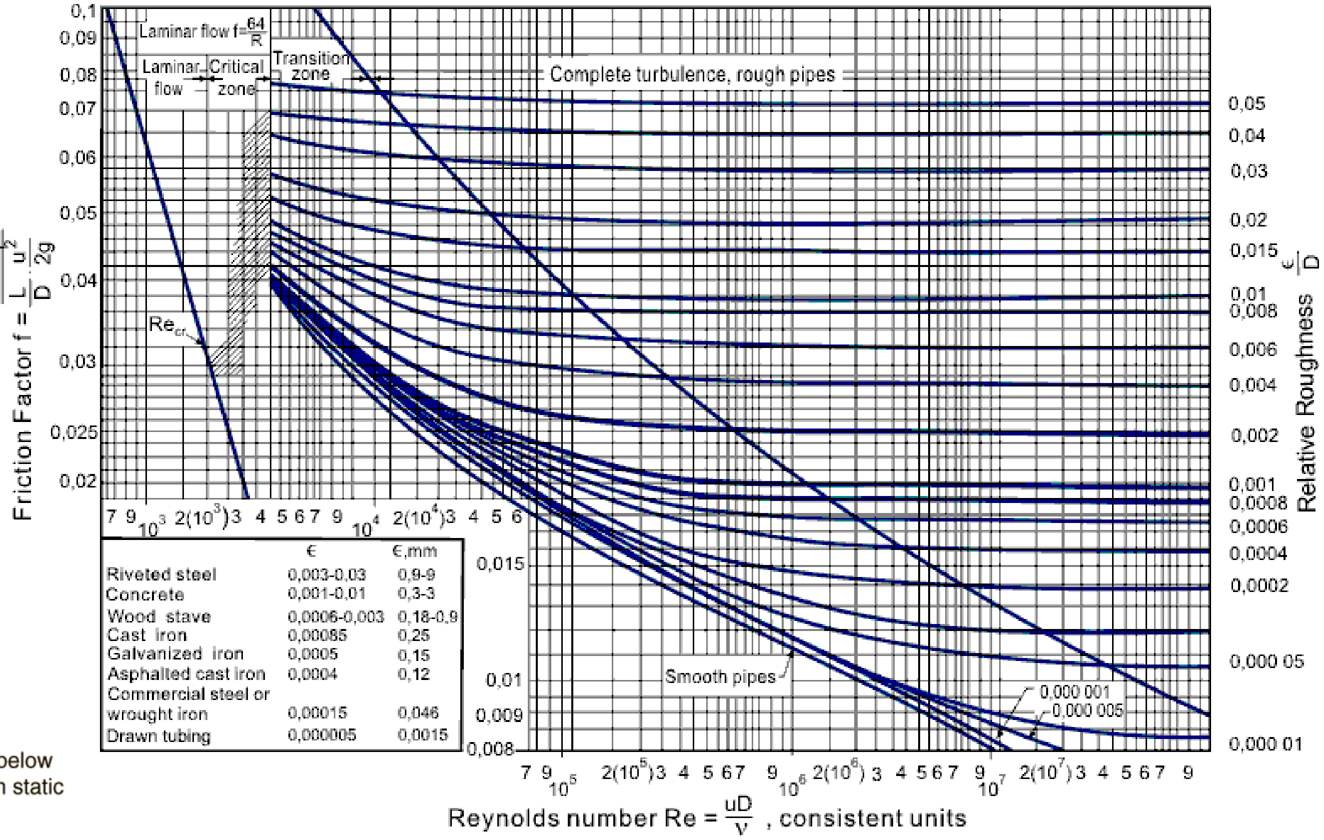
- **The Approximate solutions can be broadly classified as, those for which**
  - **viscous force are very large compared to the inertia force, and**
  - **viscous force are quite small relative to the inertia force**

Boundary Layer Theory

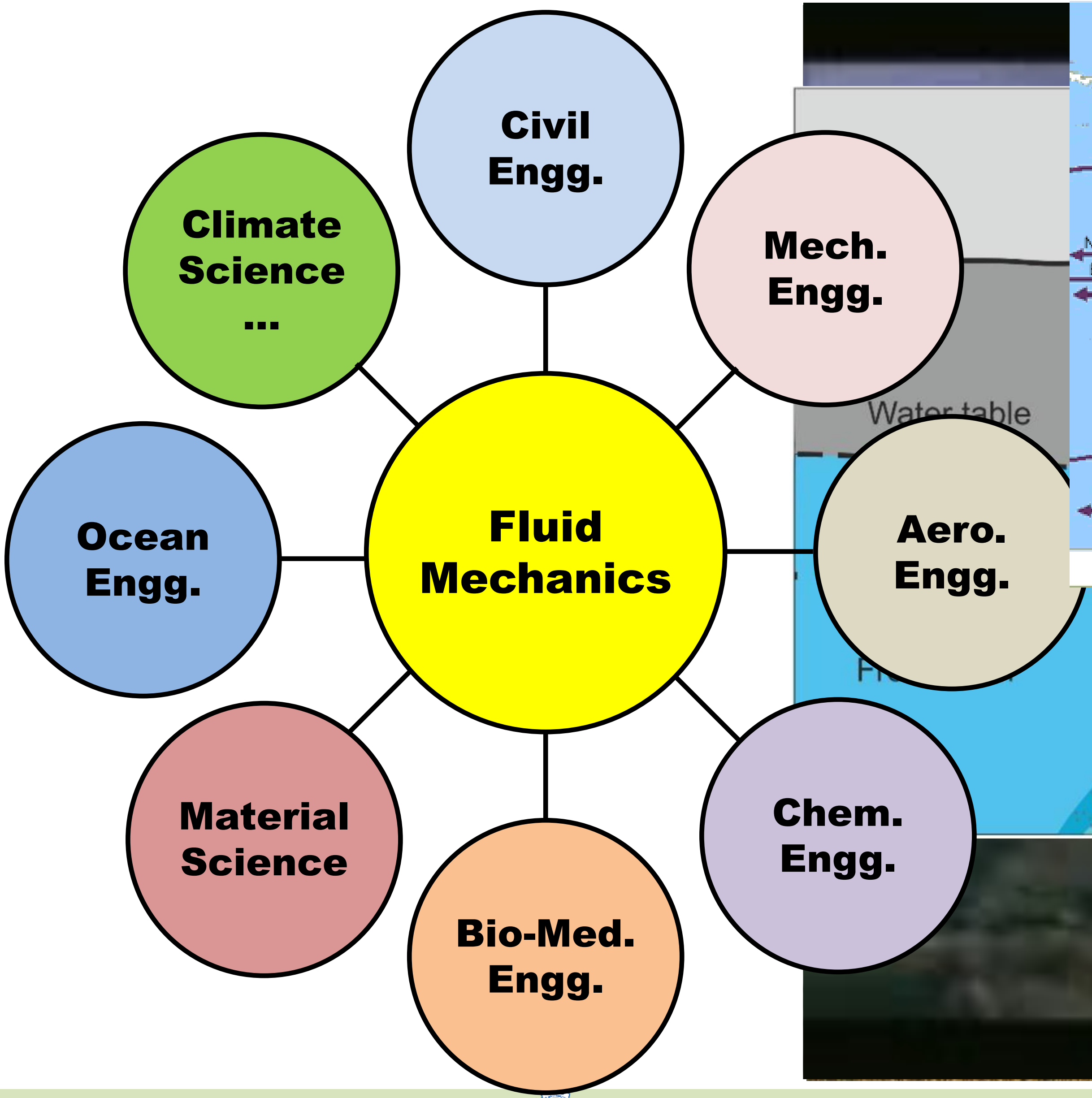


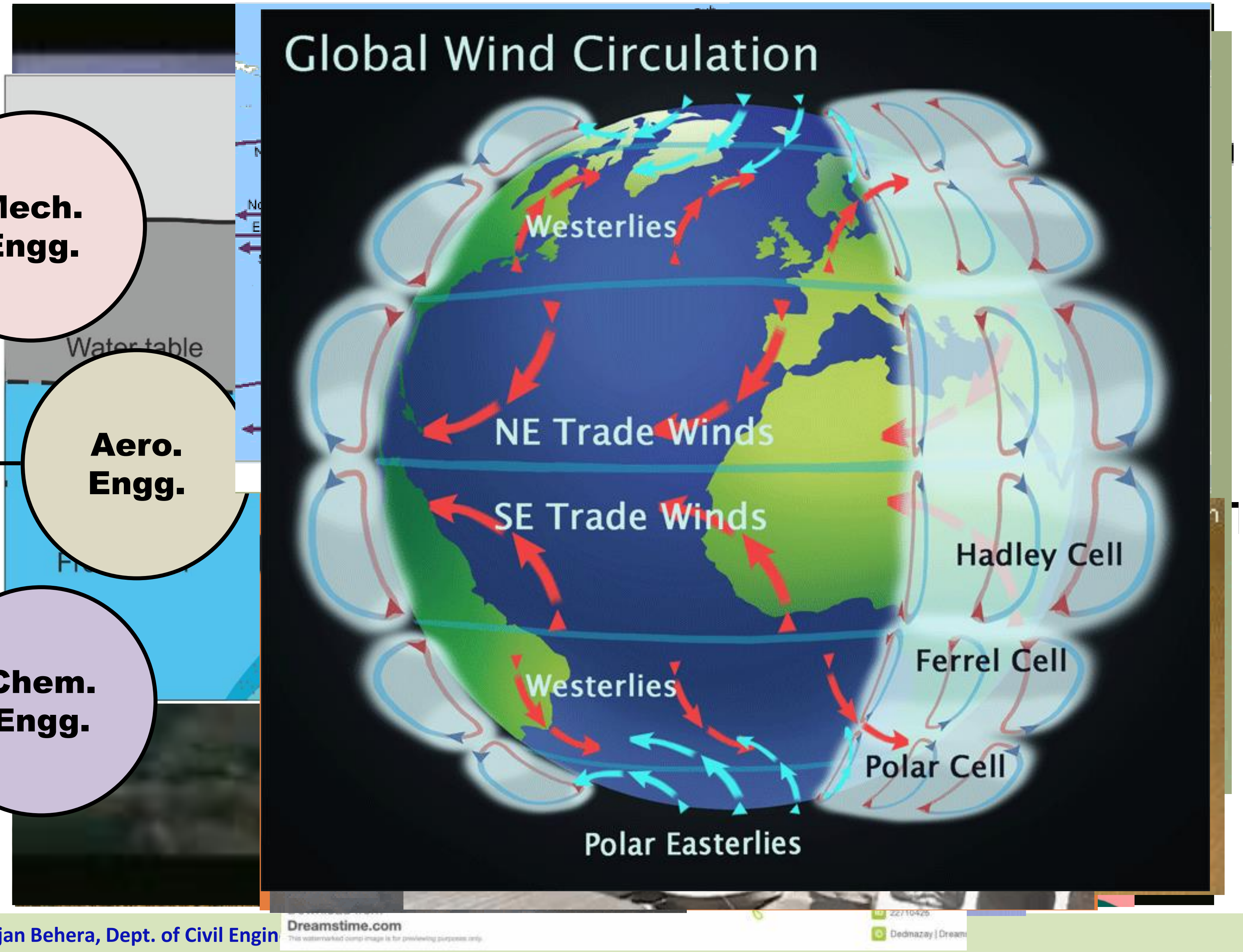




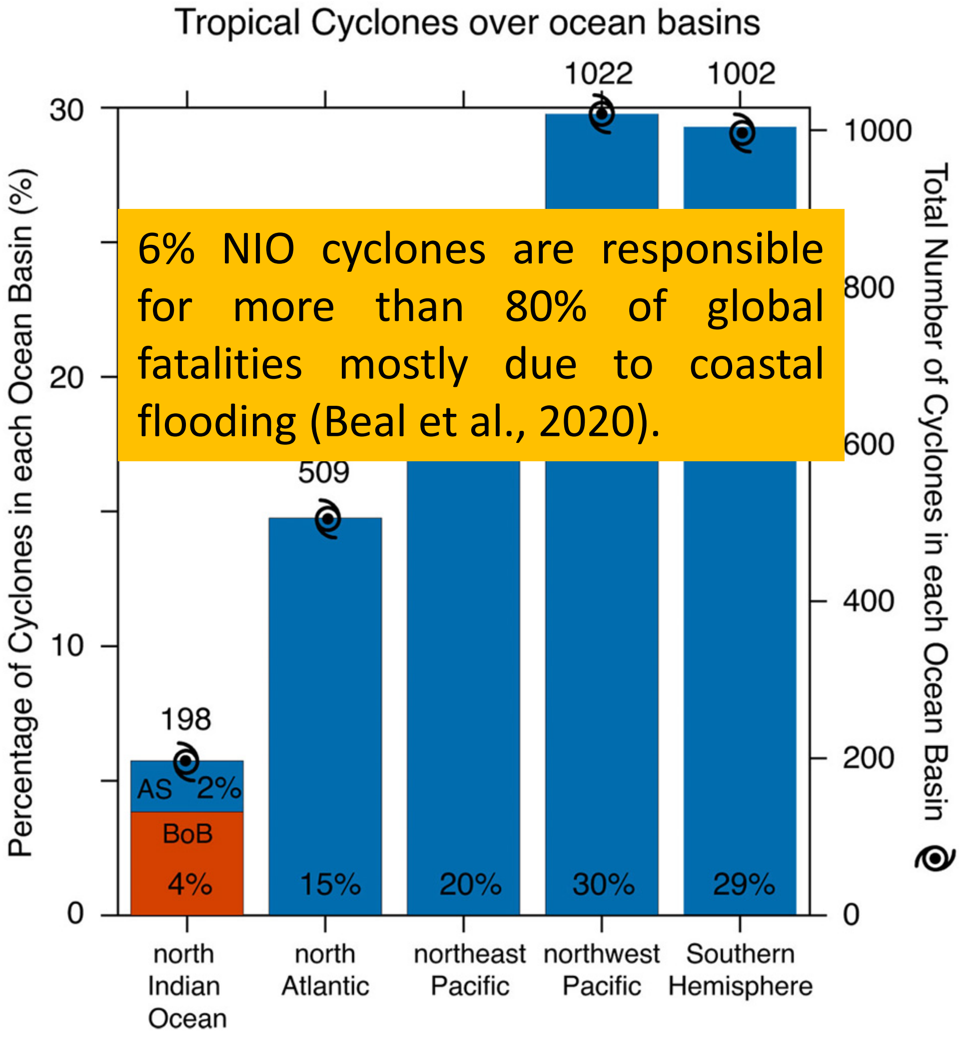


Applications



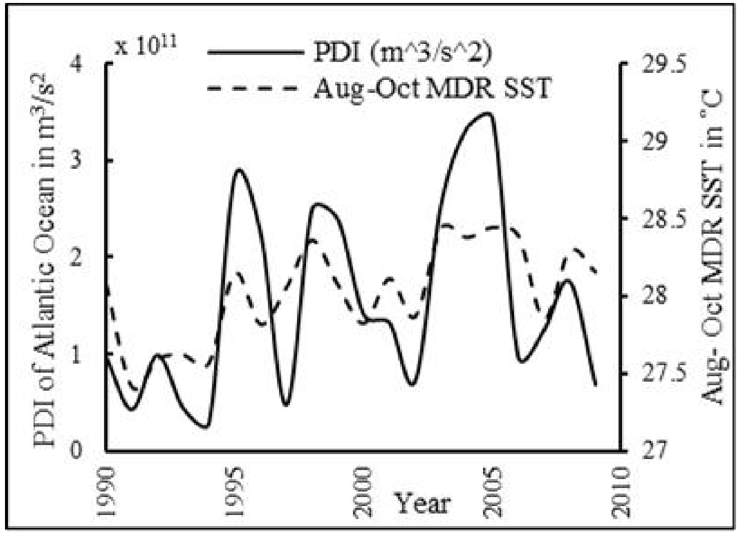


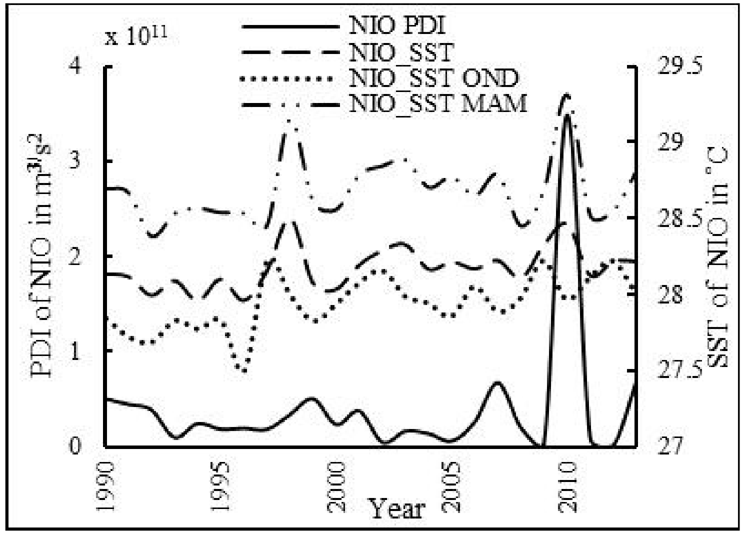
CLIMATE CHANGE IMPACT ON CYCLONES, STORM SURGE, AND COASTAL FLOODING

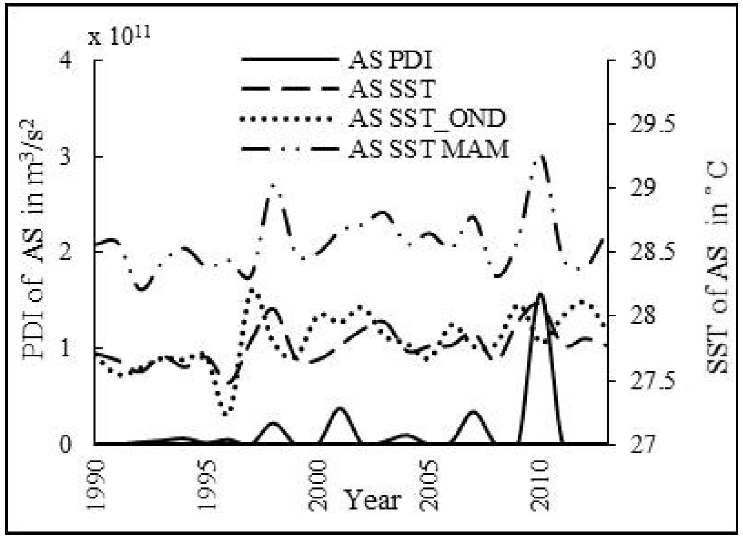


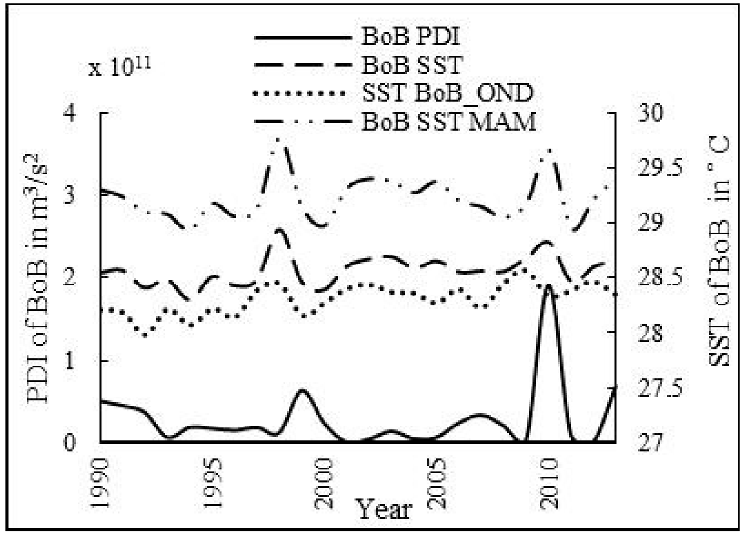
6% NIO cyclones are responsible for more than 80% of global fatalities mostly due to coastal flooding (Beal et al., 2020).

Total number of cyclones in each ocean basins, during the period 1980–2019 (Singh and Roxy, 2022)









Power Dissipative Index (PDI) for North Atlantic basin (Emanuel 2005), North Indian Ocean (NIO), Arabian Sea (AS), and Bay of Bengal (BoB) basins. (Sebastian and Behera, 2015)

Devastation due to Tropical Cyclones

SuCS-1999

(***Source:*** *https://www.indiatoday.in/india/story/odisha-super-cyclone-1516419-2019-05-03/)*

SuCS-1999

(***Source:*** *https://www.financialexpress.com/india-news/cyclone-titli-latest-news-and-live-updates-very-severe-speeds-going-up-to-165-kmph-over-3-lakh-people-evacuated/1344712/)*

Phailin-2013

(***Source:*** *http://pixshark.com/coastal-floods.html)*

Phailin-2013

(***Source:*** *https://aamjanata.com/nation/cyclone-phailin-send-aid-donate/)*

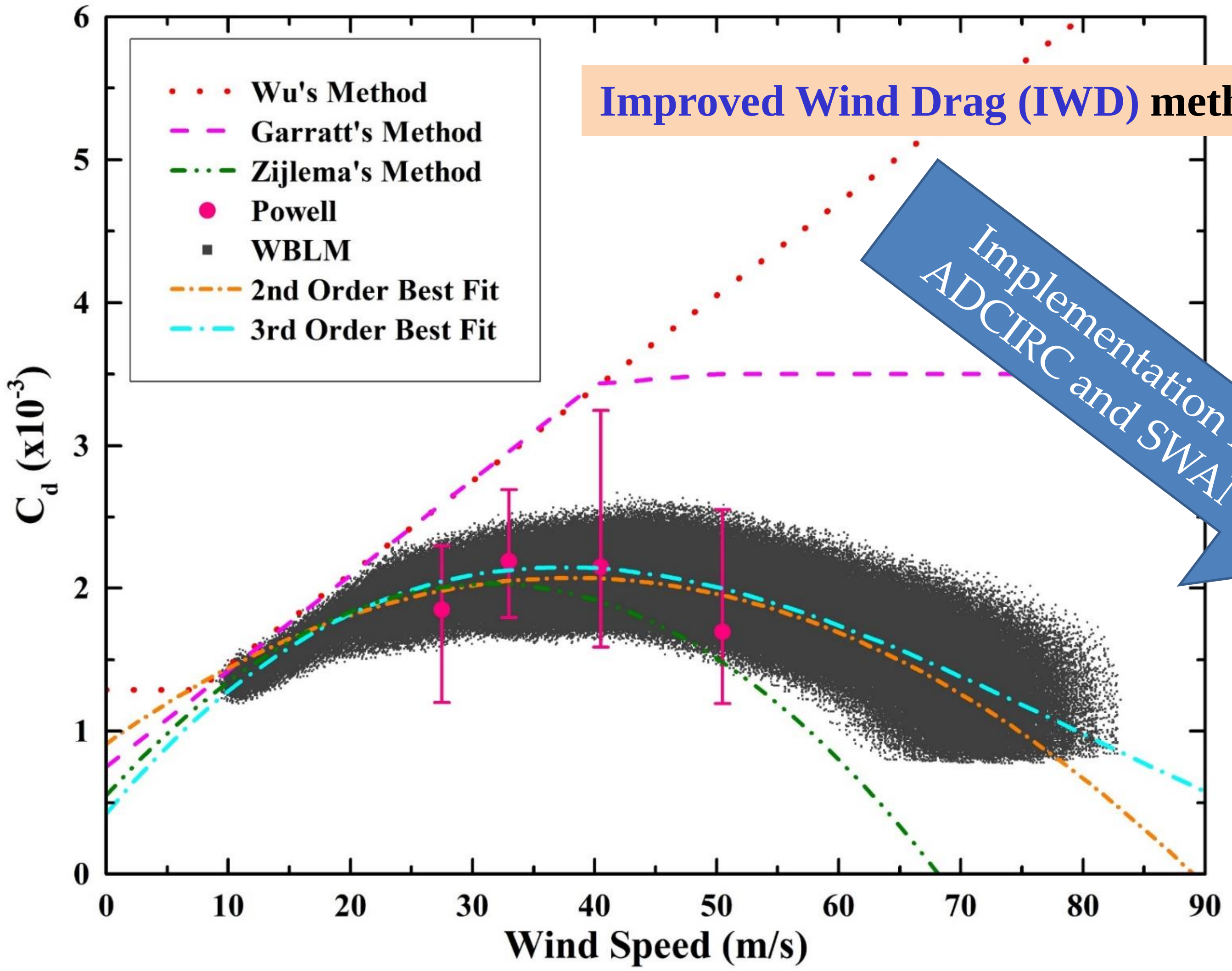
Titli-2018

(***Source:*** *https://www.financialexpress.com/india-news/cyclone-titli-latest-news-and-live-updates-very-severe-speeds-going-up-to-165-kmph-over-3-lakh-people-evacuated/1344712/?#liveblogstart)*

Fani-2019

(***Source:*** *https://indianexpress.com/article/opinion/columns/cyclone-fani-why-2019-was-not-1999-imd-odisha-coast-5723260/)*

Development of Improved Wind Drag (IWD) Method



Comparison of different wind drag coefficient methods as a function of wind speed

Improved Wind Drag (IWD) method

$$C_d = \left(0.42 + 3.86\tilde{u} - 2.53\tilde{u}^2 + 0.4\tilde{u}^3\right) \times 10^{-3}$$

where, $\tilde{u} = u_{10}/u_{ref}$

u_{ref} is the reference wind speed of 37.5 m/s at which the C_d attains its maximum value in the proposed method.

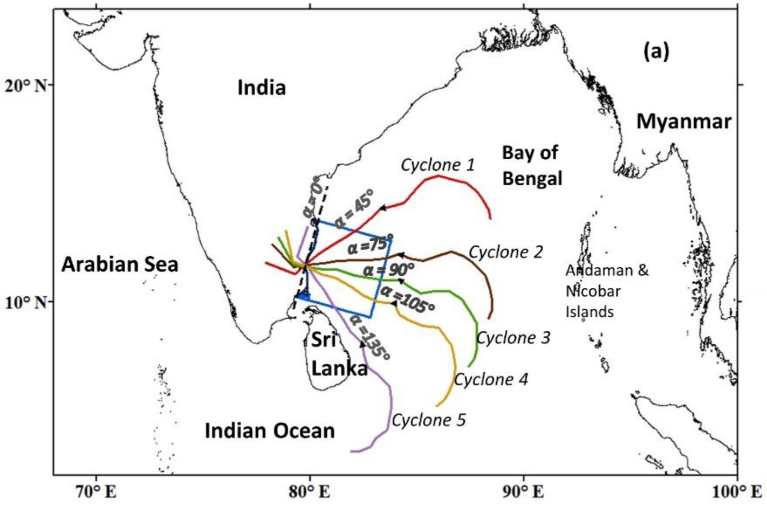
Implementation in ADCIRC and SWAN

$$\tilde{J}_x = \dots\dots\dots + \frac{\tau_{sx,wind} + \tau_{sy,waves} - \tau_{bx}}{\rho_0} + \dots\dots\dots$$

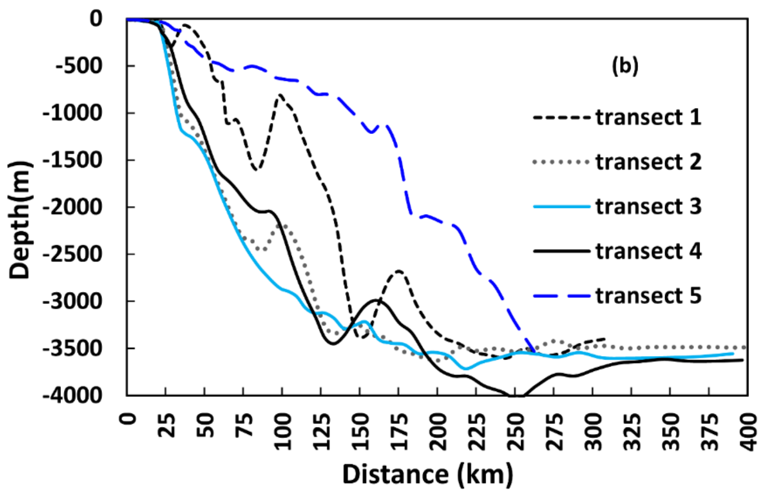
$$S_{tot} = S_{in} + \cdots$$

Shankar, C.G. and Behera, M.R., 2021. "Improved wind drag formulation for numerical storm wave and surge modeling", *Dynamics of Atmospheres and Oceans*, vol. 93, 101193, pp. 1-32. https://doi.org/10.1016/j.dynatmoce.2020.101193

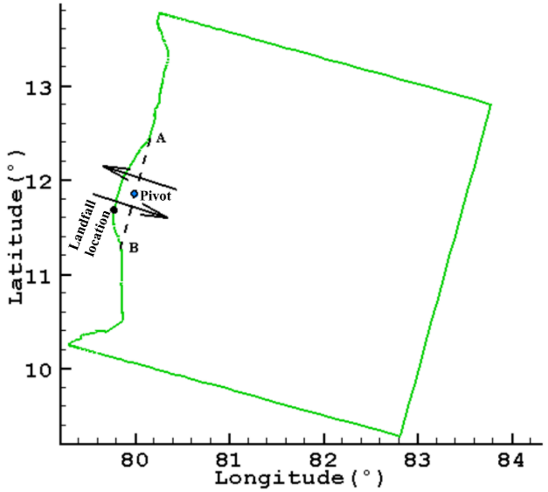
EFFECT OF COASTAL GEOMETRY STORM SURGE



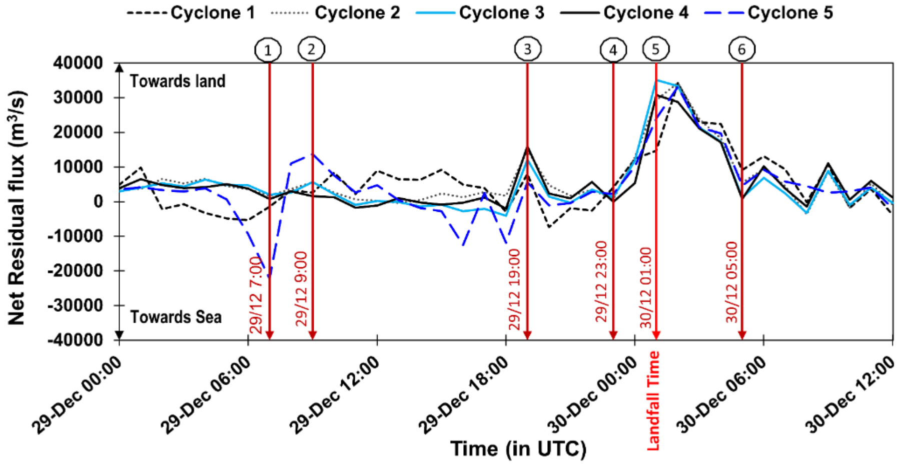
Different Cyclone tracks considered for the study



Continental shelf and slope profile of cyclone tracks considered for the study



Model domain depicting the cross-section AB used for computing the flux movement



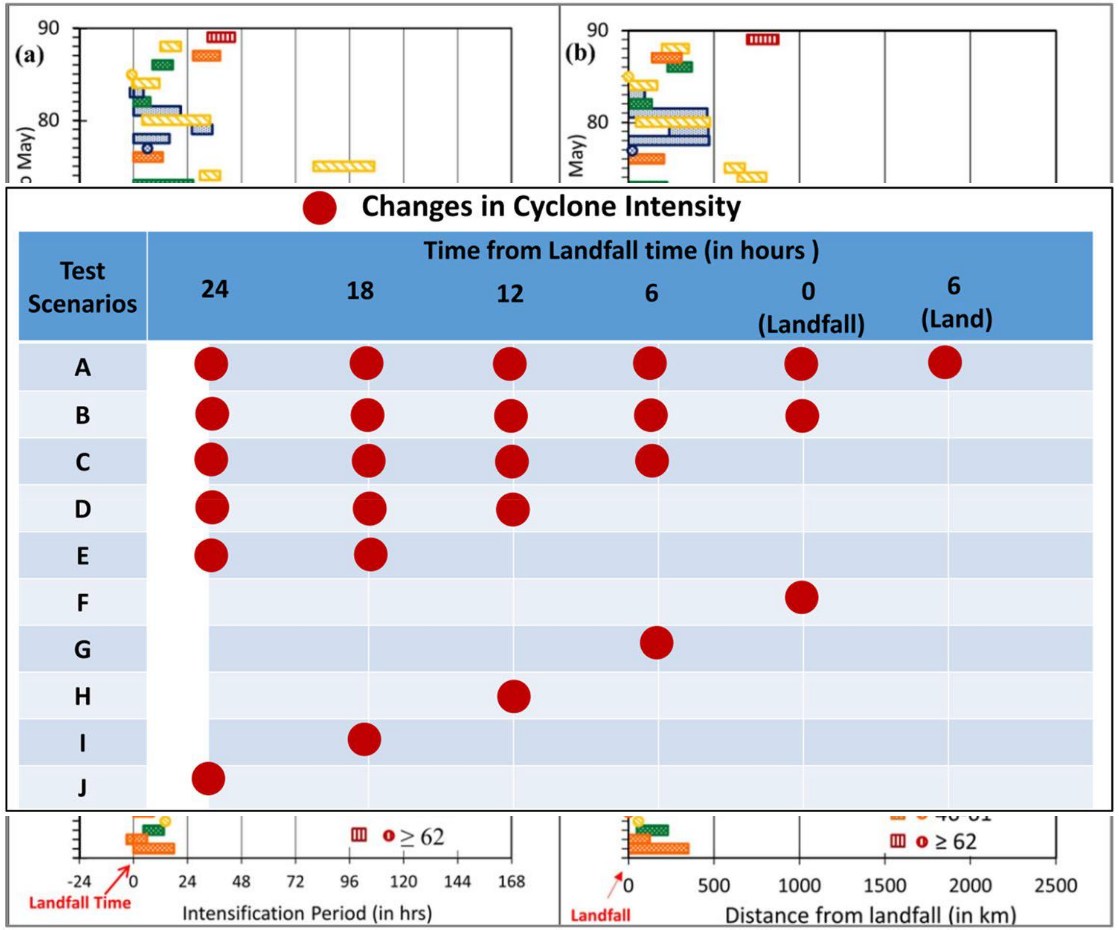
Net residual flux through cross-section AB during different approach angles of cyclone

- Maximum storm surge inside a concave coast occurs for cyclones with an approach angle of ~75°

Sebastian, M., Behera, M.R., and Murty, PLN. (2019), "Storm surge hydrodynamics at a concave coast due to varying approach angles of cyclone", *Ocean Engineering*, vol. 191, paper id: 106437, pp. 1-16.

https://doi.org/10.1016/j.oceaneng.2019.106437

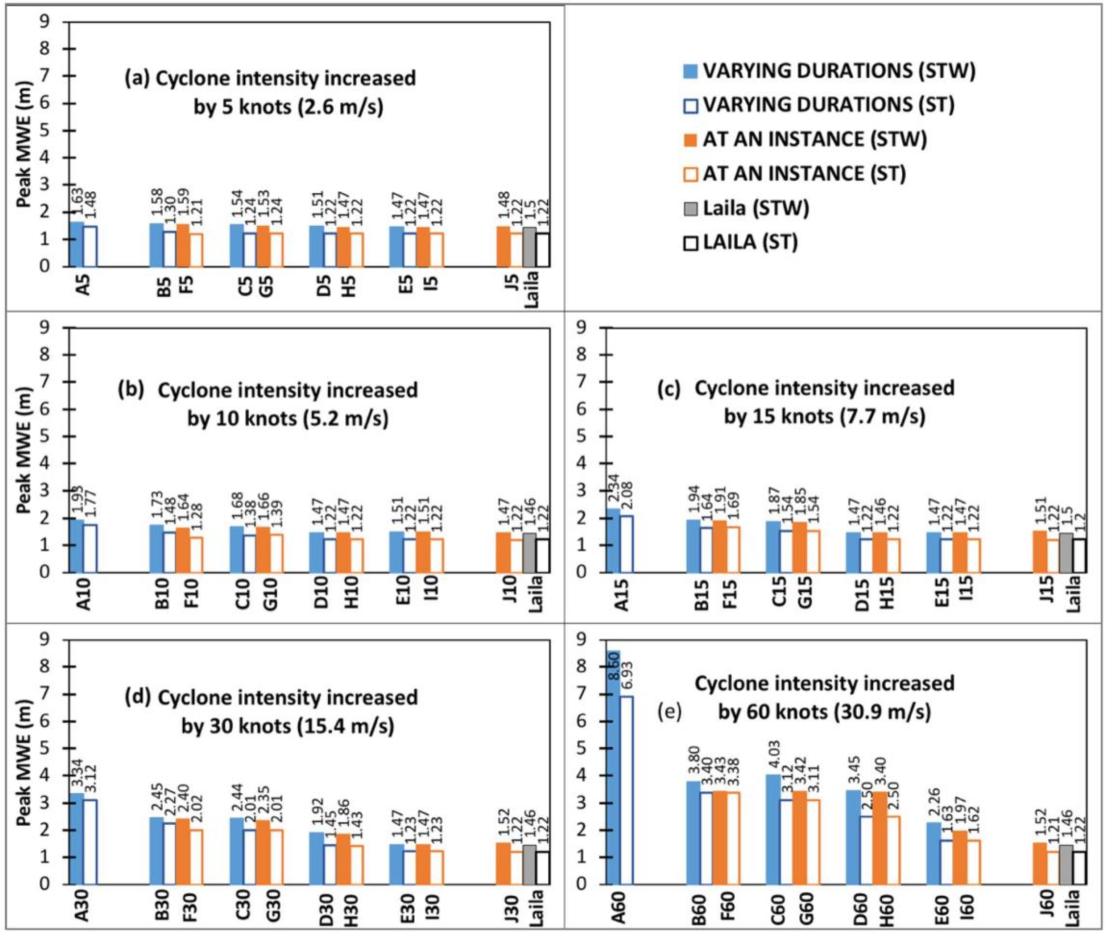
EFFECT OF CYCLONE INTENSIFICATION ON STORM SURGE



Changes in Cyclone Intensity

Test Scenarios	Time from Landfall time (in hours) 24	18	12	6	0 (Landfall)	6 (Land)
A	●	●	●	●	●	●
B	●	●	●	●	●	
C	●	●	●	●		
D	●	●	●			
E	●	●				
F					●	
G				●		
H			●			
I		●				
J	●					

TCs in BoB (1982-2020) with Intensification period and Distance from Landfall



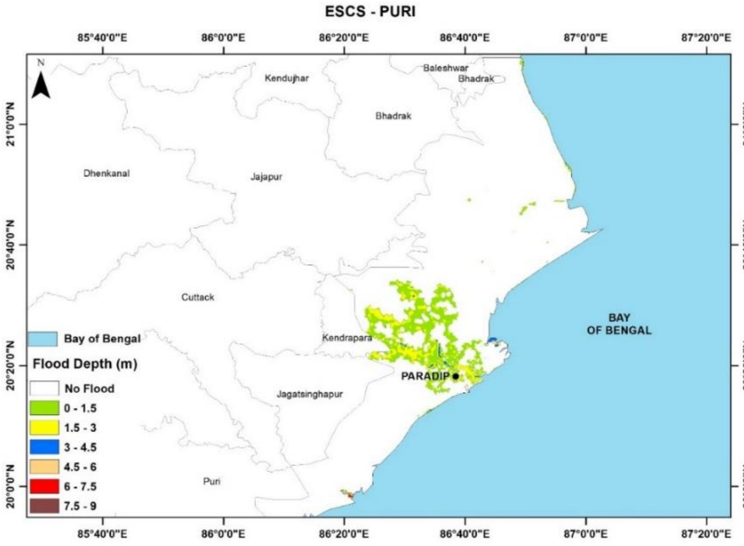
Peak Maximum Water Levels along the K-G basin for different scenarios

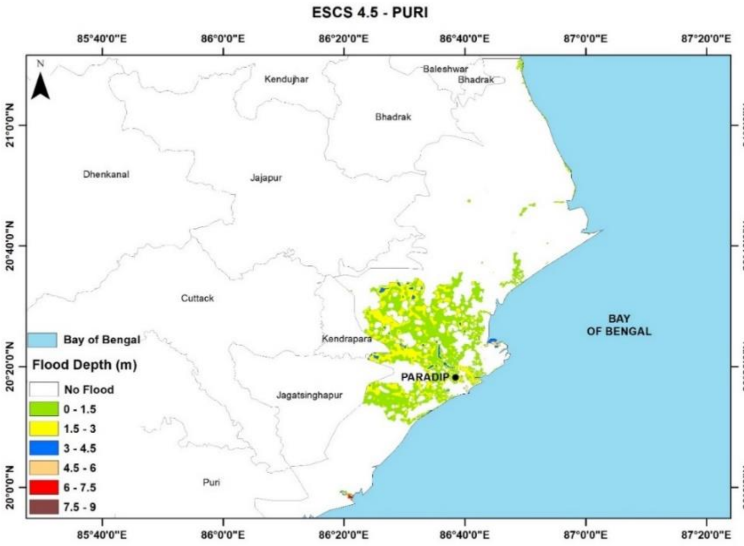
Sebastian, M. and **Behera, M.R.** (2022), "Impact of highest maximum sustained wind speed and its duration on storm surges and hydrodynamics along Krishna–Godavari coast", Climate Dynamics, https://doi.org/10.1007/s00382-022-06173-9

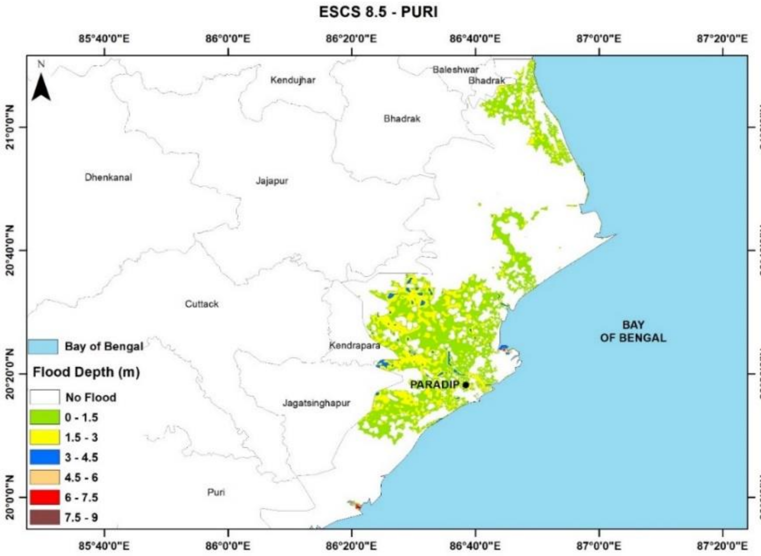
SURGE INDUCED COASTAL FLOODING IN DIFFERENT CLIMATE CHANGE SCENARIOS

Cyclone Intensity
RCP 4.5: 7% increase
RCP 8.5: 11% increase

Flood depth map along Paradip coast due to ESCS landfall at Puri



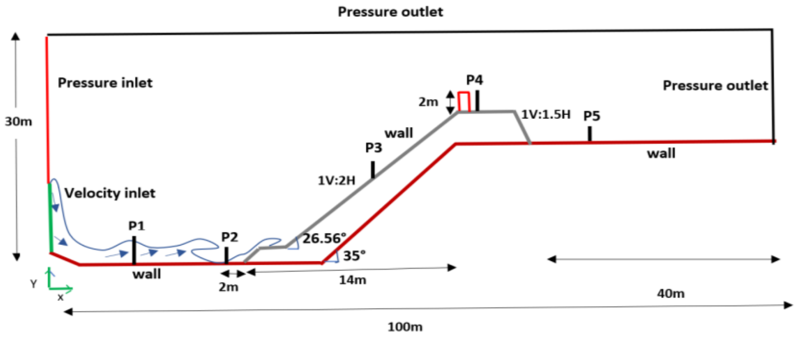


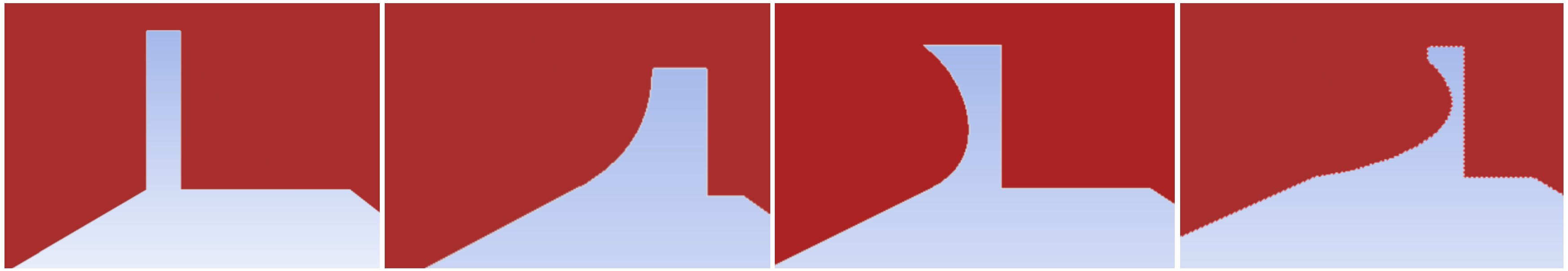


Cyclone Shelter Location Identification and Design based on Vulnerability

FRONT ELEVATION

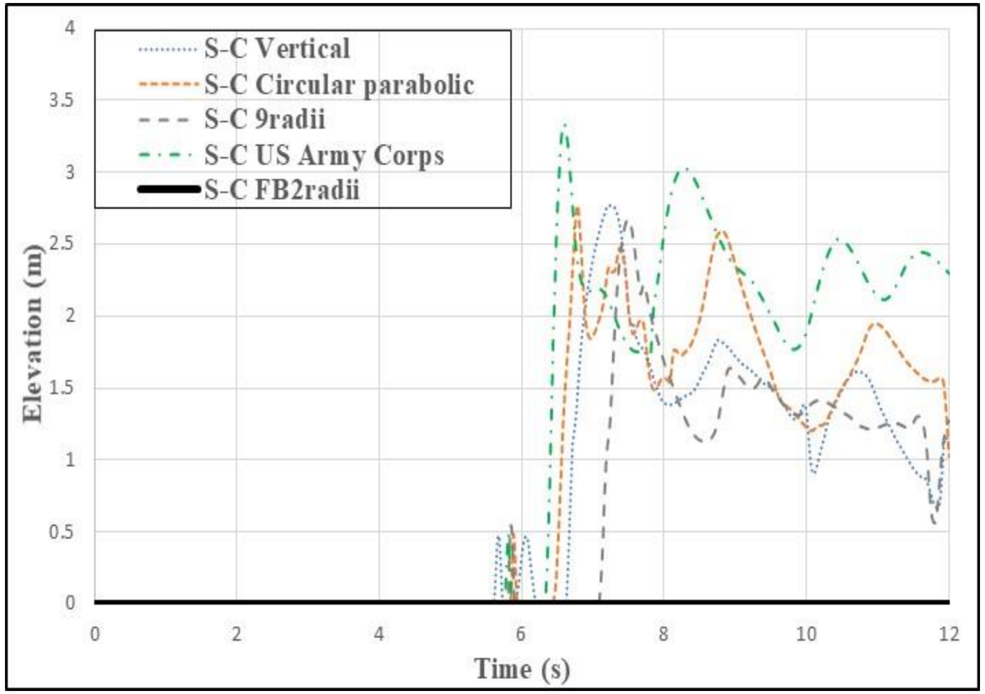
PROTECTION OF HIGH-RISK COASTAL INSTALLATIONS

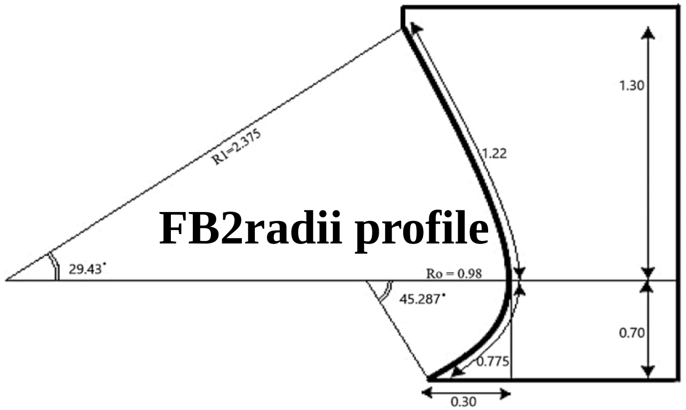




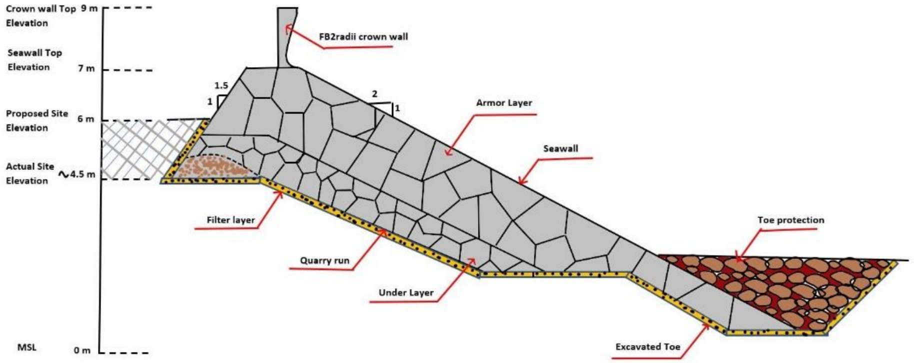
Vertical | US Army Corps | 9 radii Seawall | Circular-parabolic

(Anand and Sundar, 2010).





FB2radii profile



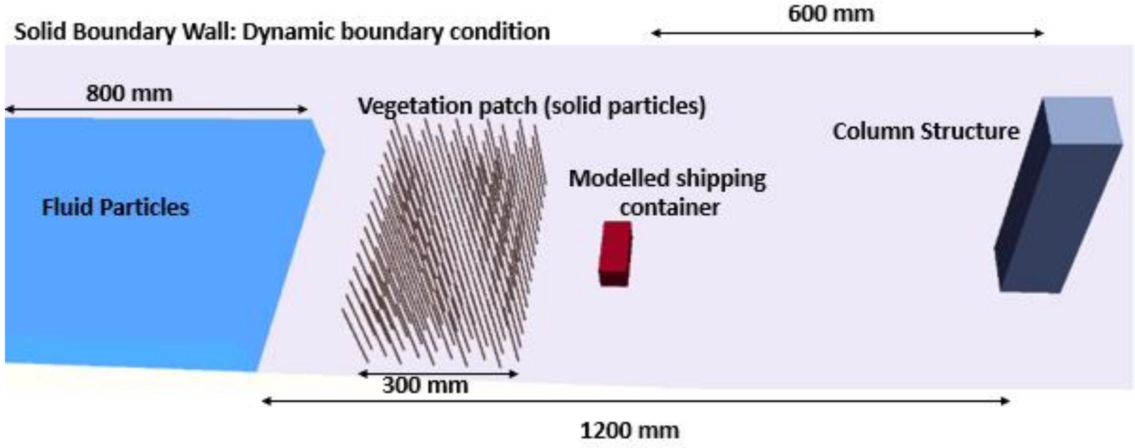
MITIGATION MEASURES USING COASTAL VEGETATION

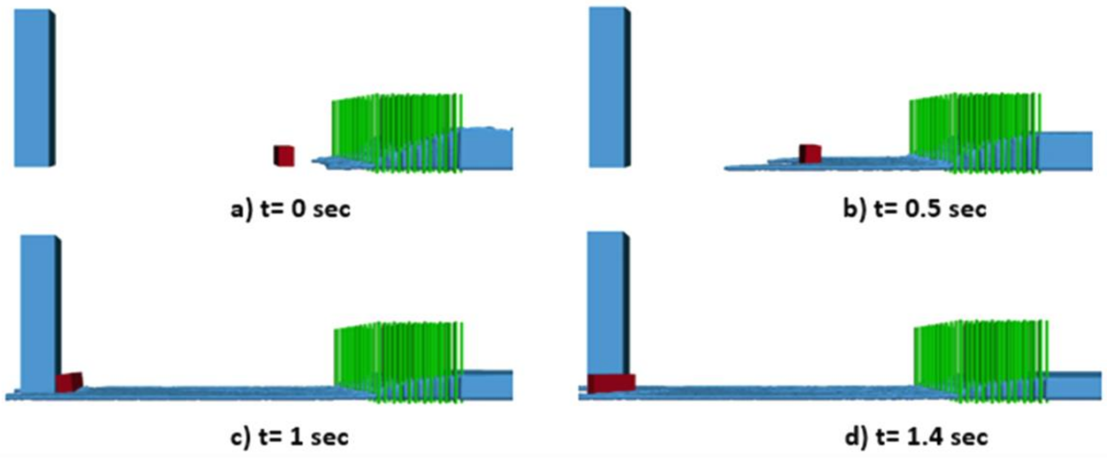
Gupta, A, Heidarpoure, A., Behera, M.R. (2022), **"Effect of structure orientation and debris initial orientation on peak debris loading during tsunami: An experimental and numerical investigation",** ***Applied Ocean Research*****, vol. 121, paper id: 103075, pp. 1 – 14.**

https://doi.org/10.1016/j.apor.2022.103075

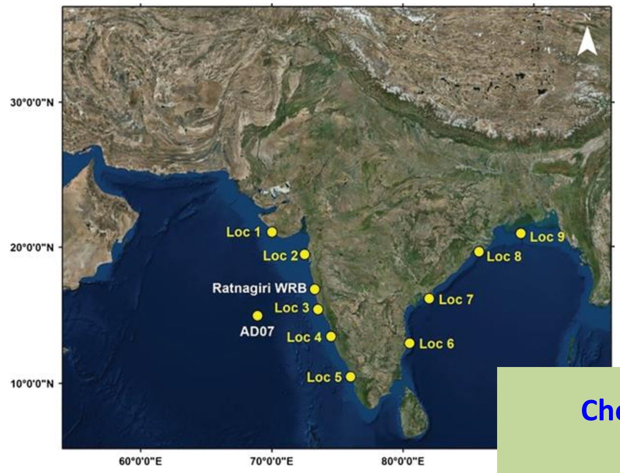
Fig. Structural Analysis of Selected Failures Caused by the 27 February 2010 Chile Tsunami. (https://www.researchgate.net/figure/)

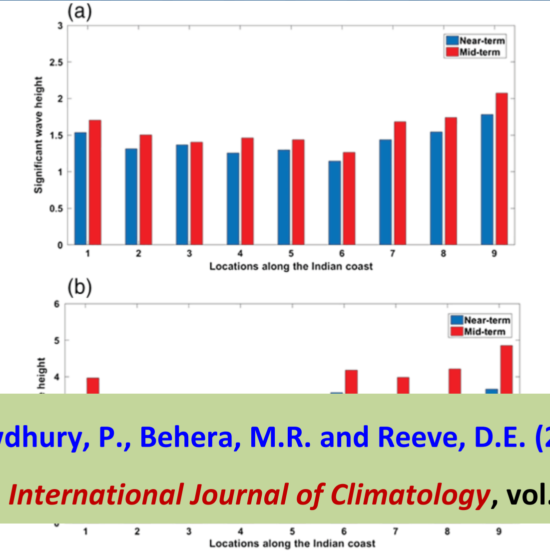
Fig. The protective role of natural and engineered defence systems in coastal hazards. Khazai et al. (2007)

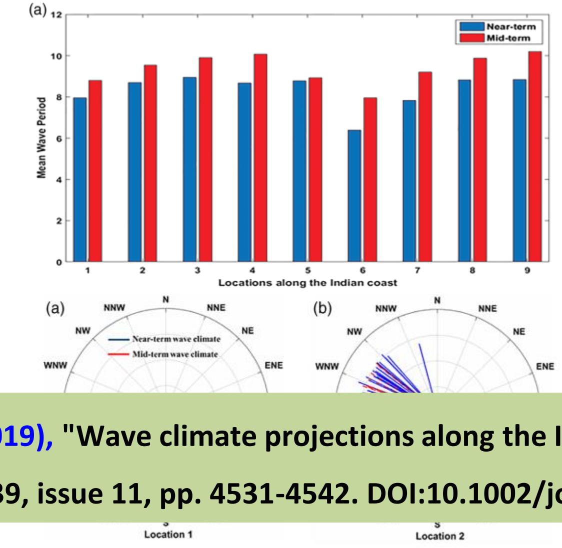


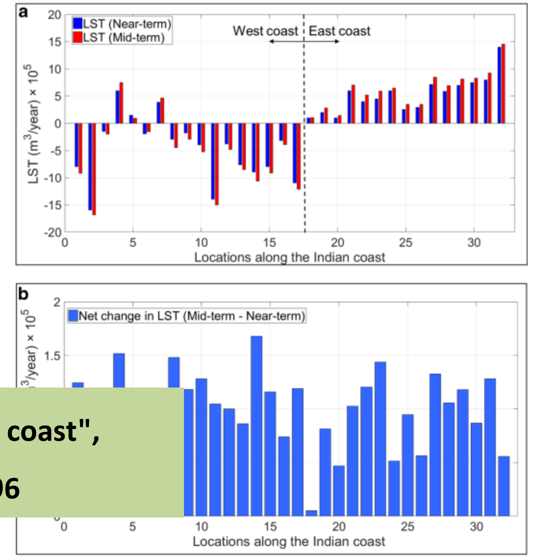


CLIMATE CHANGE IMPACT ON OCEAN WAVES AND COASTAL STABILITY



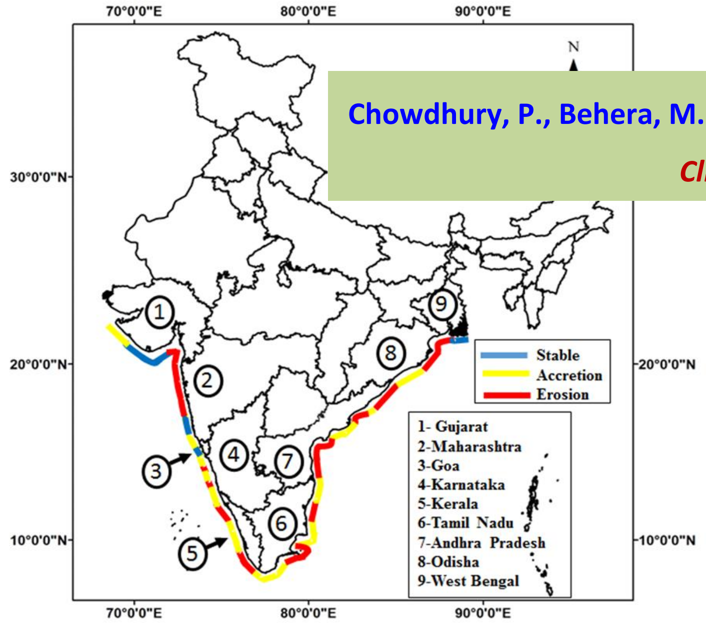


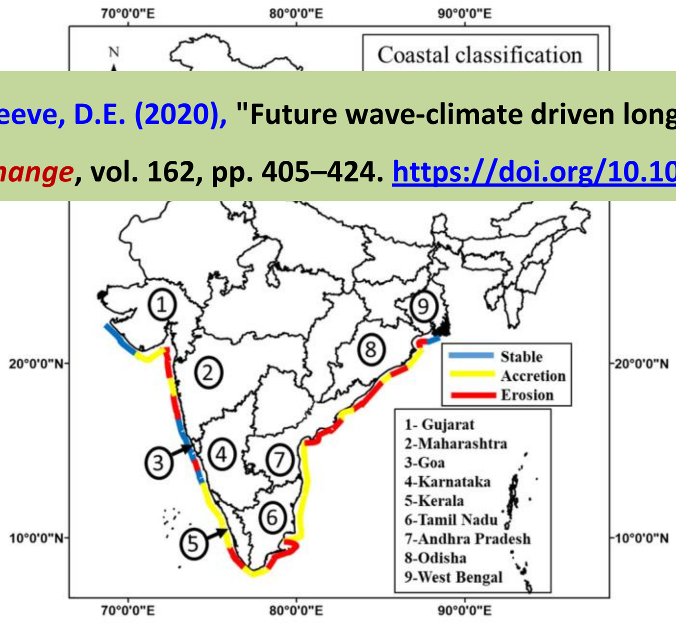


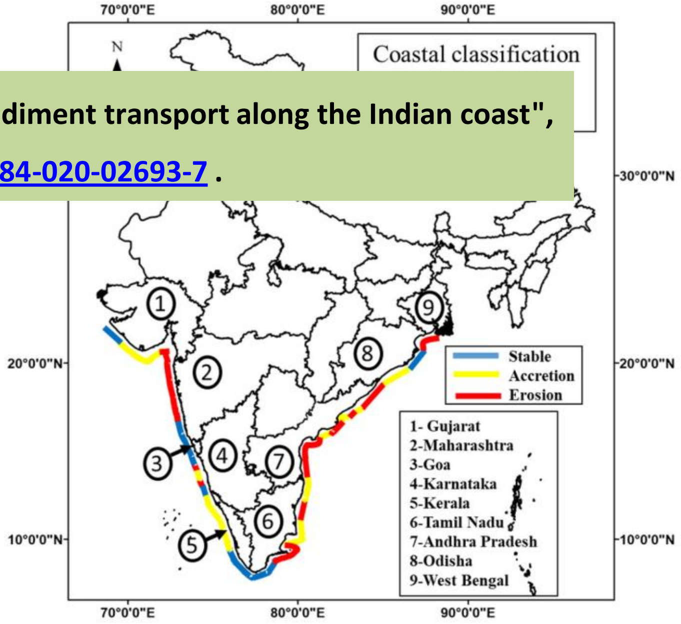


Chowdhury, P., Behera, M.R. and Reeve, D.E. (2019), "Wave climate projections along the Indian coast",

International Journal of Climatology, vol. 39, issue 11, pp. 4531-4542. DOI:10.1002/joc.6096





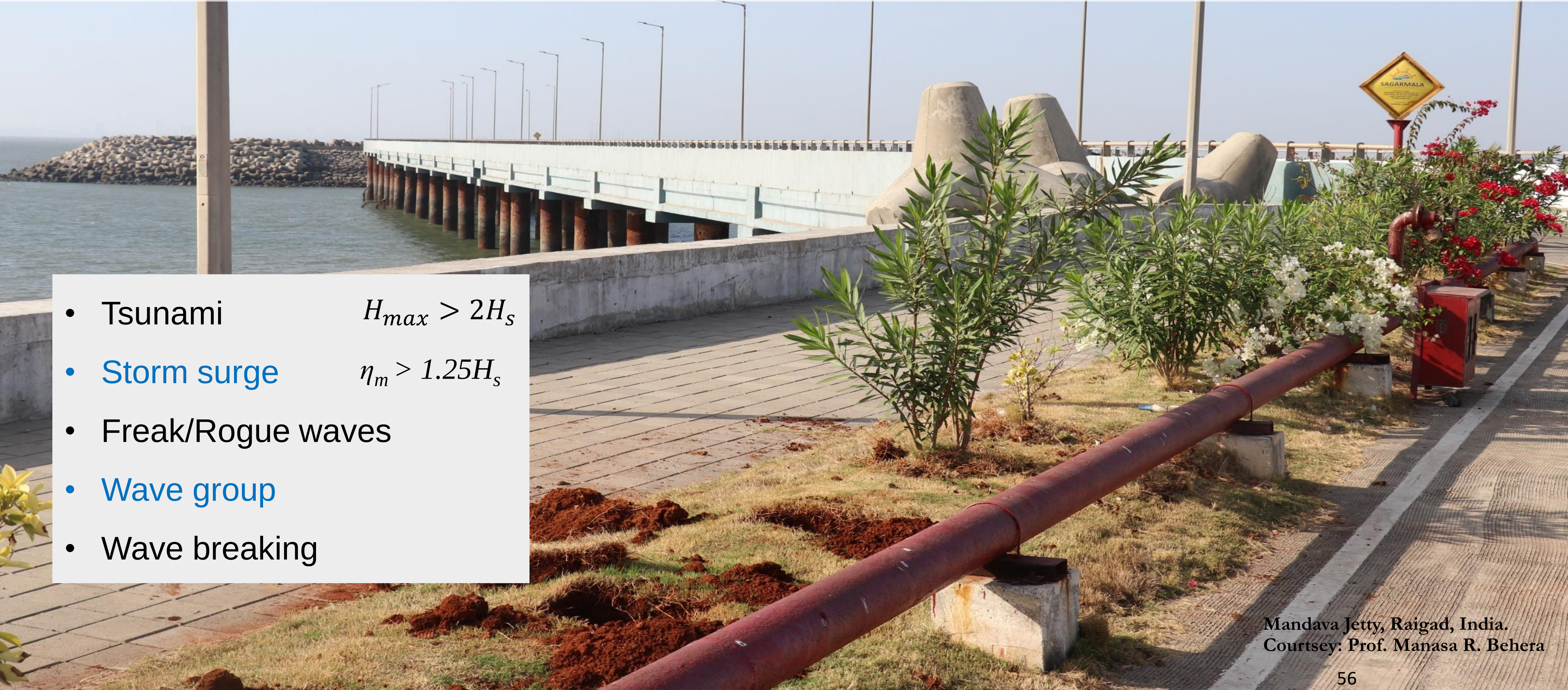


Chowdhury, P., Behera, M.R. and Reeve, D.E. (2020), "Future wave-climate driven longshore sediment transport along the Indian coast",

Climatic Change, vol. 162, pp. 405–424. https://doi.org/10.1007/s10584-020-02693-7 .

EXTREME WAVE IMPACT FORCES ON OFFSHORE AND COASTAL DECK STRUCTURES

- Tsunami $H_{max} > 2H_s$
- Storm surge $\eta_m > 1.25H_s$
- Freak/Rogue waves
- Wave group
- Wave breaking



Mandava Jetty, Raigad, India.
Courtsey: Prof. Manasa R. Behera

Wave impact on deck

COASTAL DECK
(shallow to intermediate)

FIXED OFFSHORE PLATFORM
(intermediate to deep)

Wave impact on deck is a complex non-linear phenomenon which affects the structural integrity and reliability of marine structures

Damage to Lucinda port during cyclone Yasi, 2011 (Burston et al., 2012)

Wave impacting the deck underside (Abdussamie, 2016)

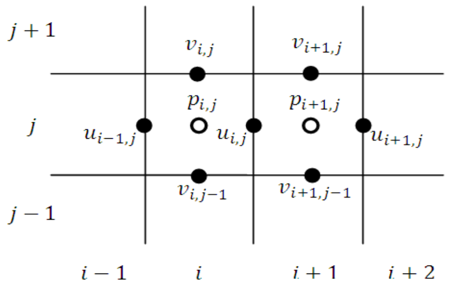
US highway bridge in Bilaxy bay (Xu, 2017)

METHODOLOGY: NWT

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i$$

INPUT BASIC DIMENSIONS OF NWT

GRID GENERATION



TURBULENCE MODELLING (**k-ω** MODEL)

GOVERNING EQUATIONS-**RANS**

Discretization

$$\varphi_x^{\pm} = \omega_1^{\pm}\varphi_x^{1\pm} + \omega_2^{\pm}\varphi_x^{2\pm} + \omega_3^{\pm}\varphi_x^{3\pm}$$

SPATIAL –**WENO SCHEME**

TIME- **RUNGE KUTTA 3rd ORDER**

$$\rho_{i+1/2} = \rho_1 H\left(\varphi_{i+\frac{1}{2}}\right) + \rho_2\left(1 - H\left(\varphi_{i+\frac{1}{2}}\right)\right)$$

$$\varphi_{i+1/2} = \frac{1}{2}(\varphi_i + \varphi_{i+1})$$

FREE SURFACE MODELLING – **LEVEL SET METHOD**

BC's and Initial conditions

SOLVING GOVERNING EQUATION- **Projection method**

CALCULATE WAVE PROPERTIES

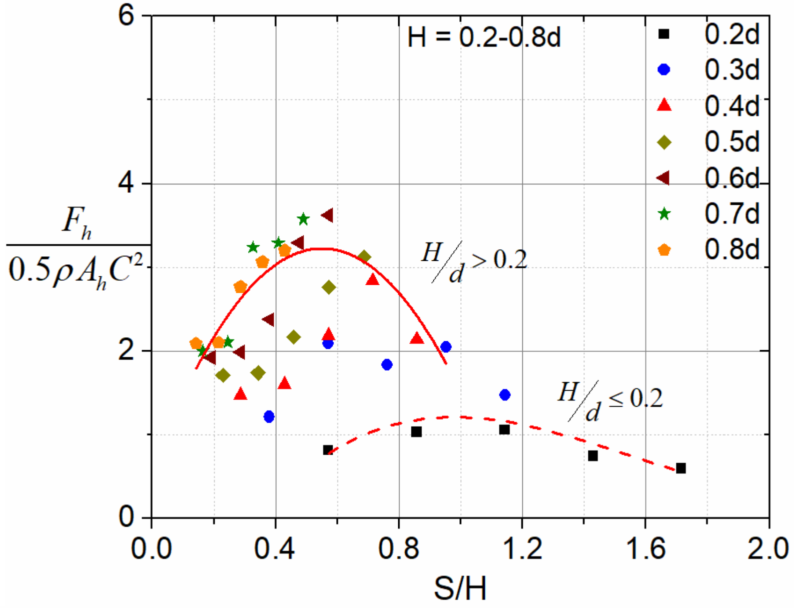
Rigid body

NON-LINEAR WAVE STRUCTURE INTERACTIONS

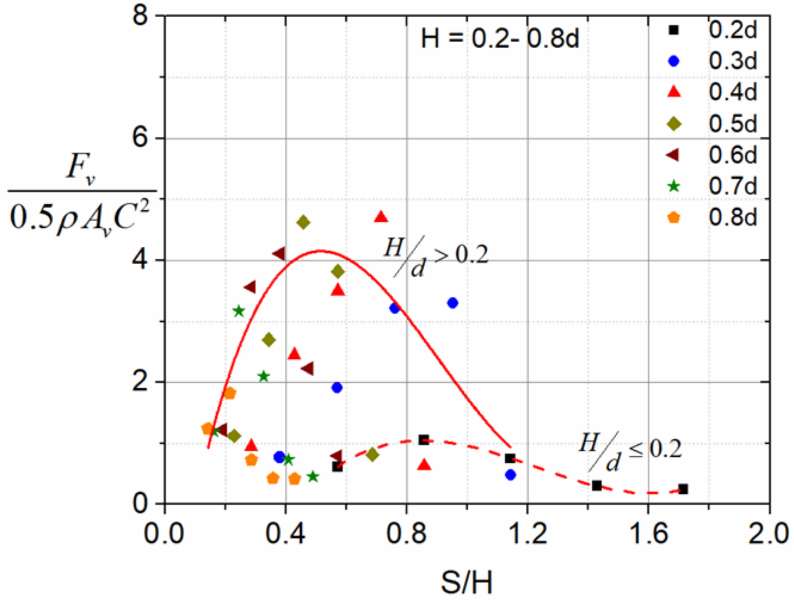
REEF3D – programming language C++

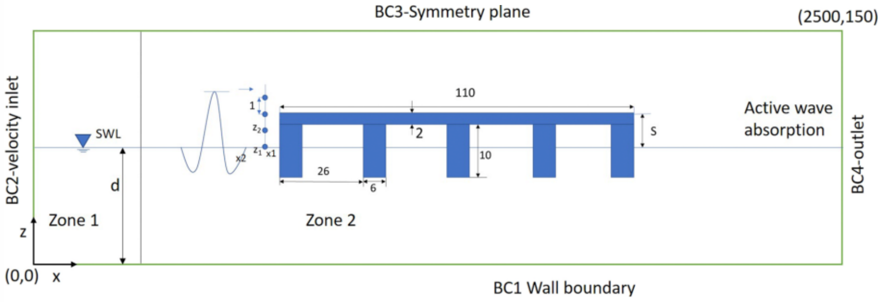
SOLITARY WAVE IMPACT ON COASTAL STRUCTURES

Variation of horizontal force coefficients for different H/d and S/H ratios.



Variation of vertical force coefficients for different H/d and S/H ratios.





According to coastal engineering manual

$$F_h = C_u A_z \gamma_w \left(\frac{w^2}{2g}\right)$$

$$F_v = C_u A_n \gamma_w \left(\frac{u^2}{2g}\right)$$

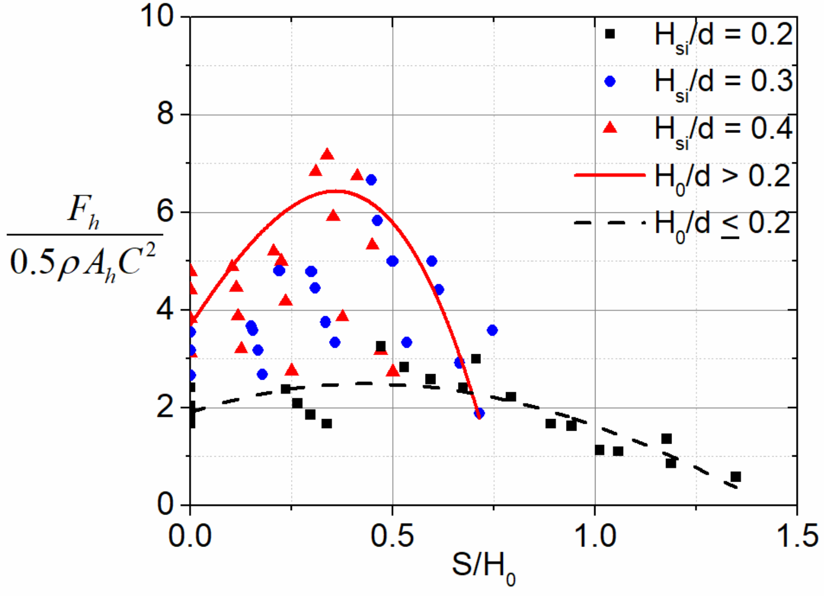
$$C_h = \begin{cases} 0.13\left(\frac{S}{H}\right)^3 - 8.8\left(\frac{S}{H}\right)^2 + 9.55\left(\frac{S}{H}\right) + 0.61, & \text{for} \quad H/d \le 0.2 \\ 1.25\left(\frac{S}{H}\right)^3 - 5.78\left(\frac{S}{H}\right)^2 + 7.73\left(\frac{S}{H}\right) - 1.985 & \text{for} \quad H/d > 0.2 \end{cases}$$

$$C_v = \begin{cases} 4\left(\frac{S}{H}\right)^3 - 15\left(\frac{S}{H}\right)^2 + 16.5\left(\frac{S}{H}\right) - 4.7 & \text{for} \quad H/d \le 0.2 \\ 15\left(\frac{S}{H}\right)^3 - 40.6\left(\frac{S}{H}\right)^2 + 30\left(\frac{S}{H}\right) - 2.6 & \text{for} \quad H/d > 0.2 \end{cases}$$

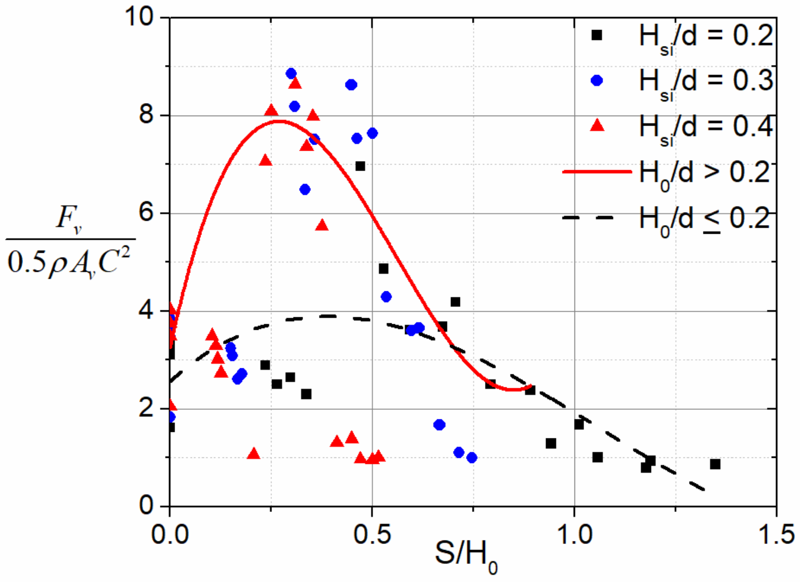
where, S is the airgap and H is the wave height.

Moideen, R., Behera, M.R., Kamath, A. and Bihs, H. (2019), "Effect of girder spacing and depth on solitary wave impact on coastal bridge deck for different airgaps", *Journal of Marine Science and Engineering*, vol. 7, issue 5, paper id: 140. https://doi.org/10.3390/jmse7050140

Variation of horizontal force coefficients for different H_{si}/d and S/H_0 ratios.



Variation of horizontal force coefficients for different H_{si}/d and S/H_0 ratios.



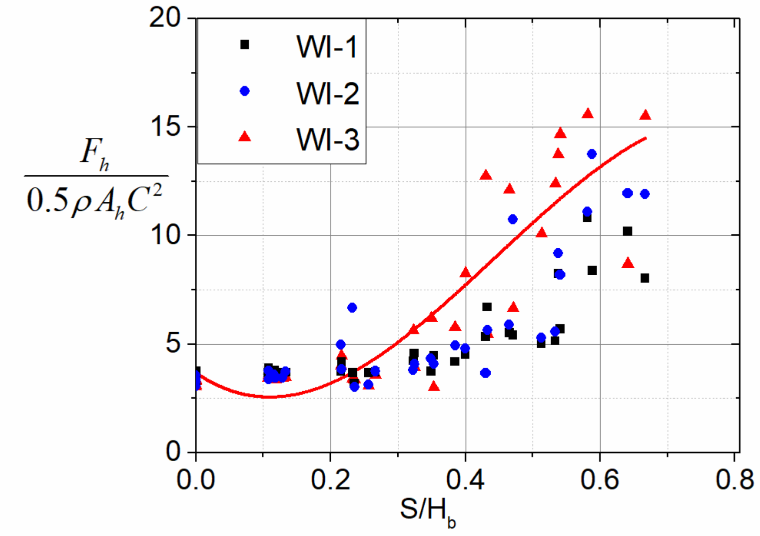
$$C_h = \begin{cases} -2.68\left(\frac{S}{H_0}\right)^2 + 2.42\left(\frac{S}{H_0}\right) + 1.9, & for \quad H_{si}/d \le 0.2 \\ -40.34\left(\frac{S}{H_0}\right)^3 + 24.12\left(\frac{S}{H_0}\right)^2 + 2.35\left(\frac{S}{H_0}\right) + 3.5801 & for \quad H_{si}/d > 0.2 \end{cases}$$

$$C_v = \begin{cases} -3.05\left(\frac{S}{H_0}\right)^2 + 2.26\left(\frac{S}{H_0}\right) + 2.7 & for \quad H_{si}/d \le 0.2 \\ 43\left(\frac{S}{H_0}\right)^3 - 78\left(\frac{S}{H_0}\right)^2 + 34\left(\frac{S}{H_0}\right) + 3.16 & for \quad H_{si}/d > 0.2 \end{cases}$$

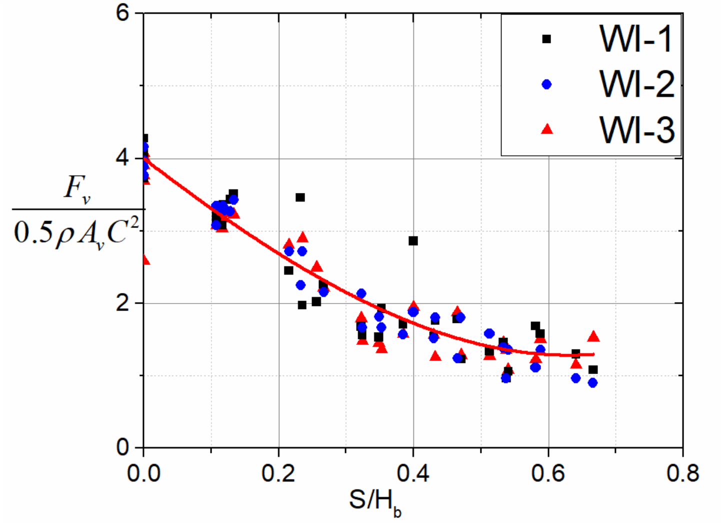
where, S is the airgap and H_0 is the maximum wave height.

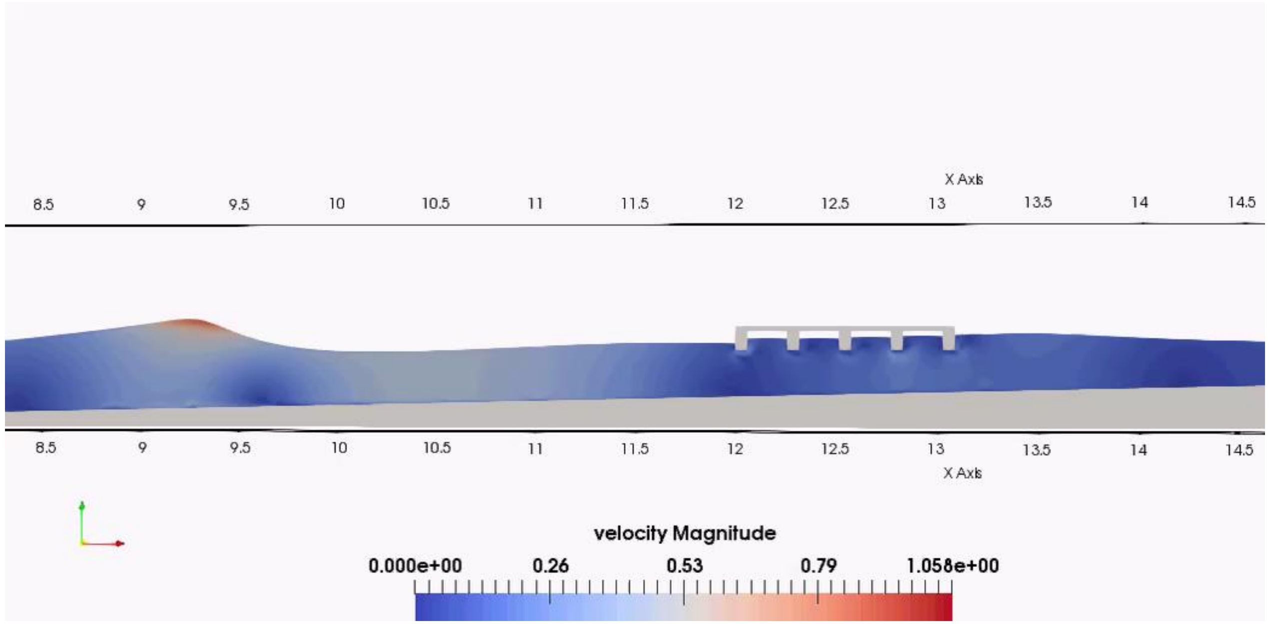
Moideen, R., Behera, M.R., Kamath, A. and Bihs, H. (2020), "Numerical simulation and analysis of phase focused breaking and non-breaking wave impact on fixed offshore platform deck", *Journal of Offshore Mechanics and Arctic Engineering*, vol. 142, issue 5, 051901, 1-8. https://doi.org/10.1115/1.4046285

Variation of horizontal force coefficients for different H/d and S/H_b ratios.



Variation of horizontal force coefficients for different H/d and S/H_b ratios.





$$C_h = -85\left(\frac{S}{H_b}\right)^3 + 113.6\left(\frac{S}{H_b}\right)^2 - 21.72\left(\frac{S}{H_b}\right) + 3.68$$

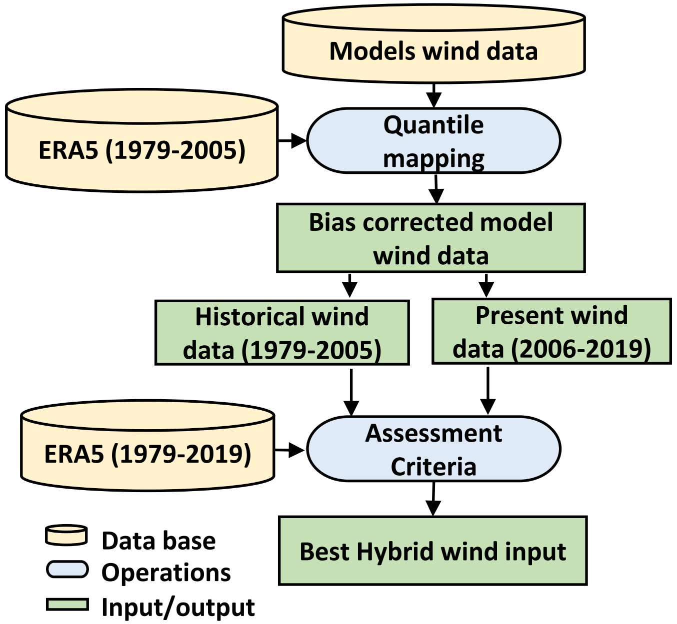
$$C_v = 17.7\left(\frac{S}{H_b}\right)^3 - 11.36\left(\frac{S}{H_b}\right)^2 - 3.5\left(\frac{S}{H_b}\right) + 3.68$$

where, S is the airgap and H_b is the breaking wave height.

Moideen, R. and Behera, M.R. (2021), **"Numerical Investigation of Extreme Wave Impact on Coastal Bridge Deck using Focused Waves"**, ***Ocean Engineering***, **vol 234, paper id: 109227, pp. 1-21.** https://doi.org/10.1016/j.oceaneng.2021.109227.

Evaluation of climate models' ability in simulating the near-surface wind speed (WS) over Indian Ocean

Developed the relative score technique to quantitatively summarise the climate models' performance



Flow chart for evaluating the skill of climate models (CMIP GCMs and CORDEX RCMs)

Summary of assessment criteria statistic

Climate variable scale	Method/Statistic	Assessment Criteria Statistic (ACS)	W
Daily mean	Perkins Skill Score (PSS)	B_{PSS} = 1 – PSS	0.5
Annual cycle	Statistical significance of positive 'r'	Percentage of statistically insignificant positive correlation coefficient (P_{ir}) (p-value of 0.001)	1
Annual mean	Statistical significance of bias	Percentage of statistically significant bias (P_b) (p-value of 0.001)	0
Seasonal mean			1
Annual mean trend	Mann-Kendall (MK) test Theil-Sen slope	Mean Absolute Bias (MAB)	1
Seasonal mean trend			
Spatio-temporal variability	Empirical Orthogonal Function (EOF) analysis 1. EOF1 variance 2. EOF1 spatial and PC1 magnitude 3. PC1 pattern	Empirical Orthogonal Function (EOF) analysis 1. Absolute Bias (AB) 2. MAB 3. 1-r	1

Statistical techniques will quantitatively summarize the performance of the climate model relative to the reference dataset

$$\text{Total Relative Score }(\mathrm{TRS_i}) = \sum_{J=1}^{n} \mathrm{RS_{ij}W_j}$$

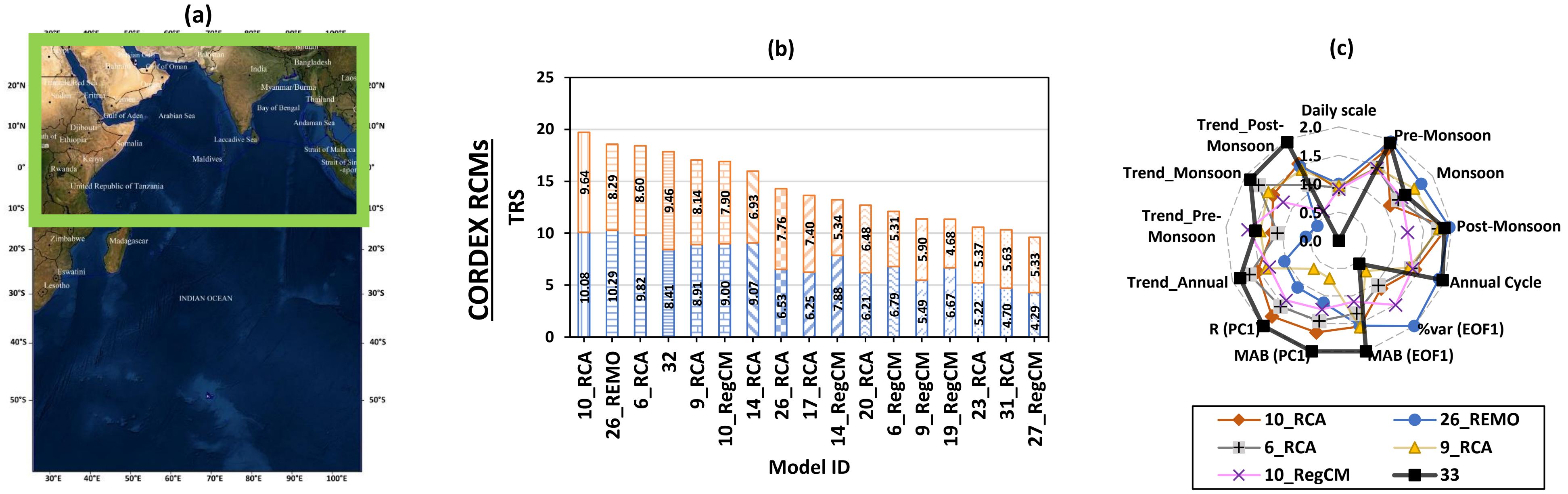
$$\text{Relative Score }(\mathrm{RS_{ij}}) = \frac{\mathrm{ACS_{j,max}} - \mathrm{ACS_{ij}}}{\mathrm{ACS_{j,max}} - \mathrm{ACS_{j,min}}}$$

ACS_{ij} is j^{th} assessment criteria statistic between i^{th} model and ERA5

Summarize the comparability of a climate model relative to the best and poor performing climate model

Evaluation of climate models' ability in simulating the near-surface wind speed (WS) over Indian Ocean

Assessed the performance of 16 CORDEX RCMs in representing historical and present wind climate over South Asian domain

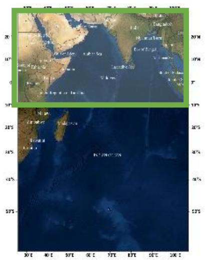


Summary of climate models skill in simulating WS over SA domain

- MME-5_CORDEX (6_RCA, 9_RCA, 10_RCA, 10_RegCM4, 26_REMO) is identified as best performing model over ocean in both considered time slices.
- Developed the score based approach to assess the competence of climate models in simulating the near-surface wind speed.
- Sensitivity analysis shows the rank assigned to the particular model when all the assessment criteria are considered as reliable and robust

Evaluation of climate models' ability in simulating the near-surface wind speed (WS) over Indian Ocean

Do CORDEX RCMs outperform CMIP5 GCMs in simulating WS climate over the IO region of South Asian domain?



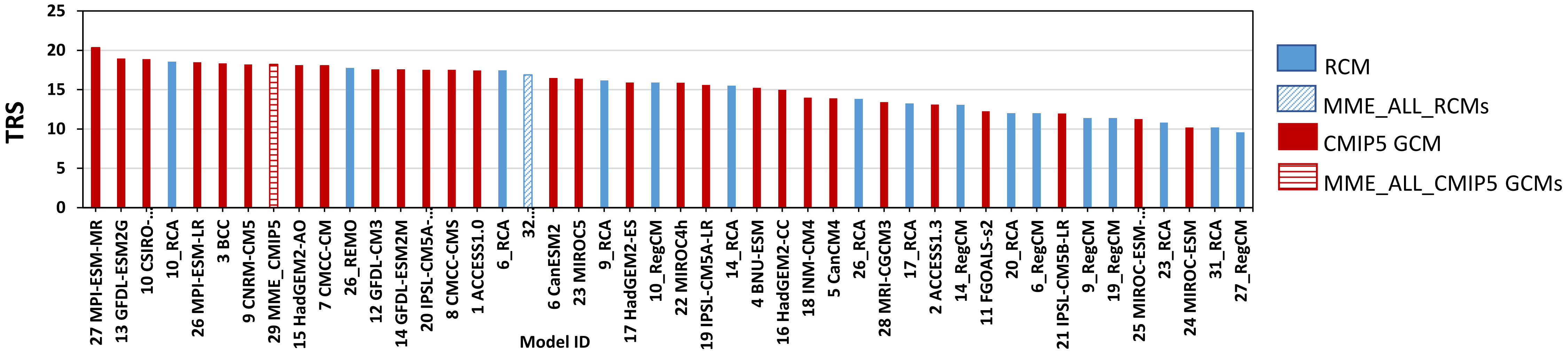


Fig. 8 summary of GCMs and RCMs skill in simulating the near surface wind speed over South Asian domain, TRS=Total relative score

- All the parent GCMs show higher skill compared to all RCMs, expect for 6_RCA and selection of RCM based on parent GCM performance is not recommended.
- It is observed from inter-comparison of climate models that the climate with high (low) atmospheric resolution does not necessarily to exhibit the best (worst) performance, whilst the dynamic components in the model configuration plays the major role, especially the atmosphere component relative to other dynamical components.
- Establishing combined hybrid wind input (RCM-GCM) is not required, since the GCMs outperforms RCMs.

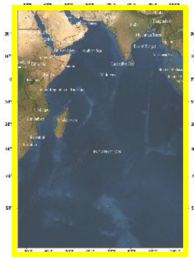
Publications:

✓ **Lakku, N.K.G.; Behera, M.R.** **Skill and Intercomparison of Global Climate Models in Simulating Wind Speed, and Future Changes in Wind Speed over South Asian Domain.** ***Atmosphere*, 2022, *13*, 864. https://doi.org/10.3390/atmos13060864**

✓ **Lakku NKG, Behera MR.** **Skill and Inter-Model Comparison of Regional and Global Climate Models in Simulating Wind Speed over South Asian Domain.** ***Climate*, *2022*; 10(6):85. https://doi.org/10.3390/cli10060085**

Evaluation of climate models' ability in simulating the near-surface wind speed (WS) over Indian Ocean

Do CMIP6 GCMs outperform CMIP5 GCMs in simulating WS climate over the Indian Ocean?



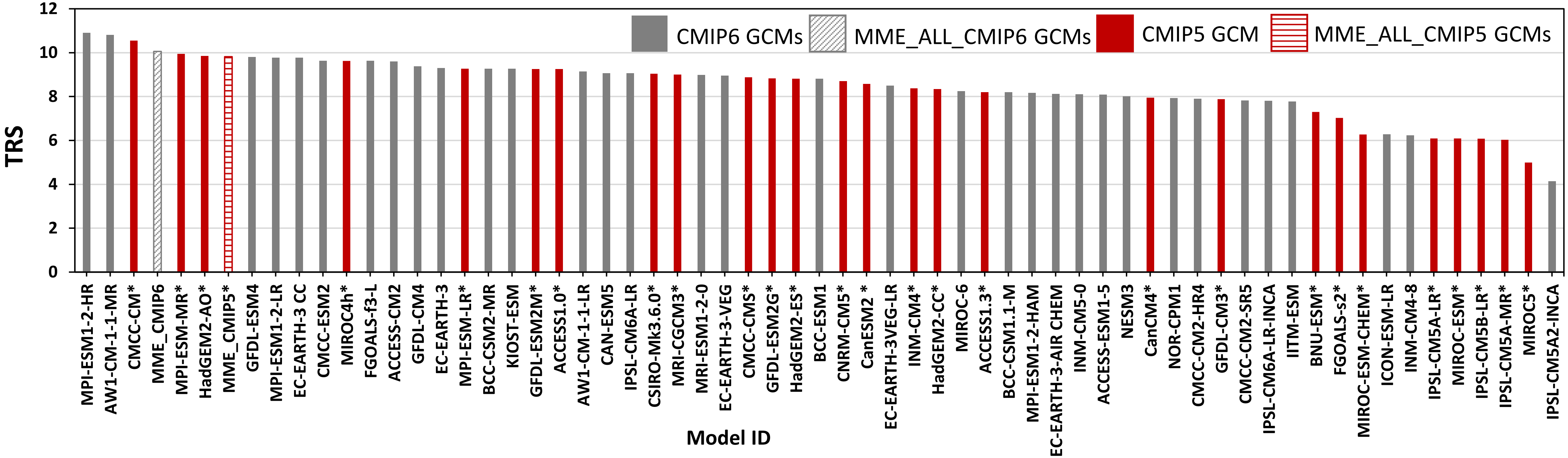
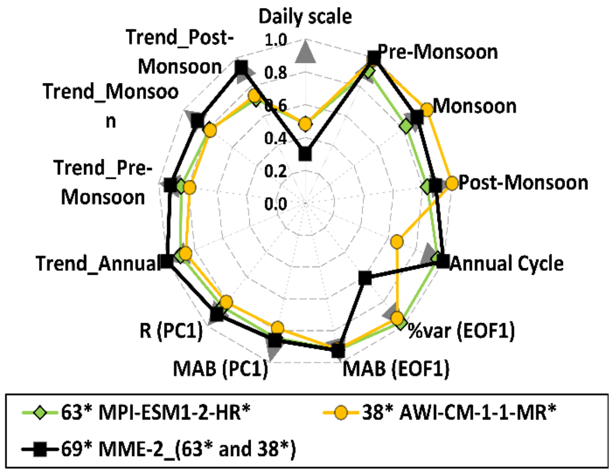


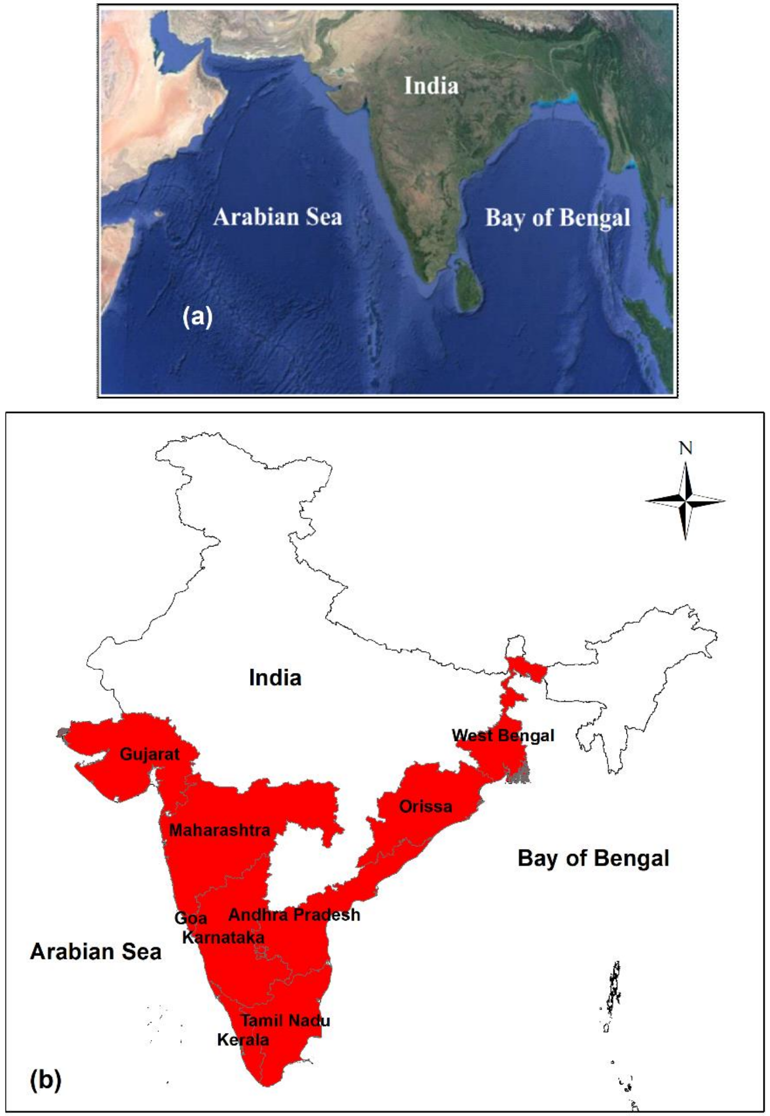
Fig. 9 summary of CMIP6 GCMs and CMIP5 GCMs' skill in simulating the near surface wind speed over Indian Ocean, TRS=Total relative score

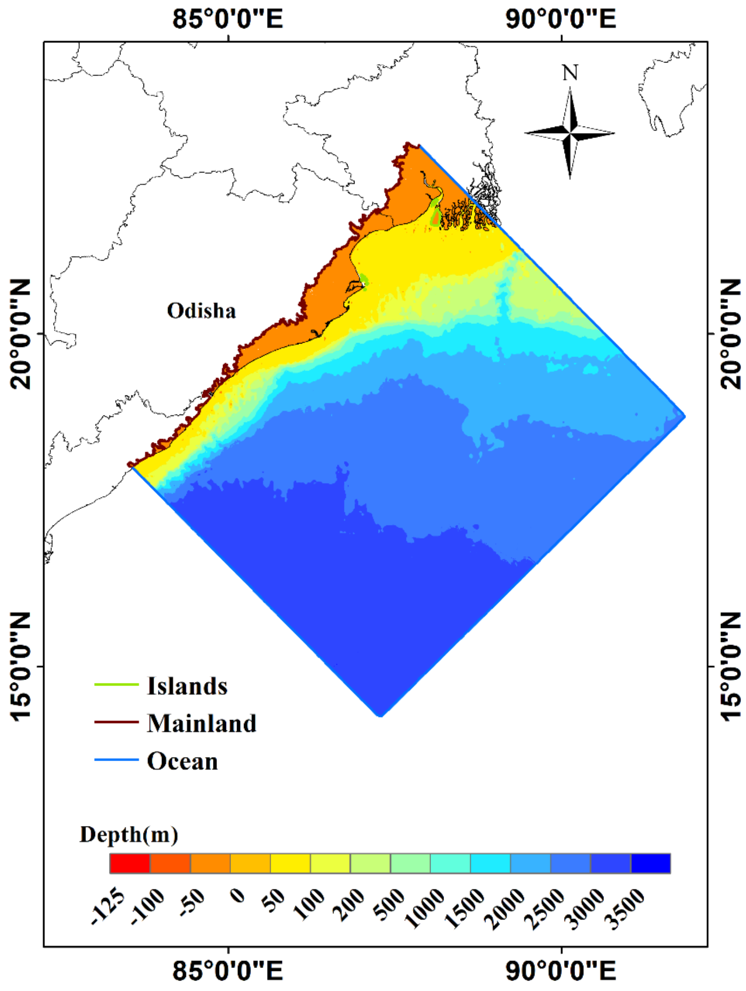


Relative Score of constructed best-performing model

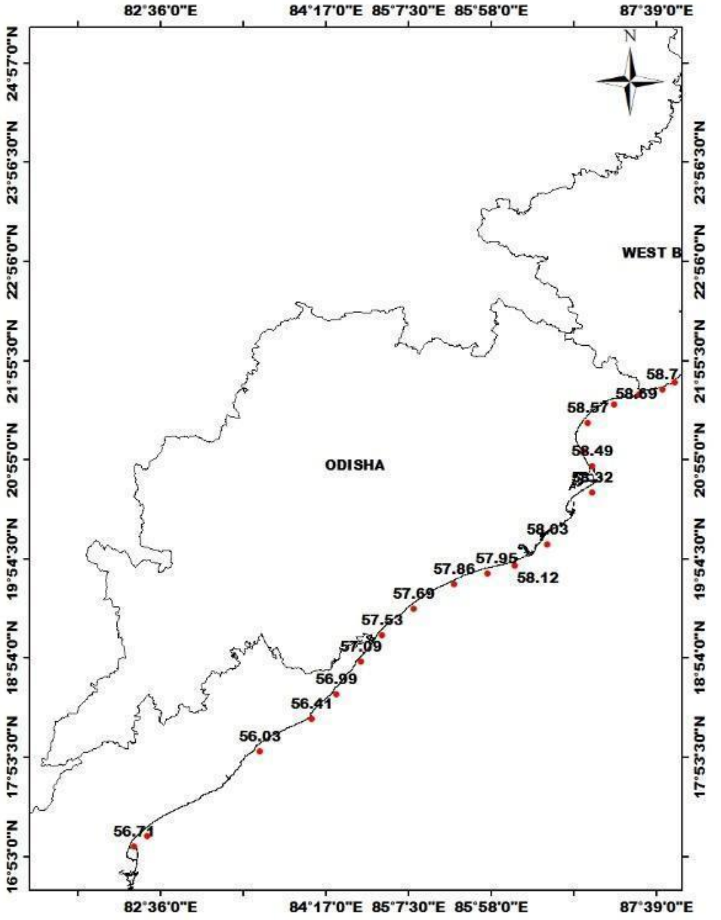
- Most of the CMIP6 GCMs show significant improvement than CMIP5 GCMs.
- The top-performing climate model is MPI-ESM-1-2-HR CMIP6 GCM, however the poor-performing climate model is also from CMIP6 GCM
- The multi-model mean ensemble of MPI-ESM1-2-HR and AWI-CM-1-1-MR will be used as driving force in numerical spectral wave model to simulate the future waves for the different Shared Socioeconomic Pathways (SSPs) over Indian Ocean

COASTAL ZONE VULNERABILITY DUE TO SEA LEVEL RISE



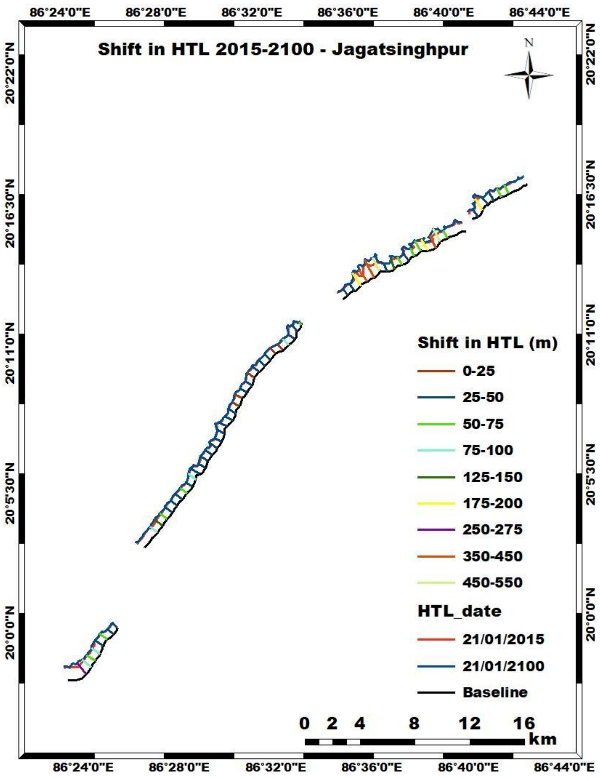


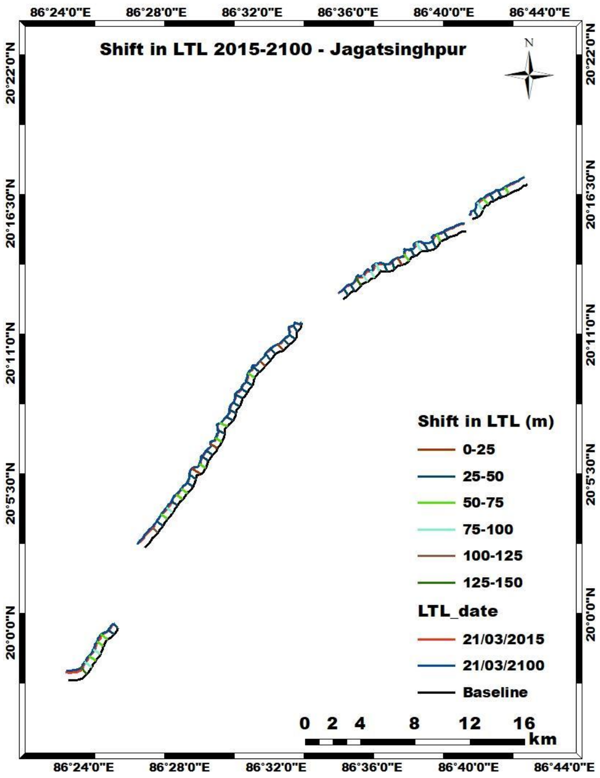
Topography and Bathymetry

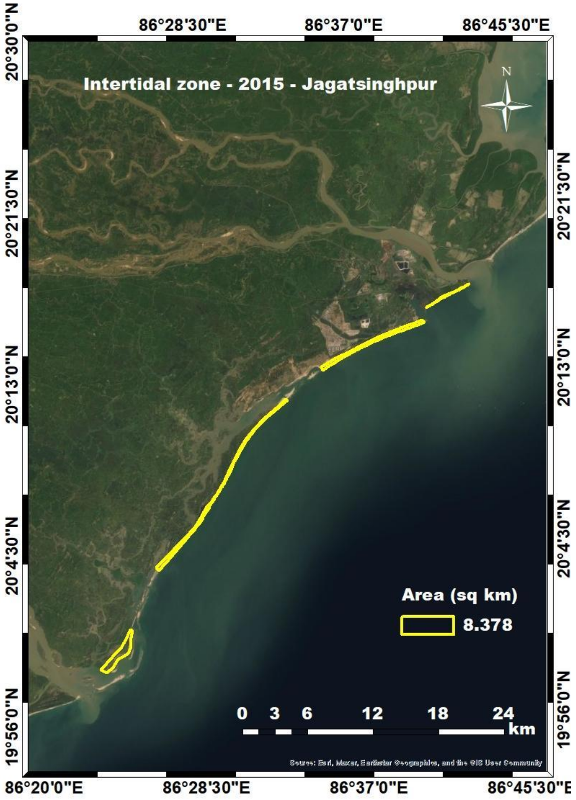


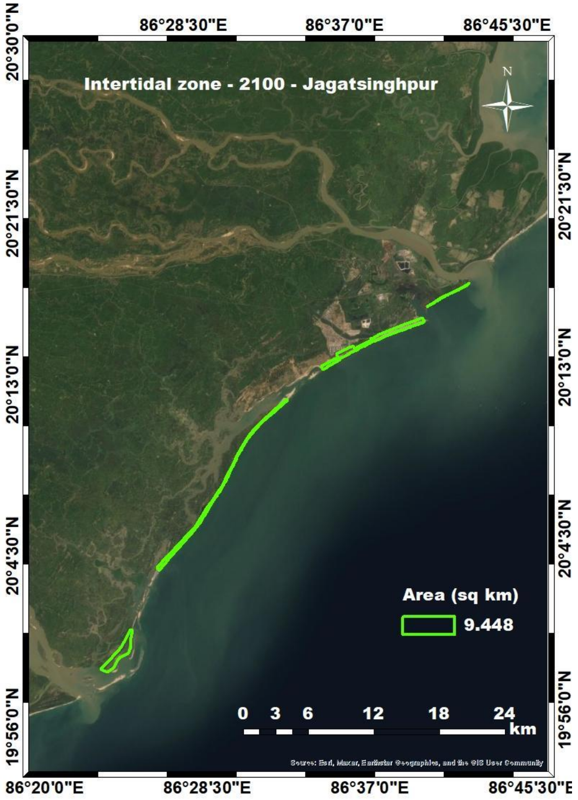
Average SLR (in cm) expected at the year 2100 in the near shore region of Odisha

COASTAL ZONE VULNERABILITY DUE TO SEA LEVEL RISE









Research Group

Coastal Vulnerability due to Climate Change

https://www.youtube.com/watch?v=P7z9QEbH8zc

THANK

YOU