Stochastic-Deterministic Assessment of the current and future storm surge flooding hazard in the Bengal delta

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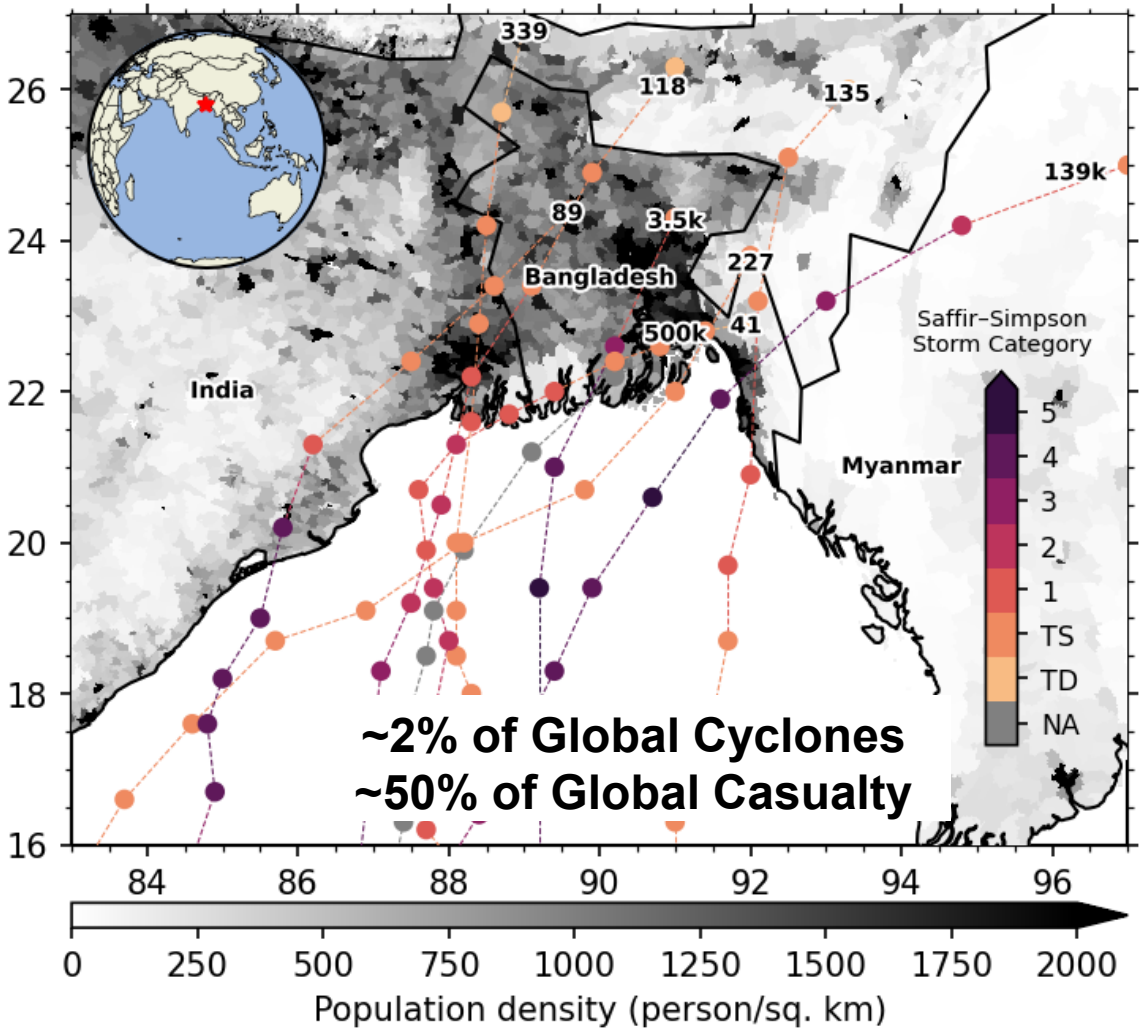
Cyclonic flooding hazard

Landfalling cyclones over Bengal delta in the past decades



Ganges-Brahmaputra (Bengal) delta is –

- densely populated (150M+ habitants)
- highly vulnerable to flooding from -
  - Pluvial – surface water flood
  - Fluvial – riverine flood
  - Coastal – surge flood

Compound flooding!

More than **half a million casualty** over last 50 years – deadliest place for coastal flooding hazard.

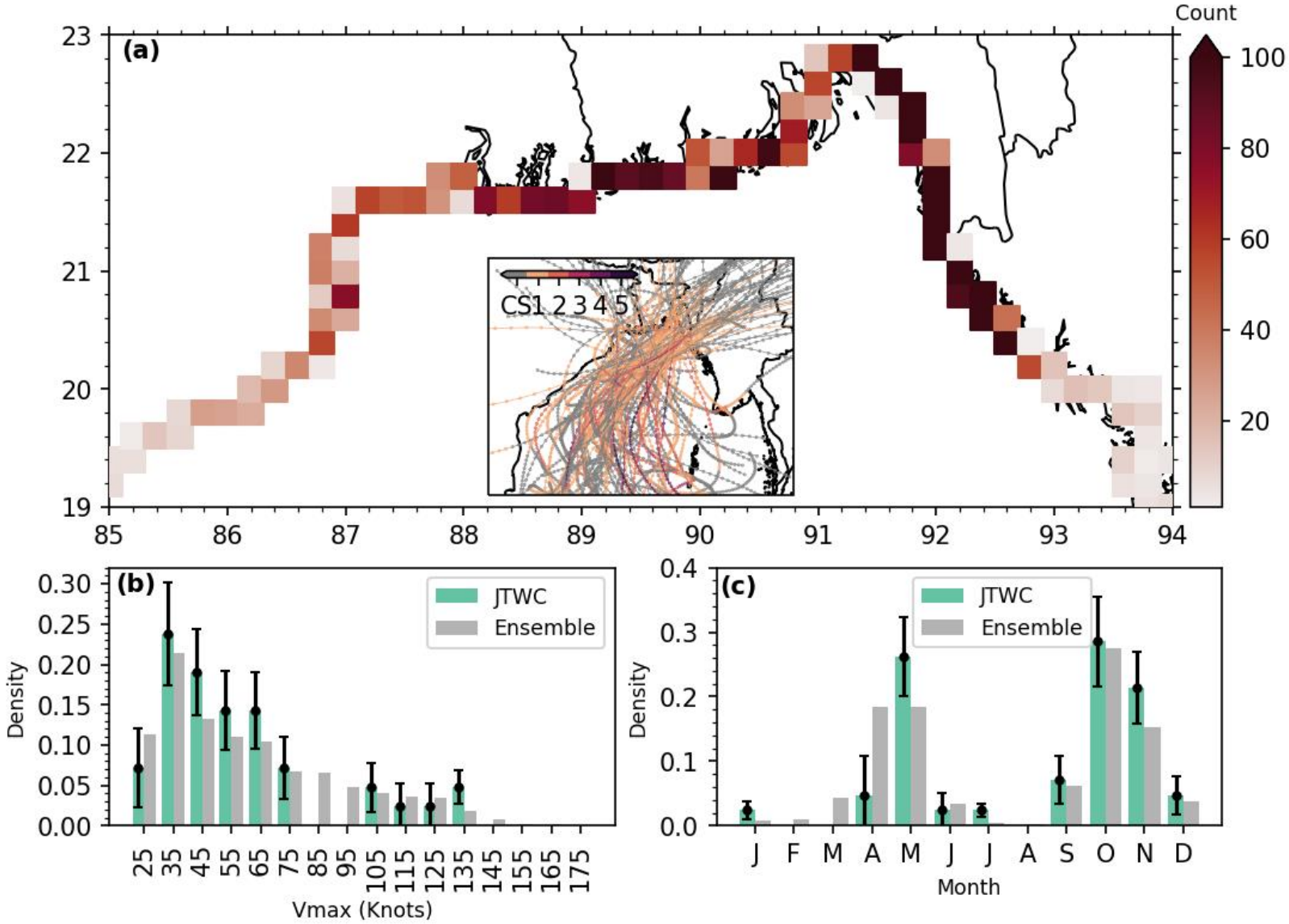
What is the inundation hazard from storm surges along the shoreline of the Bengal delta under current climate? Future climate?

- **Limited historical records of past cyclones (no wind-pressure record before ‘90s)**
- **Limited availability of observed water level**

Stochastic-Deterministic Cyclone Modeling Approach

(Emmanuel et al. 2006, Khan et al. 2022)

Cf. talk of Christian Appendini this morning



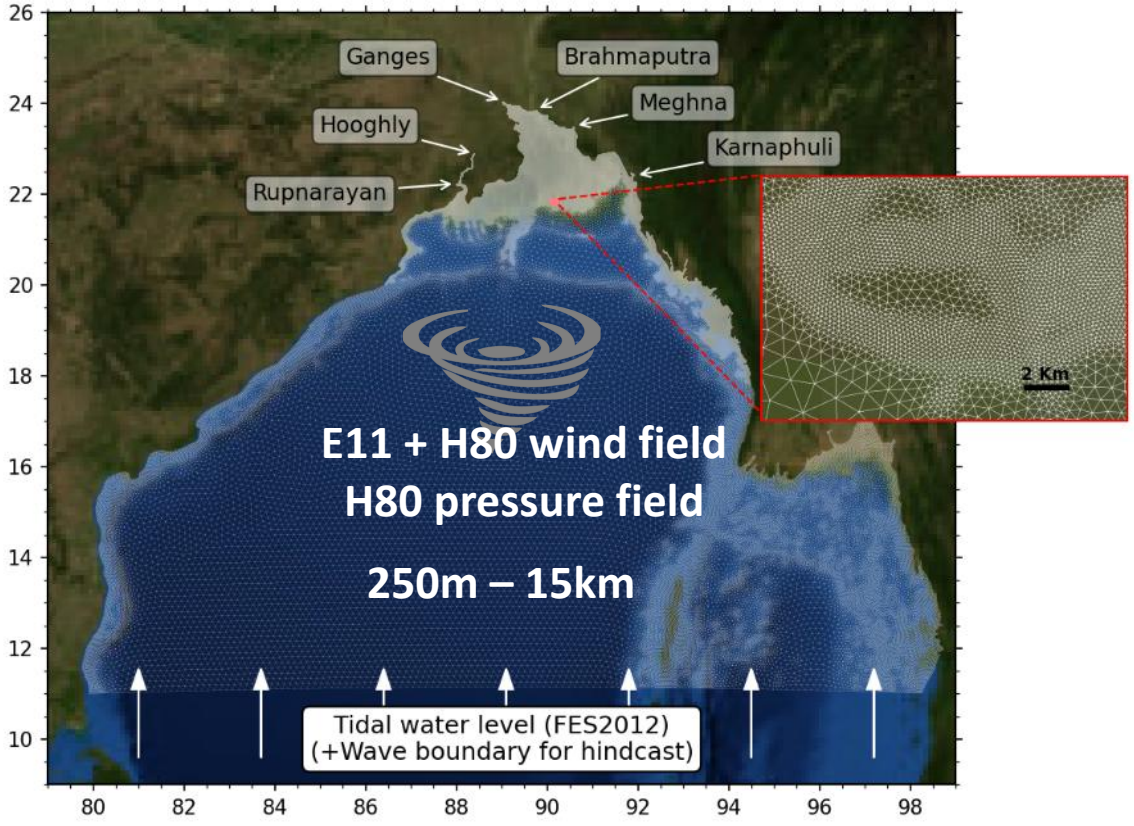
3600 Storm events

~5000 years of simulated cyclone activity over Bengal delta under **current climate**.

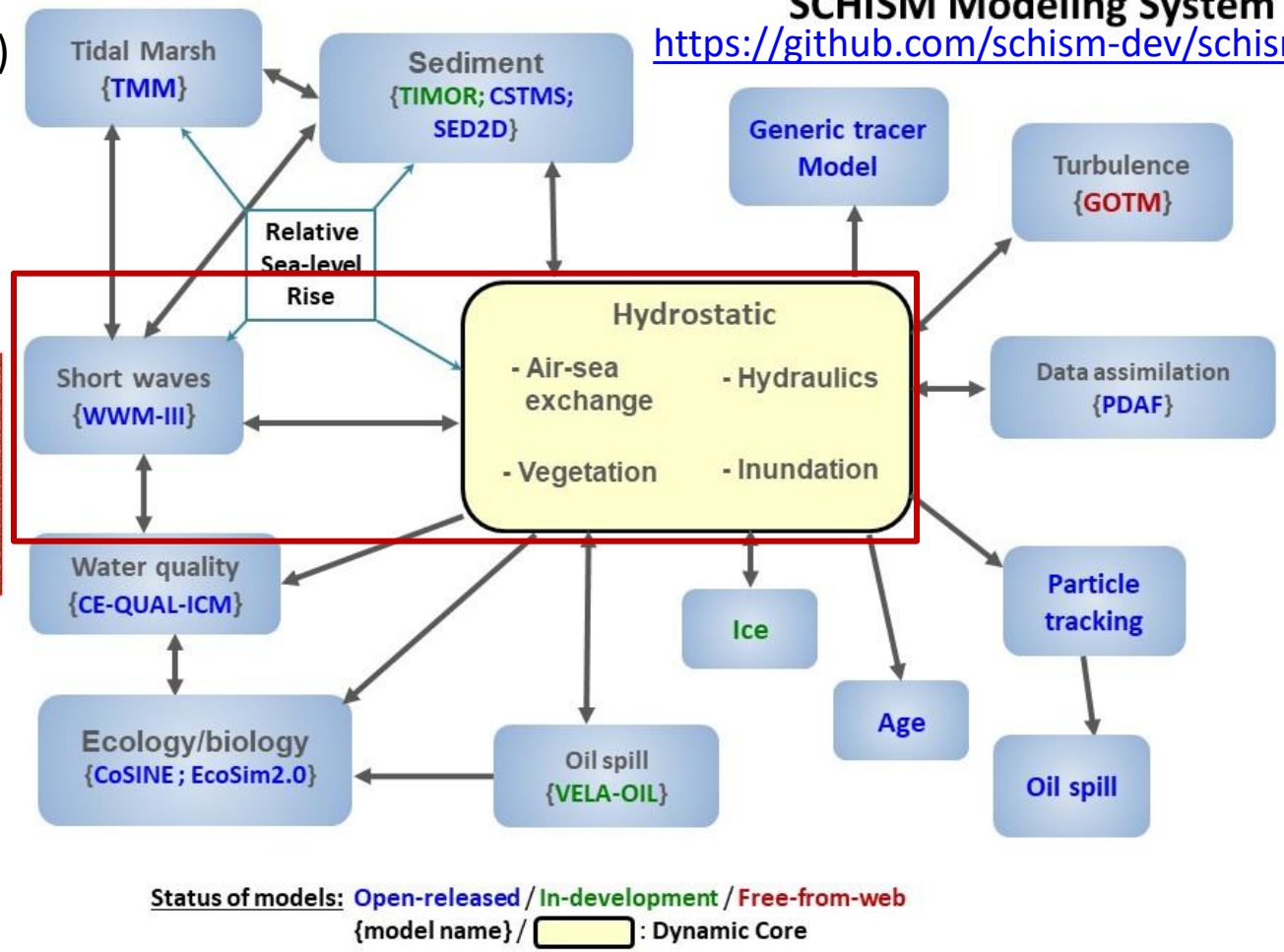
Storm Surge Modelling

Coupled **Tide-Surge-Wave** model - **SCHISM-WWM**
+ Revised short wave breaking criteria (Pezerat et al. 2021)

600k nodes, **1.1M** triangular elements



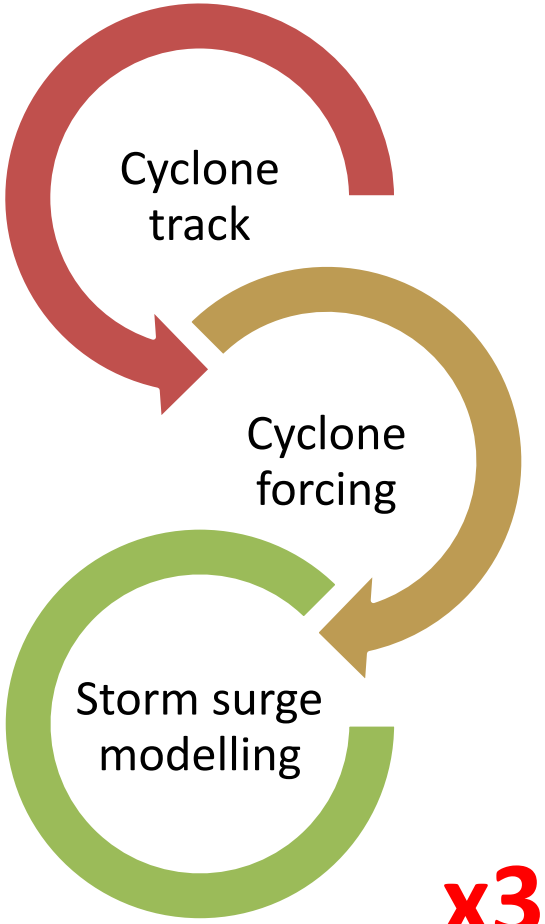
SCHISM Modeling System
https://github.com/schism-dev/schism



Validated extensively for -

- Tide (Khan et al. 2019, 2020), 5-10cm complex error.
- Cyclone Sidr (Krien et al. 2017) and cyclone Amphan (Khan et al. 2021) with <= 5% error in peak water level

Calculating the storm surge ensemble



1. Cyclone track and intensity is extracted.

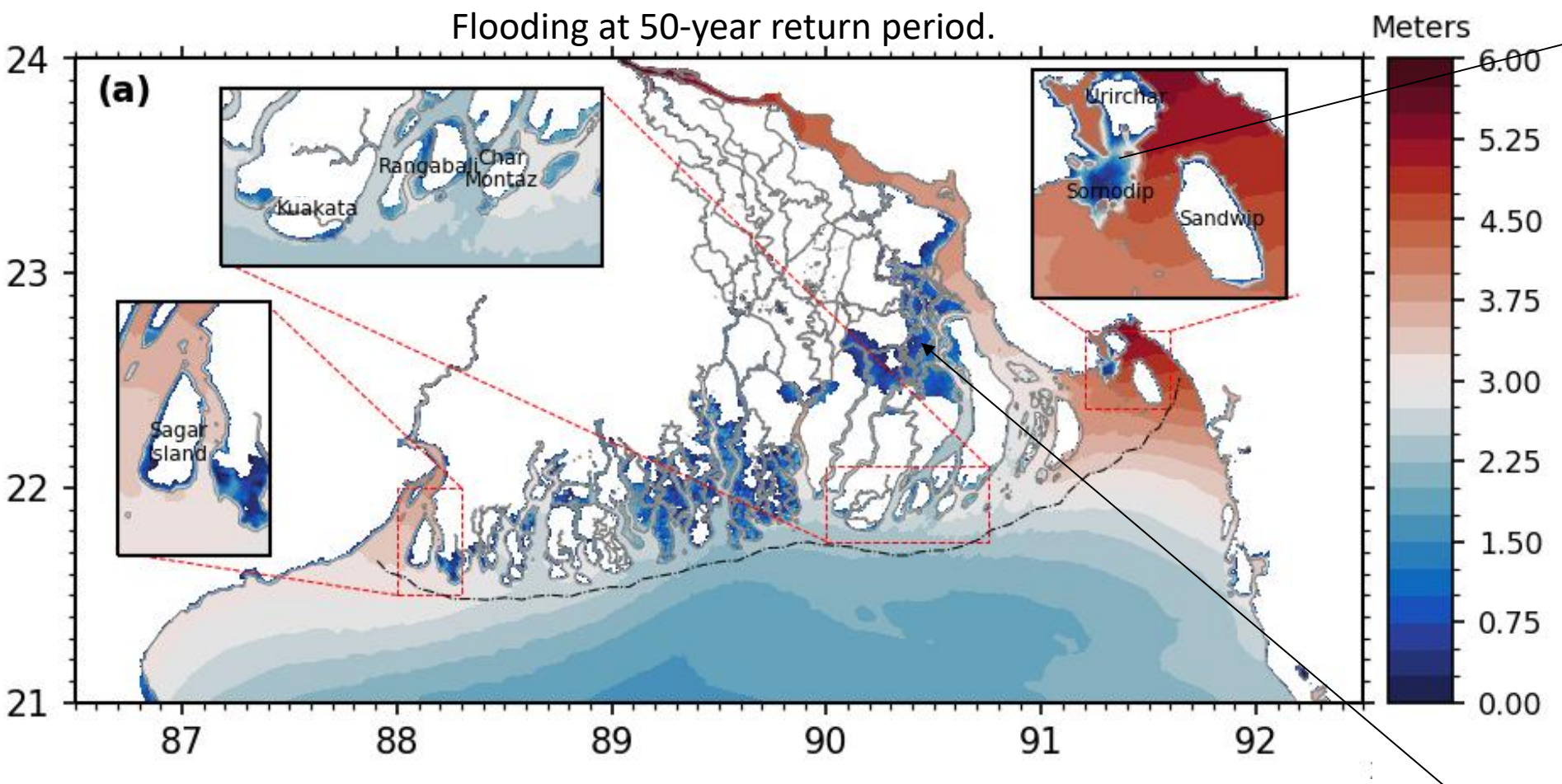
2. Wind and pressure fields are generated (Krien et al. 2018, Khan et al. 2021**)**

3. Water level and inundation computation with SCHISM-WWM.

x3600 **= Storm surge ensemble**

Now we can do large value empirical rank-based statistics…

Mapping of the storm surge flooding hazard

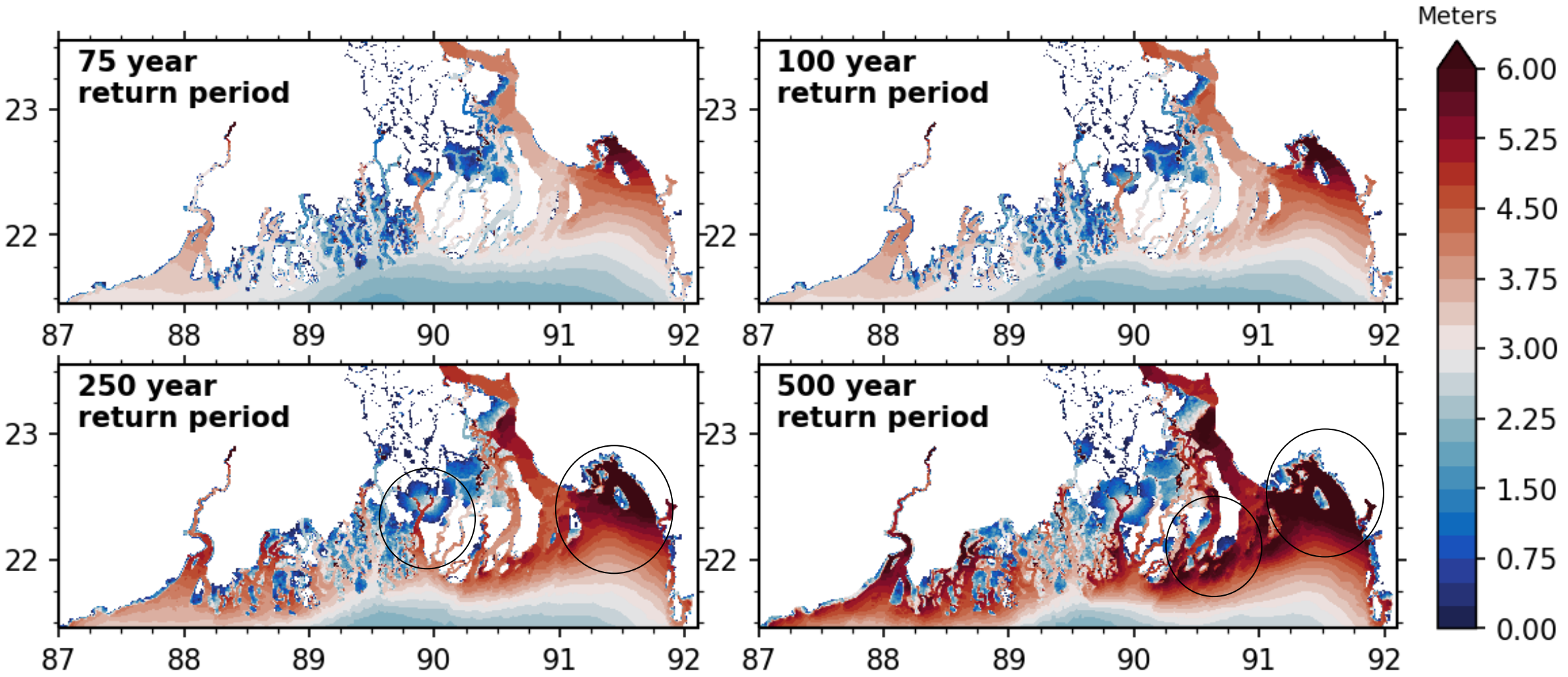


Expected to be inundated by 1.5m at-least once in 50-year

Flooded during cyclone Amphan (Khan et al. 2021)

- The expected flooding at 50-year return period is strongly constrained by the embankments.
- Unprotected mangroves as well as inland regions get flooded.

When the embankments start to be overflowed?



(Khan et al., 2022)

Sea Level Projections vs. Milestones

IPCC AR6 Figure 9.27 | Projected global mean sea level rise under different Shared Socio-economic Pathway (SSP) scenarios.

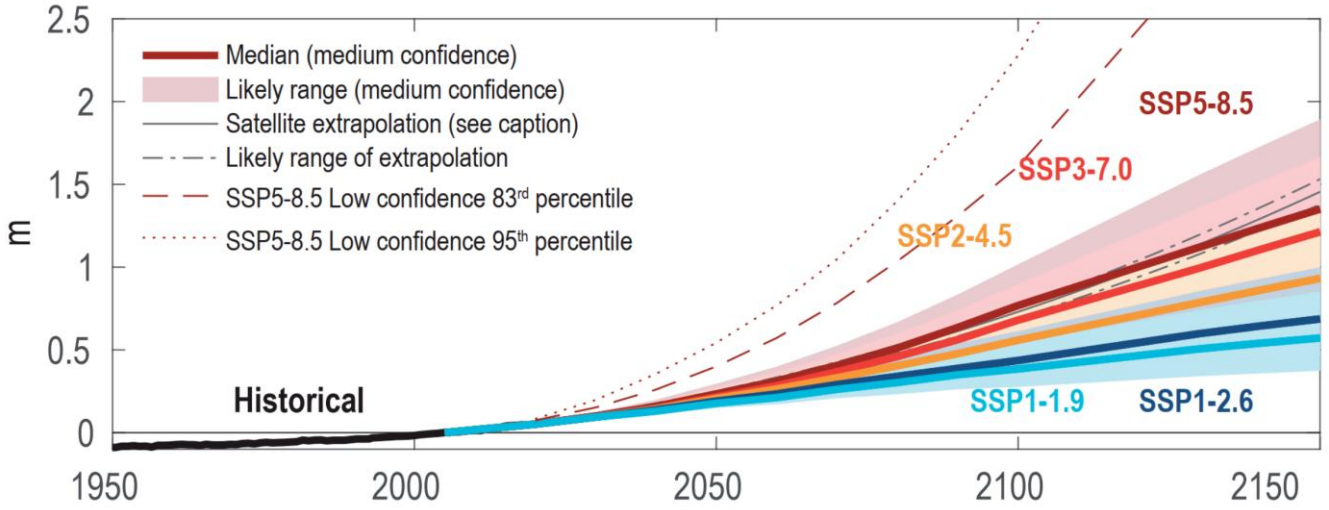
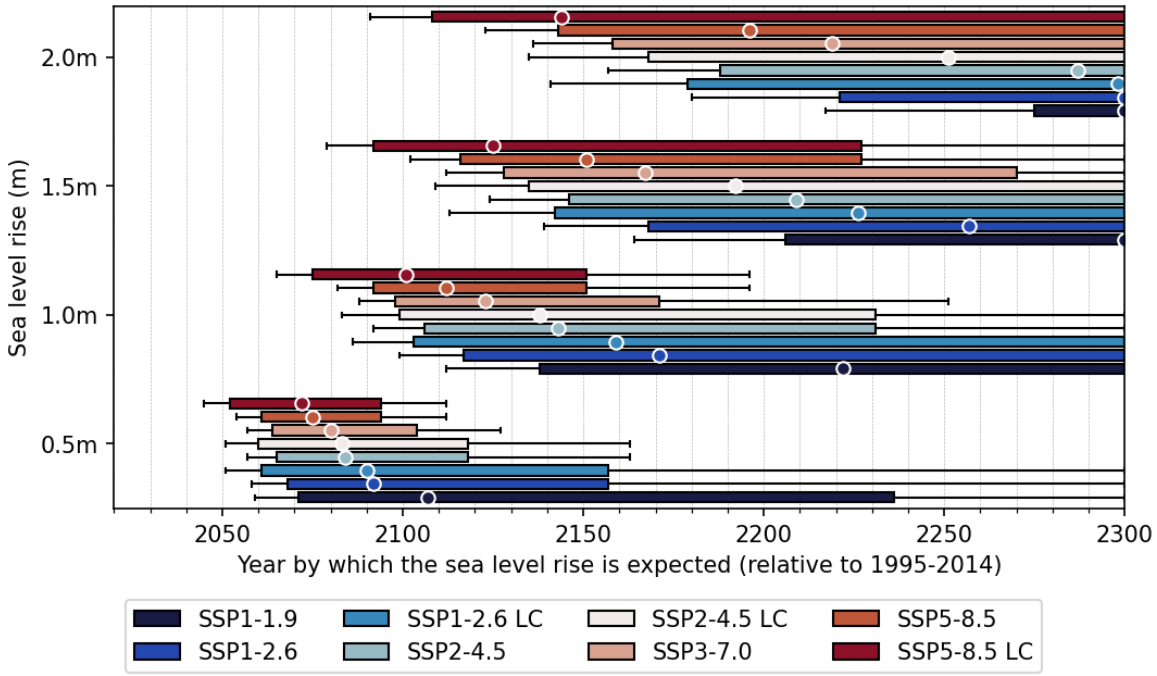


Fig. Projected Sea level rise milestones at **Hiron Point**

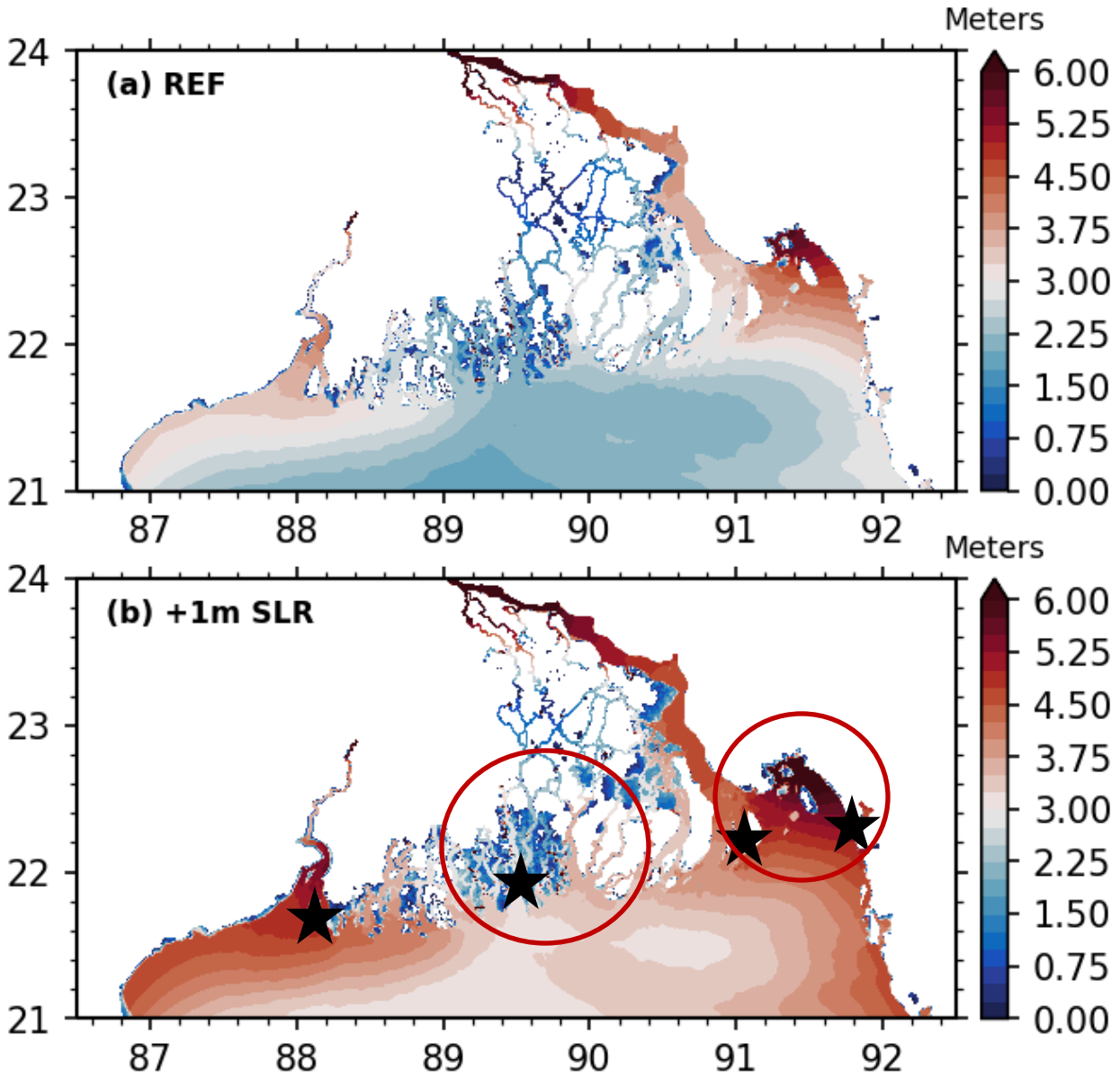


Approach 1: Gradually changing sea level
Each storm is attached to a sampled sea level in the future period (e.g., Qui et al. 2025)

Approach 2: Sea level rise milestones
Each storm is modelled with the same sea level rise conditions (4 milestones)

3600 x 4 = 14400 storm simulations

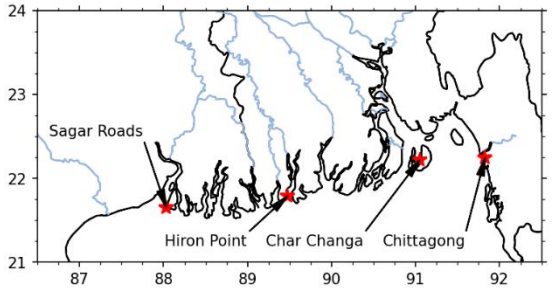
Sensitivity to Sea level Rise



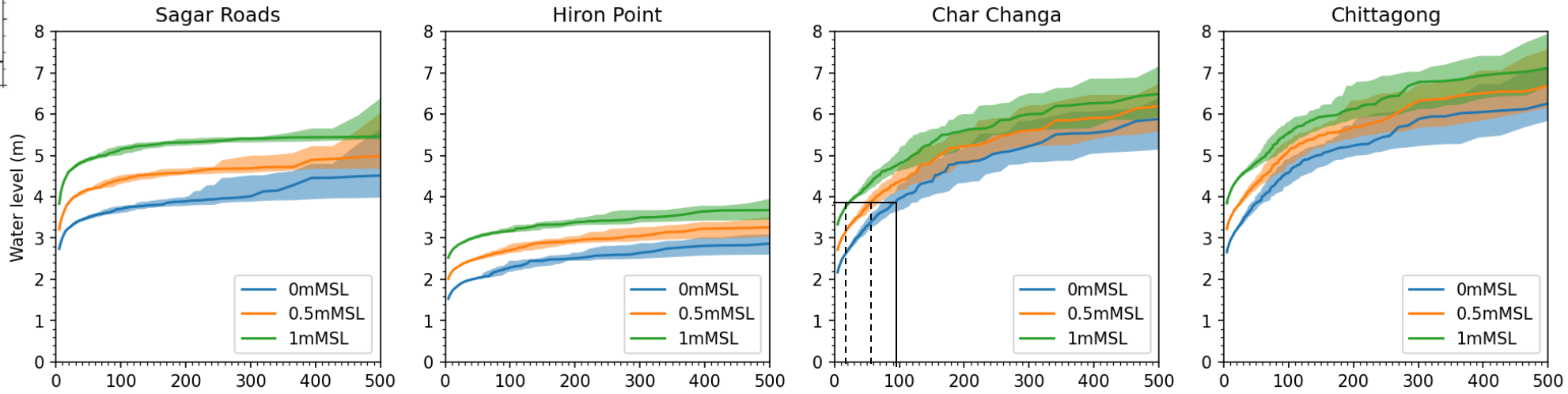
About half of the embankments starts to overflow in different places

★ Tide gauge locations

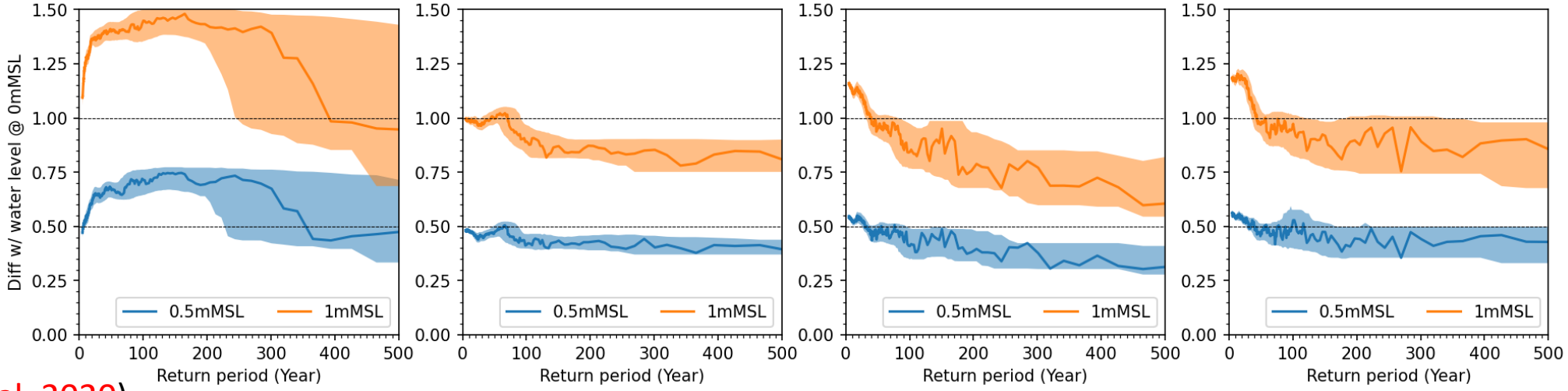
Sensitivity to Sea level Rise



Extreme Water level



Changes from 0m MSL



Two potential factors –

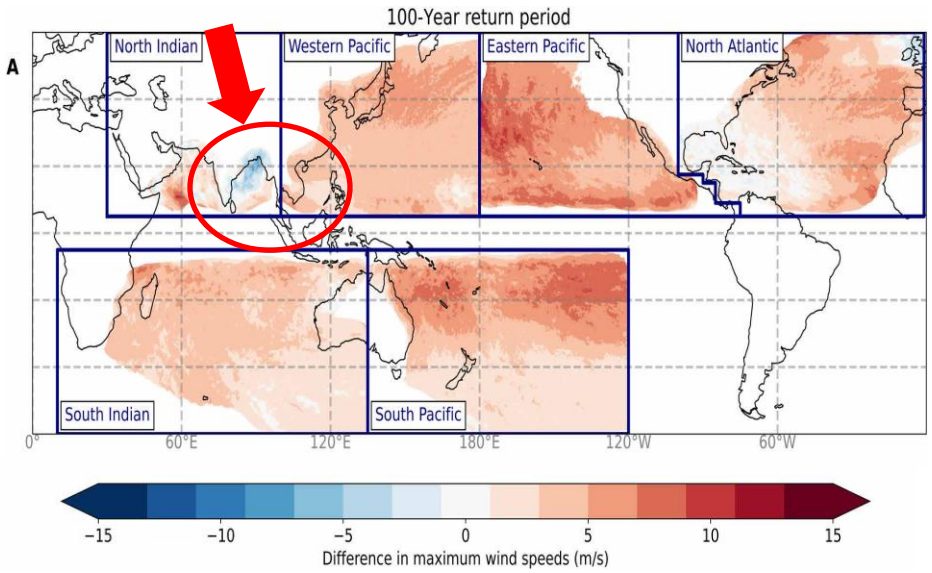
1. Tidal change (Khan et al. 2020)
2. Inland flooding (Khan et al. 2021)

General agreement that ESL changes are largely driven by MSL change (Knutson et al. 2020)

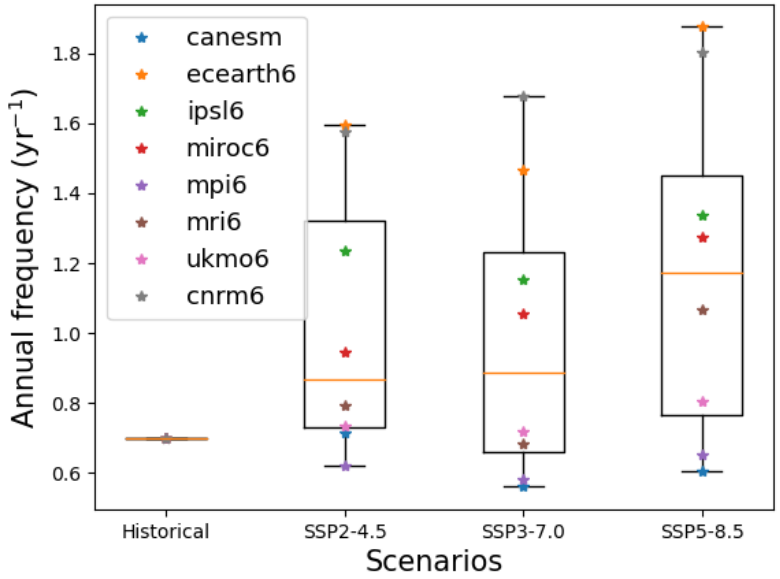
Changes in Storm Frequency and Intensity ?

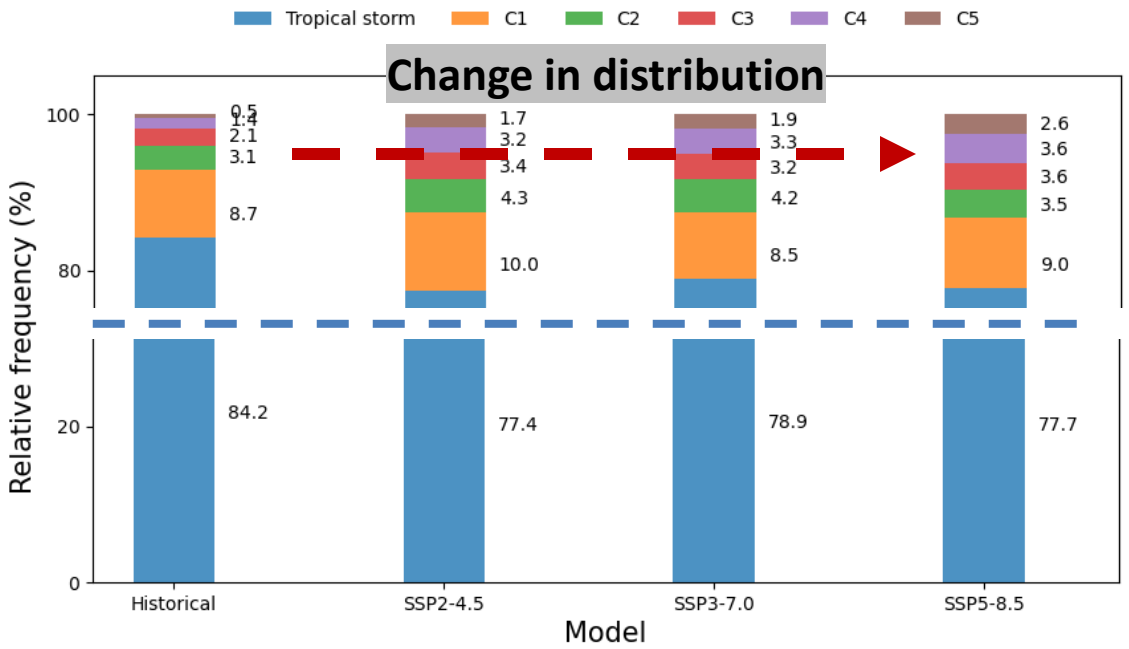
[An overall assessment is in Knutson et al. 2021]

Bloemendaal et al. 2022 (STORM)



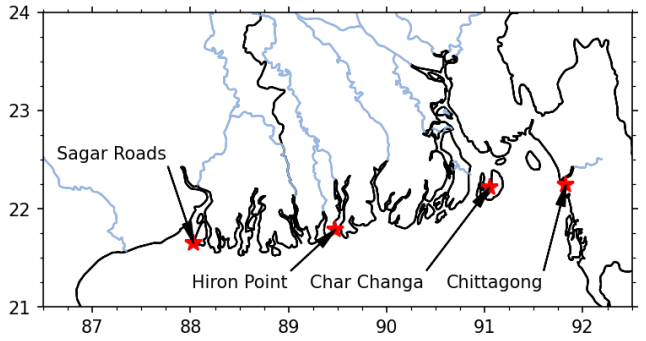
Emanuel (2021) – Statistical Deterministic Approach
future climate (2081-2100) – past climate (1981–2000)
8 CMIP6 Models

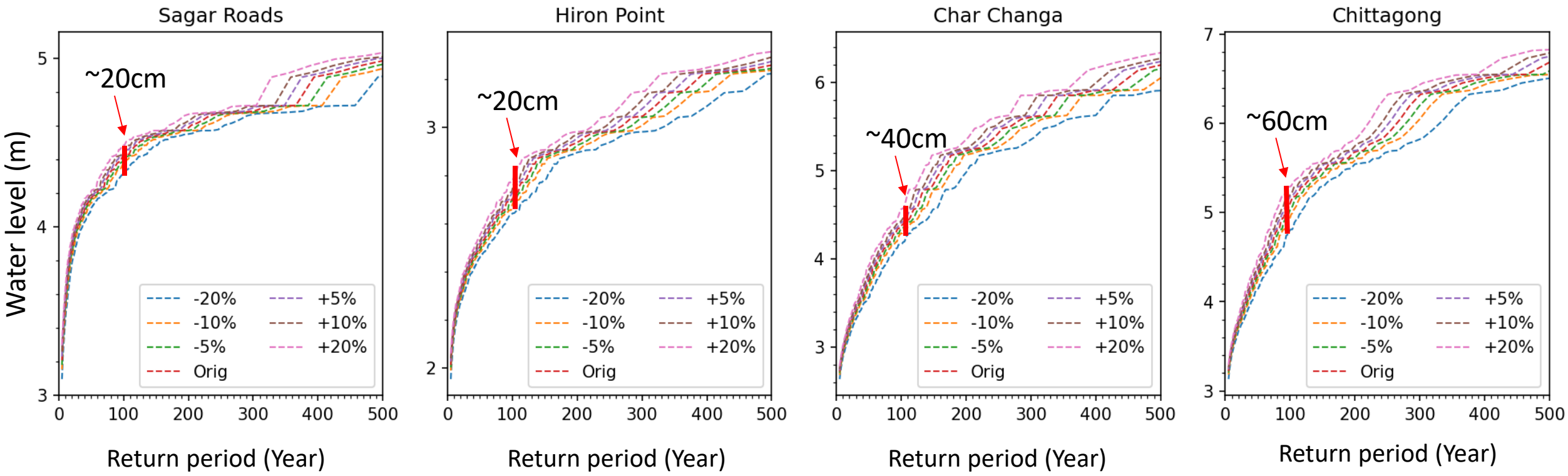


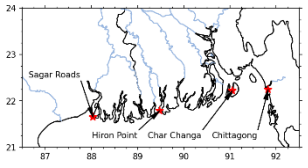


- Projection between models and/or approaches varies significantly with contradictory results
- Consequence – higher uncertainty range.

Sensitivity to Change in Frequency



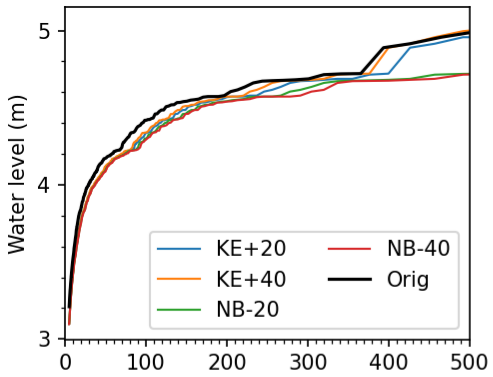
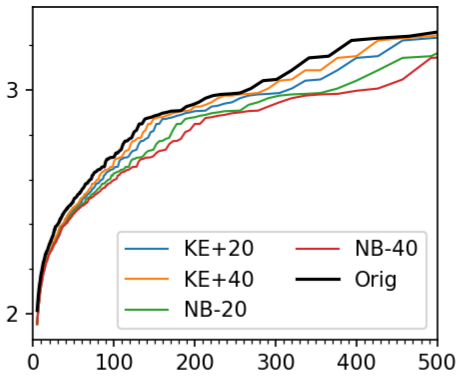
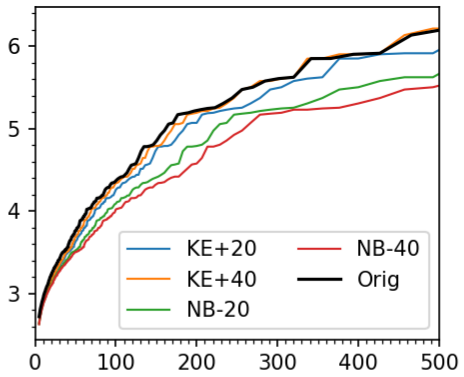
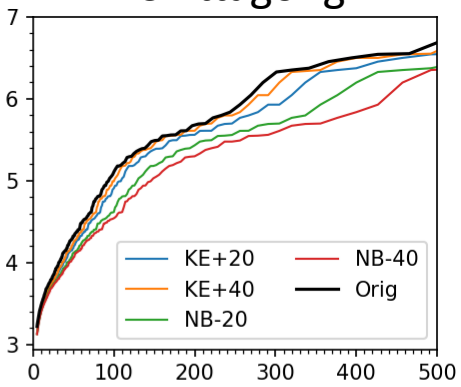
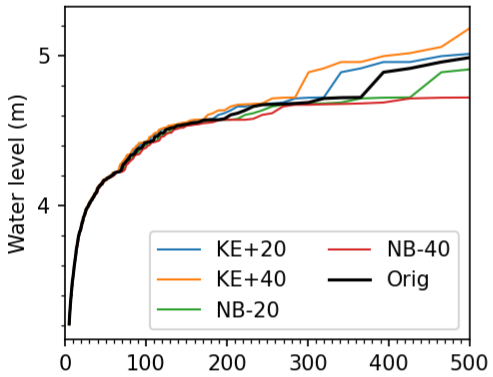
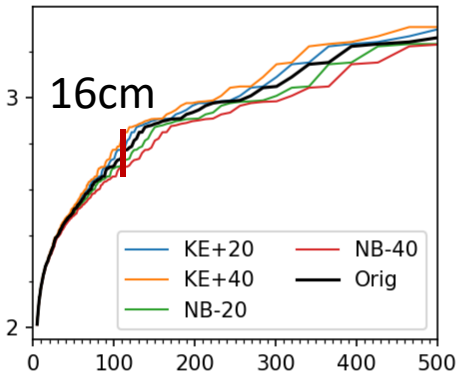
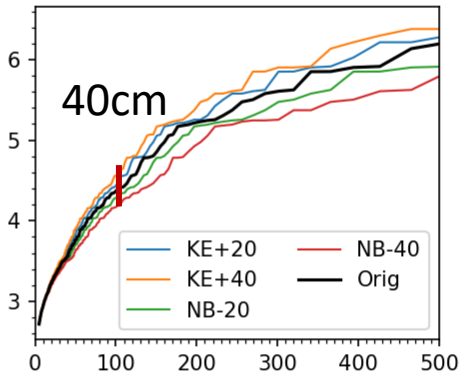
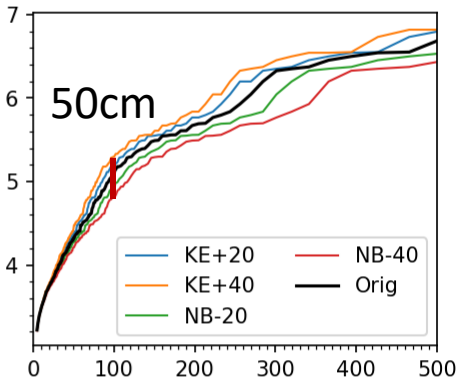
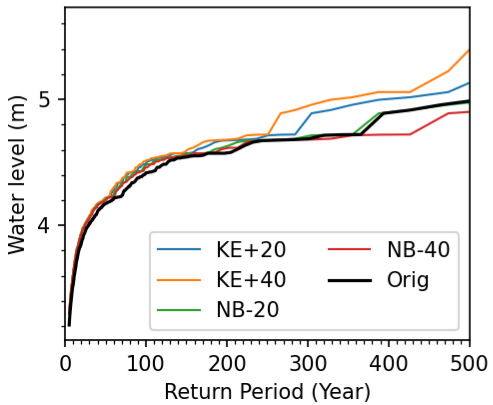
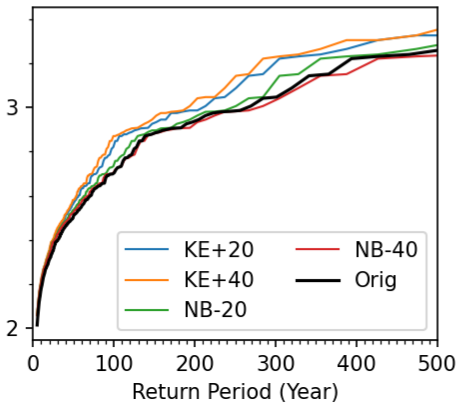
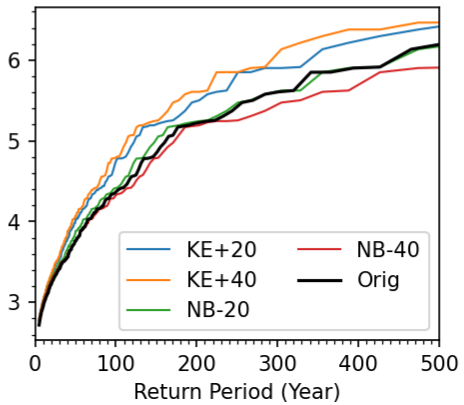
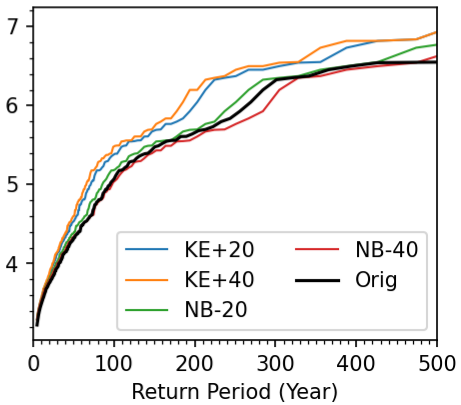




Sensitivity to Changed in Frequency and Intensity Distribution

Cat 4-5 modified

± 20 & 40%

	Sagar Roads	Hiron Point	Charchanga	Chittagong
10% Reduced Frequency				
Same Frequency				
10% Increased Frequency				

Conclusions and Perspectives

- Future assessment of storm surge hazard presents challenges -
  - Interaction of **surges** with **increasing sea-level**
  - Large **uncertainty and disagreement** between projections
- Sensitivity experiments shows -
  - **Stronger impact** from the **sea level scenarios**, compared to changes in cyclone frequency, intensity changes
  - Mean sea level rise is **increasing the risk of storm surge flooding** by multiple-fold (return period)
  - **Changes** in extremes related to **storm properties (frequency and intensity)** requires further investigation and sensitivity experiments.
- Other assumptions that's needs to be keep in mind –
  - Constant bathymetry
  - Constant shoreline/protection system

Ongoing work on the future scenarios…. Any comment is welcome!

Thanks for your attention!

Stochastic-Deterministic Approach

(Emmanuel et al. 2006)

1. Random sampling of genesis location and assessment of the climatology of wind shear to check if the system sustains
2. Advection in time till dissipation to obtain the storm track
3. Run through a coupled ocean-atmosphere model to estimate the intensity of the storm.

Repeating thousands of times…

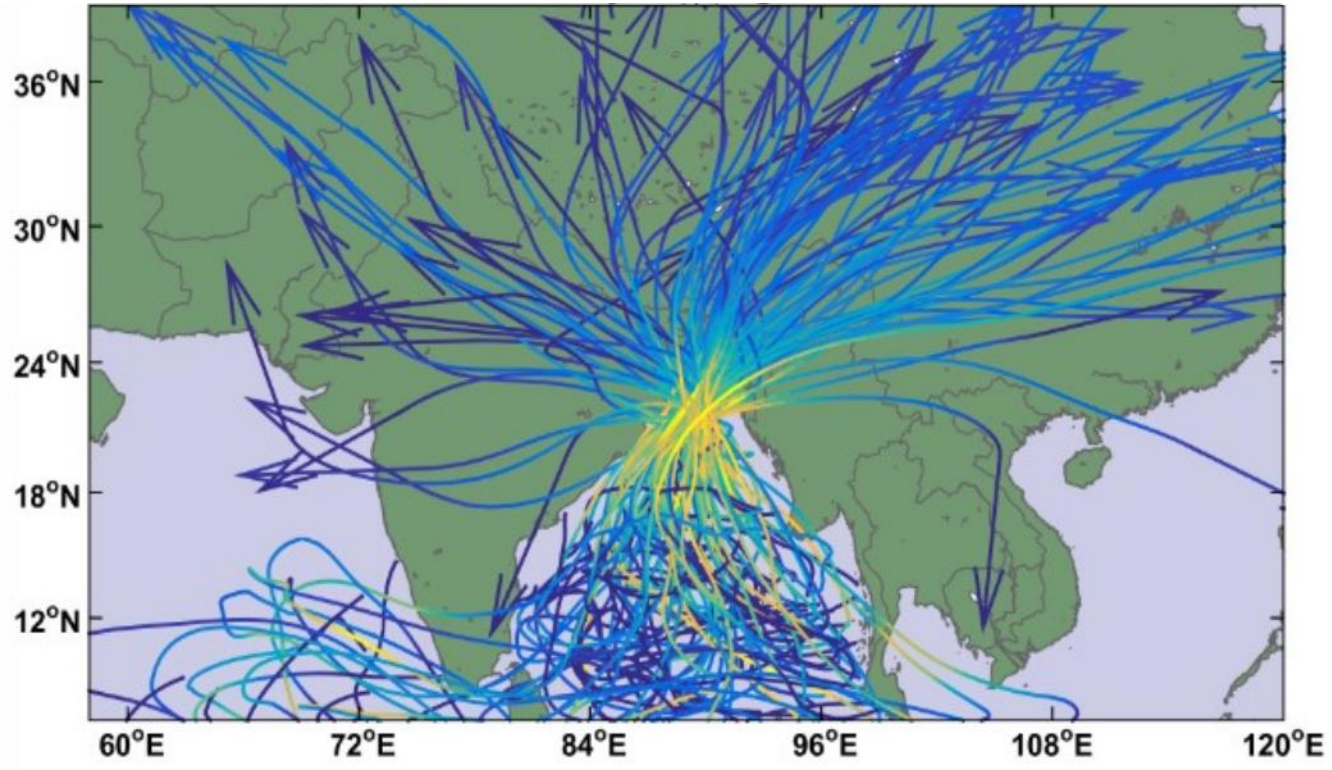
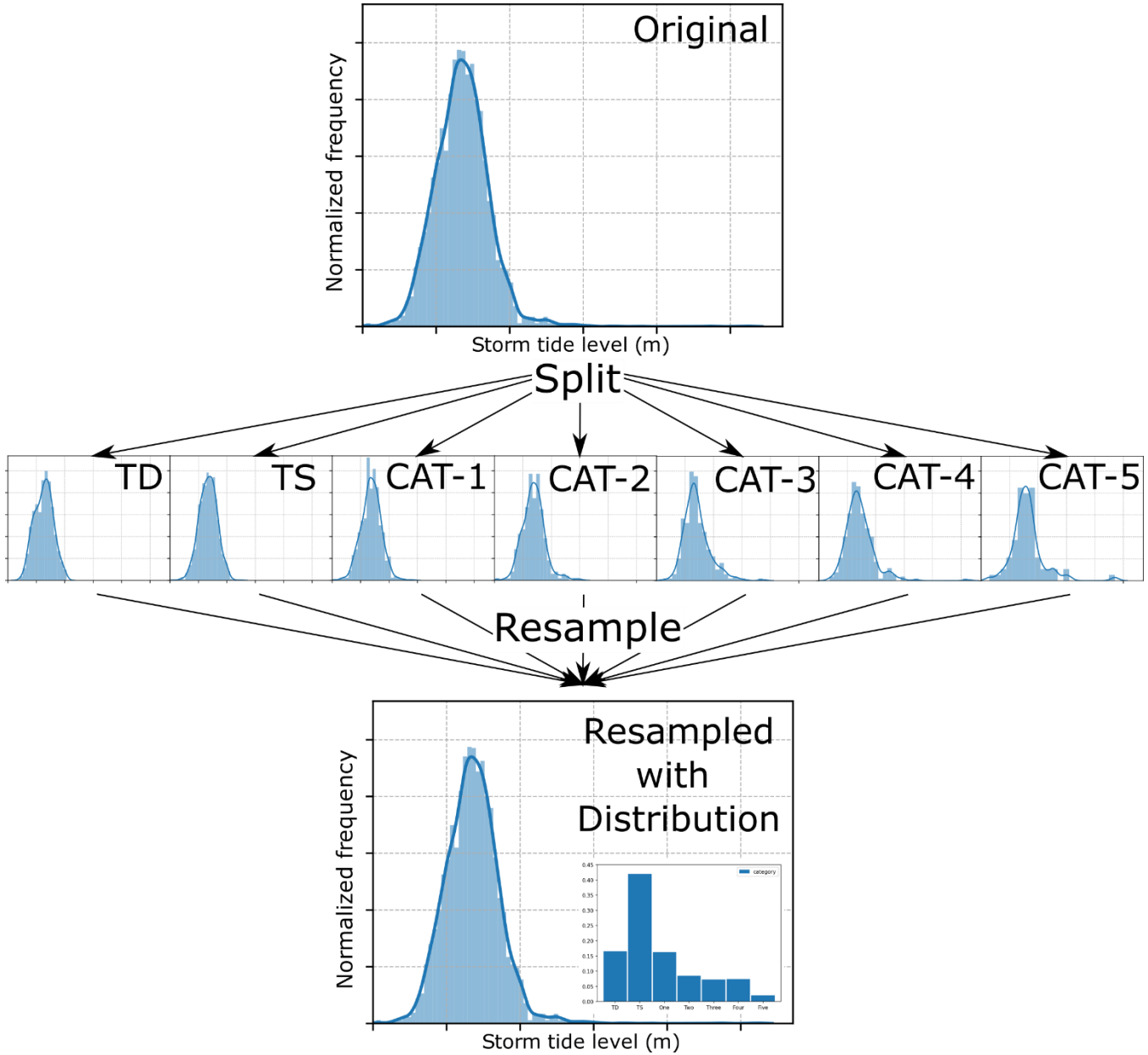


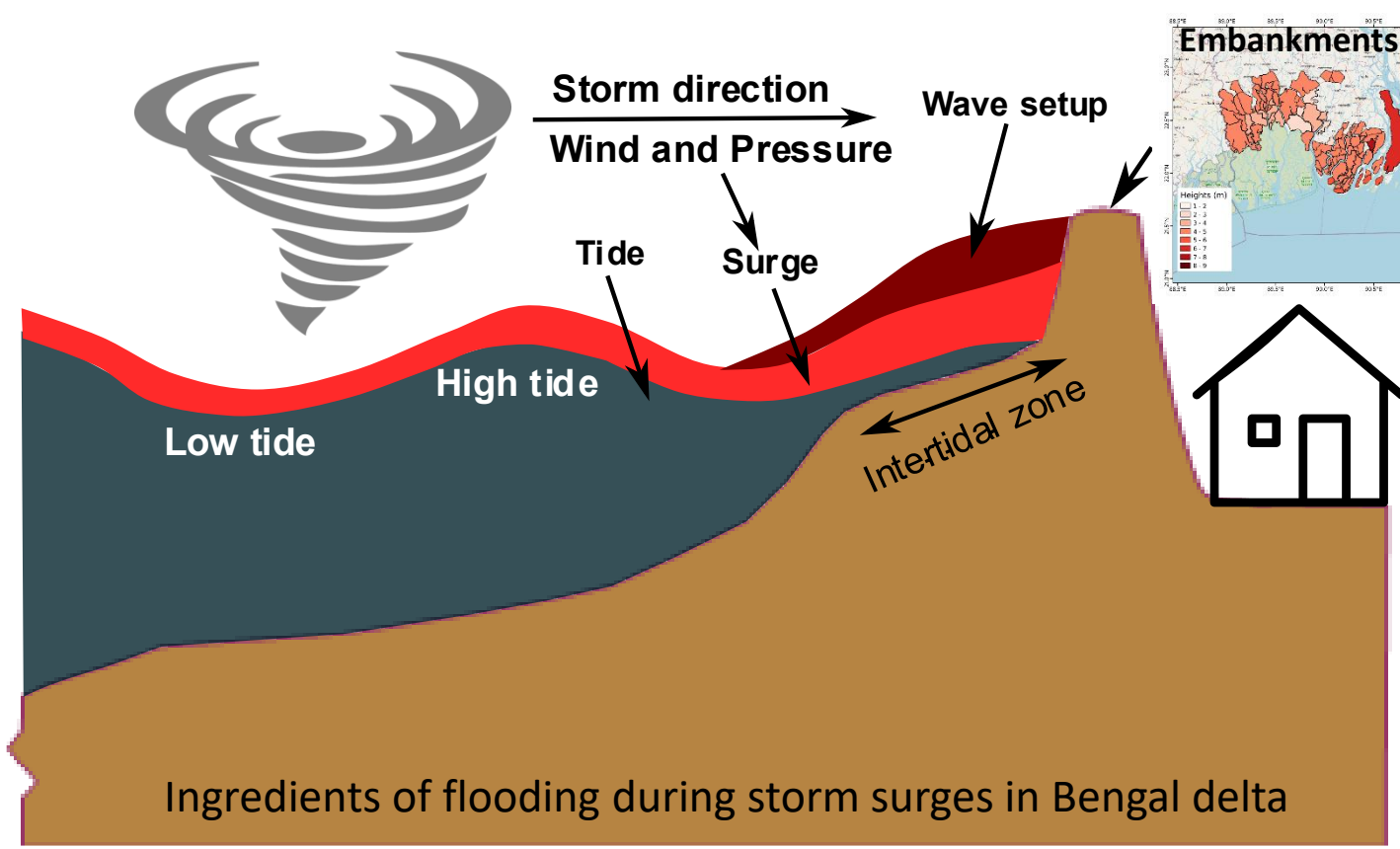
Figure: A subset of cyclones from the ensemble

3600 Storm events, ~5000 years of simulated cyclone activity over Bengal delta under **current climate**.

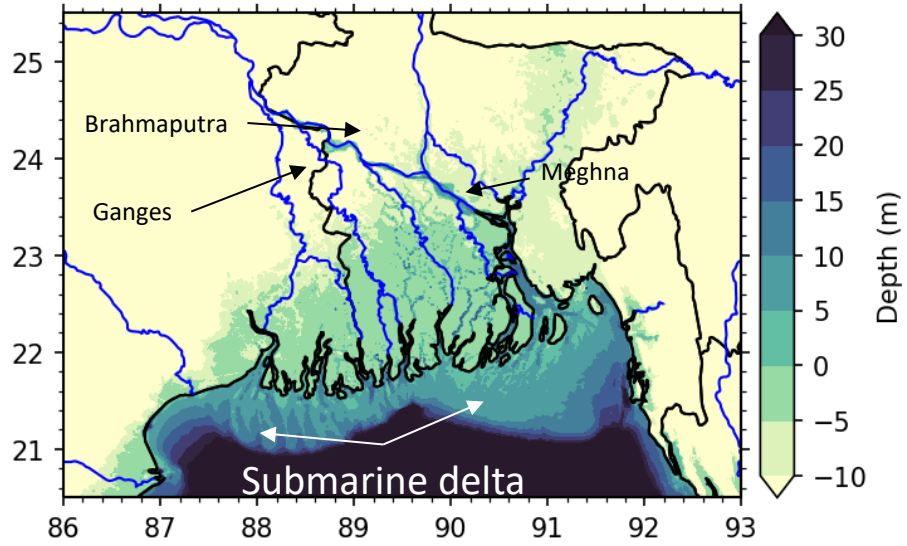
Resampling Strategy



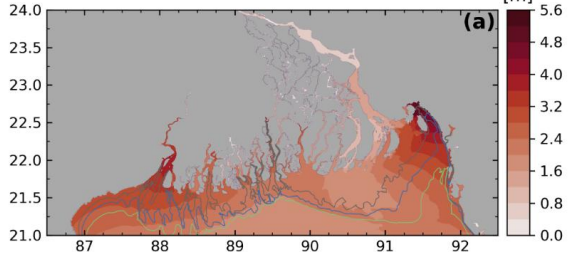
Ingredients of Cyclonic Inundations



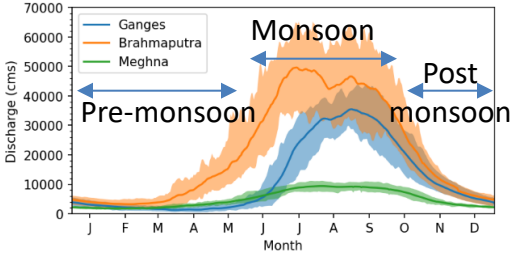
Bathymetry (Krien et al. 2016, Khan et al. 2019)



Tidal range (Khan et al. 2020)



Observed discharge (1980-2015)

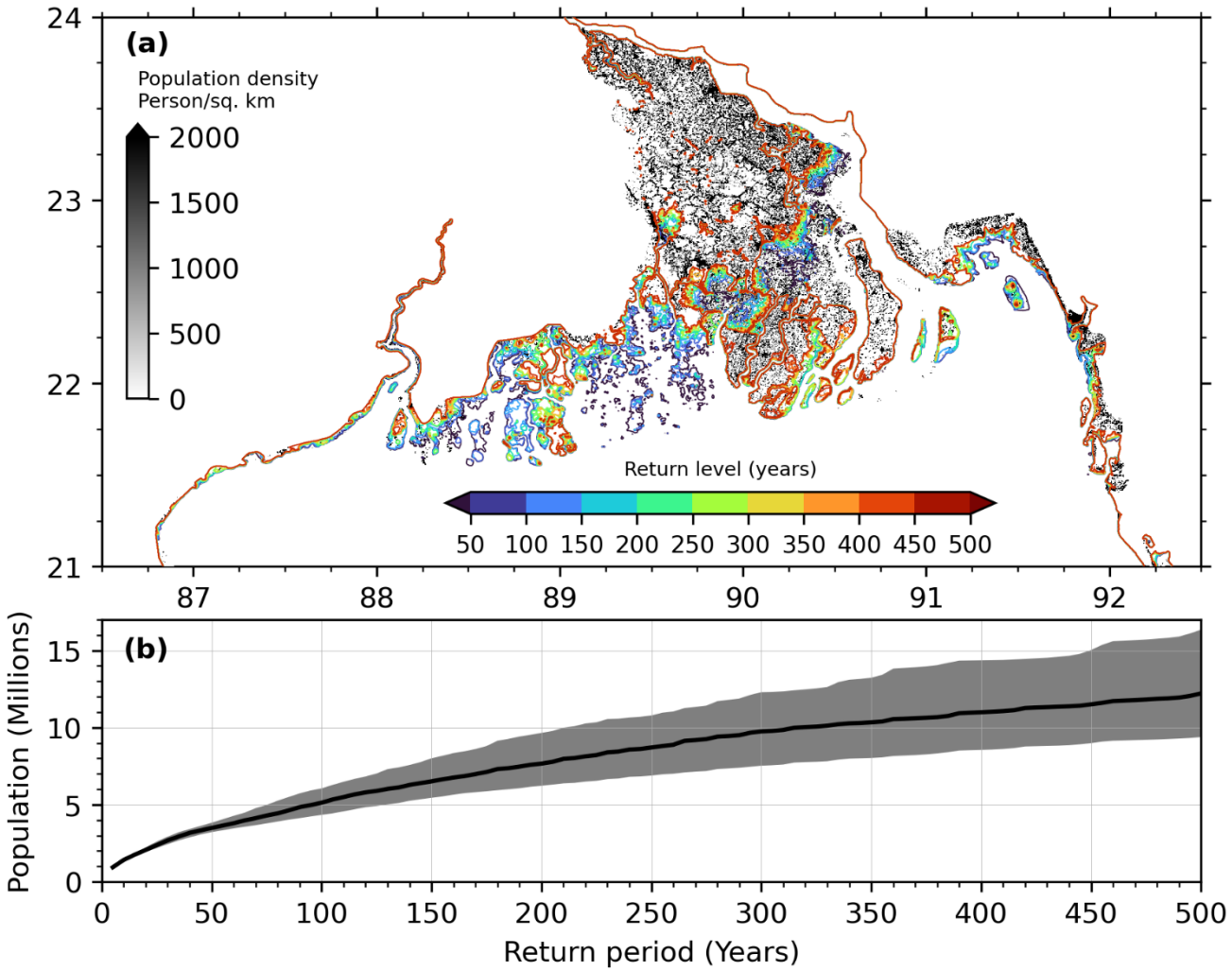


It is common practice in Bengal delta region –

- to model without inland flooding (does not capture peak lowering)
- to de-couple tide from surge -separate tide and surge simulations (misses tide-surge interaction)
- to model without waves (misses wave-setup)

Coupled tide-surge-wave modelling is essential to capture the cyclonic storm surge flooding

How many people are exposed to storm surge flooding?



Dataset:

- GHSL Population layer (250m) - https://ghsl.jrc.ec.europa.eu/ghs_pop.php

- An estimated 1 million people live below 5-year return period flood level.
- At 50-year return period, 3 million more people are exposed to coastal flooding.

Currently under review (Khan et al., 2022)
https://nhess.copernicus.org/preprints/nhess-2021-329/

Tidal range change in response to SLR (Khan et al. 2020)