Efficient impact-based forecasting of coastal flooding on reef-fronted islands using a deep learning surrogate model

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Coastal flooding: Local TCs

TC TINO, Photo taken at Sir Roberts Wharf on Saturday morning 18th January 2020. P.C – Coral Pasisi

TC TINO, Photo taken at Avatele Beach on Saturday morning 18th January 2020. P.C – Tifaga Tupuiliu

Birdseye view of the destruction caused to the Huanaki Cultural Centre in Niue after Tropical Cyclone Heta.

Coastal flooding: distant TCs

Recorded by a resident of Nanumaga, Tuvalu during TC Pam

Coastal flooding: distant swells

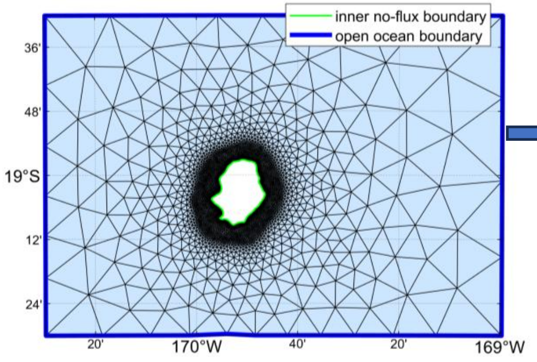
Recorded by Jens Krueger on Fiji's Coral Coast in May 2018

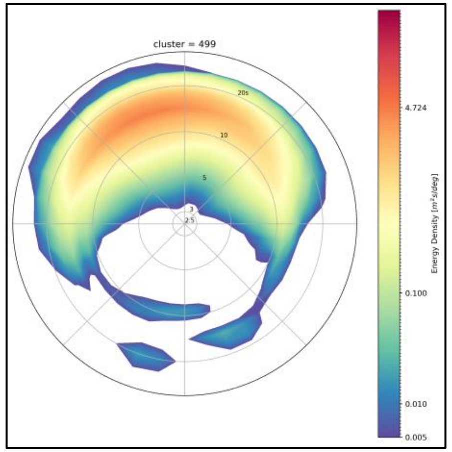
Niue


Niue
Hikutavake
Mutalau
Namukulu
Toi Village
Tuapa
Makefu
Lakepa
Alofi Bay
Baie d'Alofi
NIUE
ALOFI
Liku
Fonuakula
Tamakautonga
Avatele Bay
Baie d'Avatele
Avatele
Hakupu
Vaiea
0
Kilometres
10

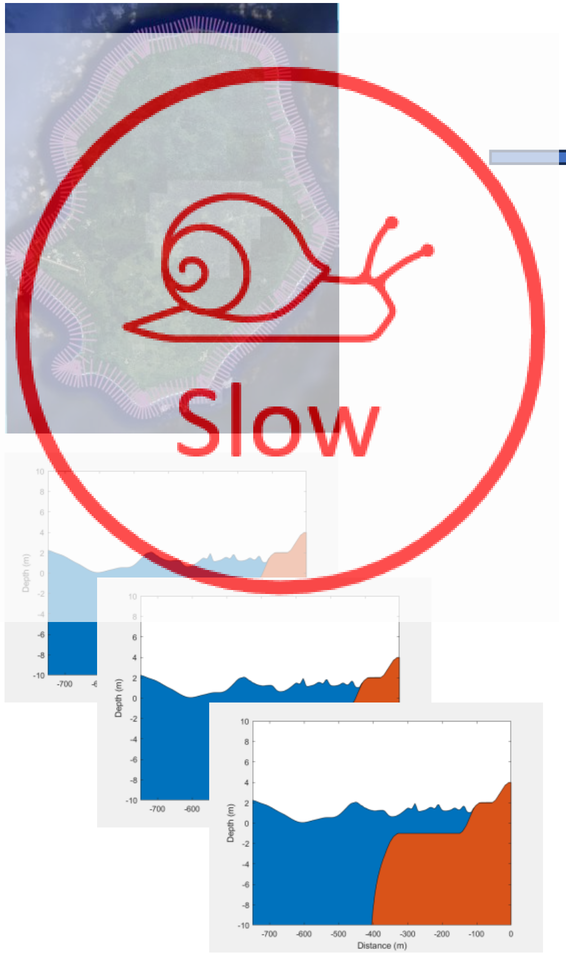
Inundation modelling

SWAN





Xbeach Nonhydrostatic

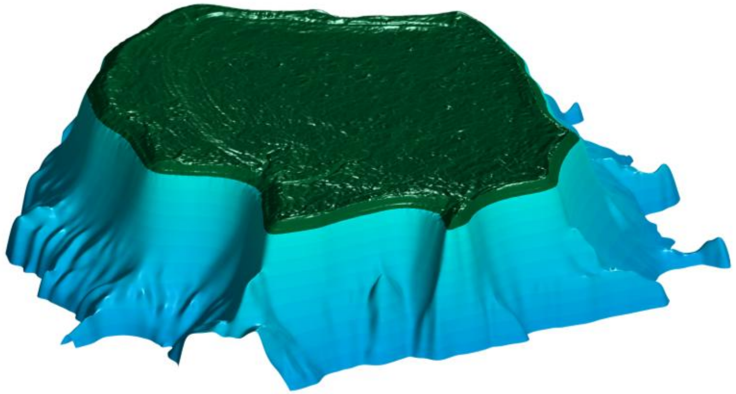


181 transects

SFINCS

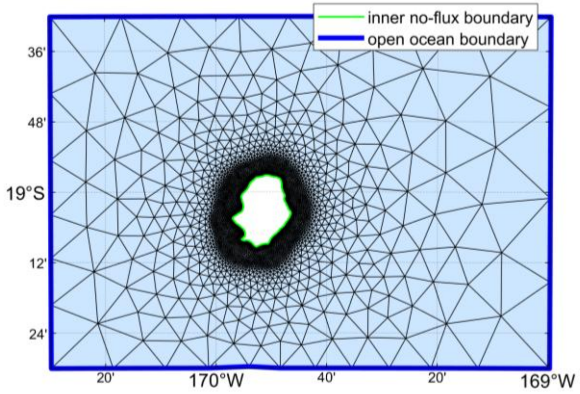
Offshore ocean conditions

Baseline data



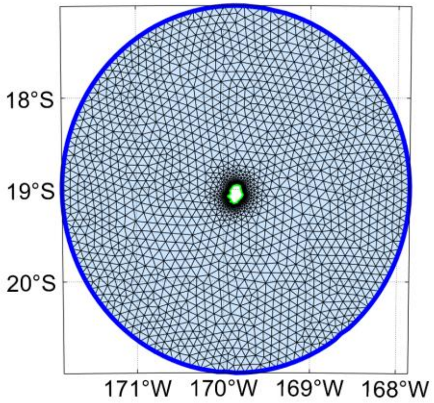
- Lidar bathy + topo
- Multibeam
- GEBCO

Distant storms



- Tides
- Sea level anomalies
- Waves
  - High-resolution (200 m) UnSWAN model

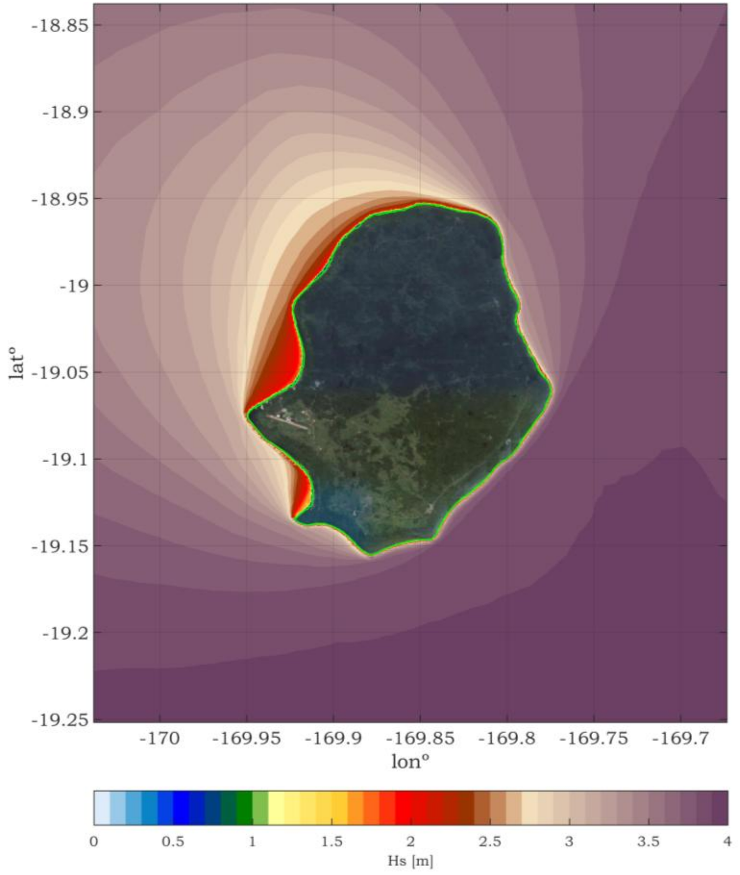
Local TCs



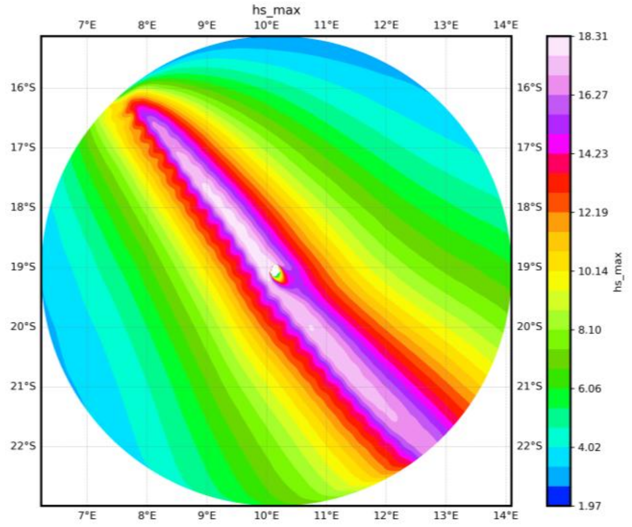
- Tides
- Sea level anomalies
- Waves and storm surge
  - High-resolution UnSWAN model coupled to ADCIRC

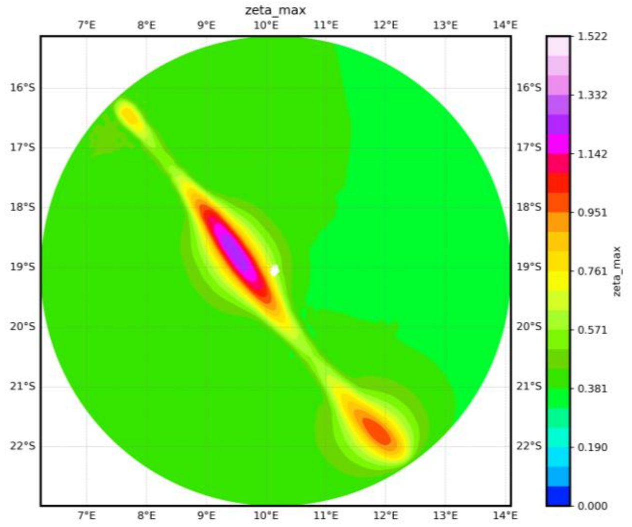
Offshore ocean conditions

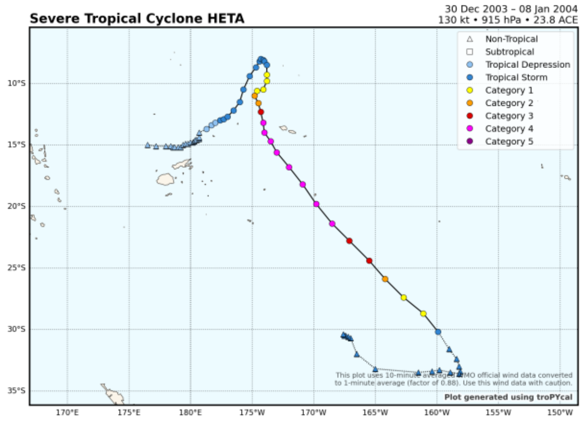
Distant swell



Local TC







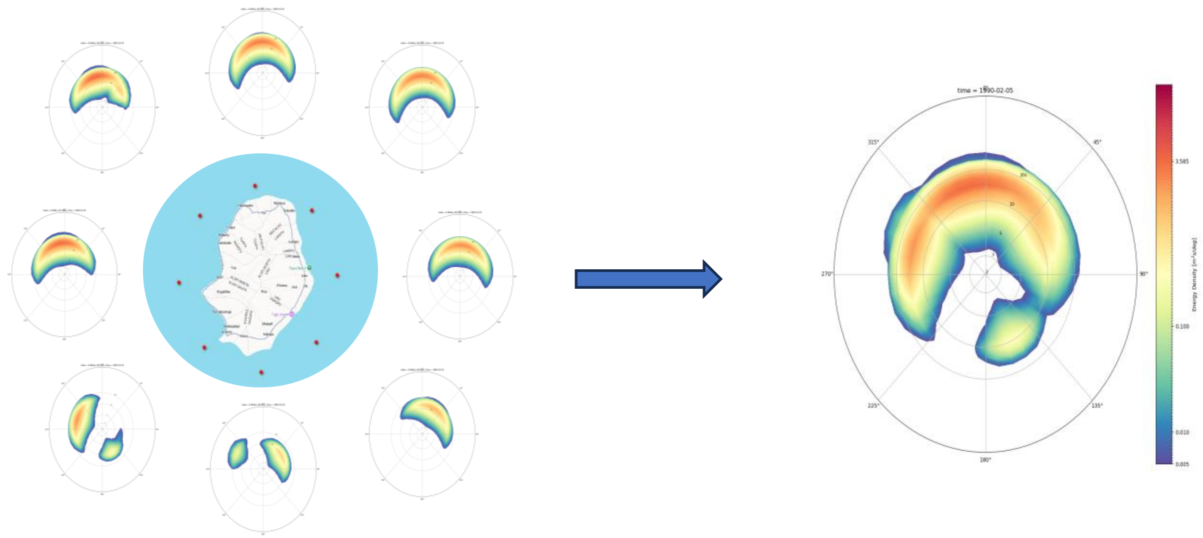
Machine learning

Input:

- Waves (Superpoint spectrum)
- Water level (tides/storm surge/MSLA)
- DEM

Output:

- Inundation depth



Cagigal et al. (2021)

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Spectral emulator

Multi-decadal wave hindcast

↓

Generate superpoint wave spectrum

↓

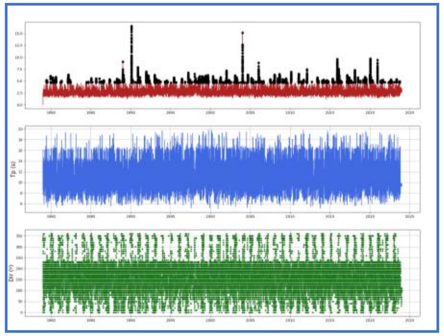
Apply PCA with optimal number of components

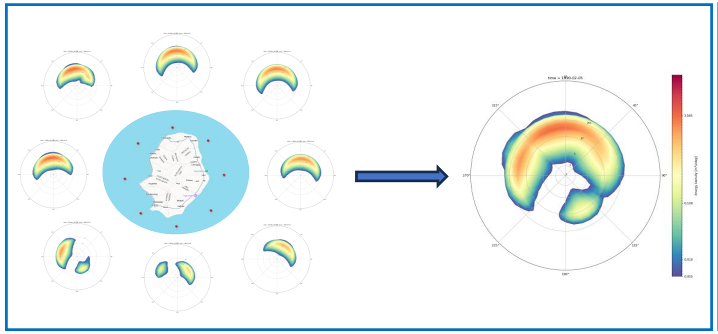
↓

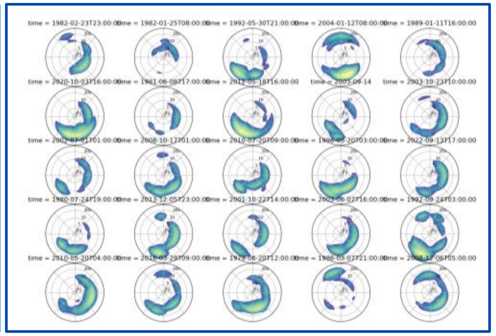
Fit a Gaussian mixture model

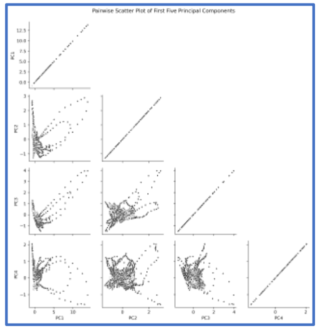
↓

Generate 100,000 random samples from the fitted distribution and generate spectra using inverse PCA

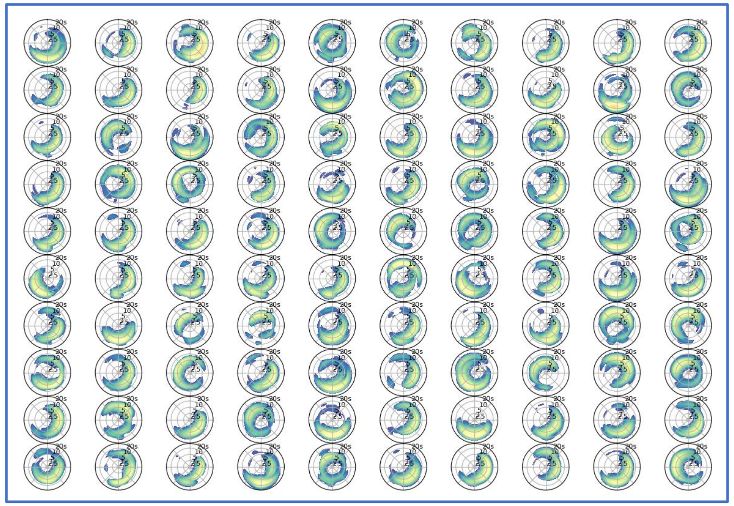






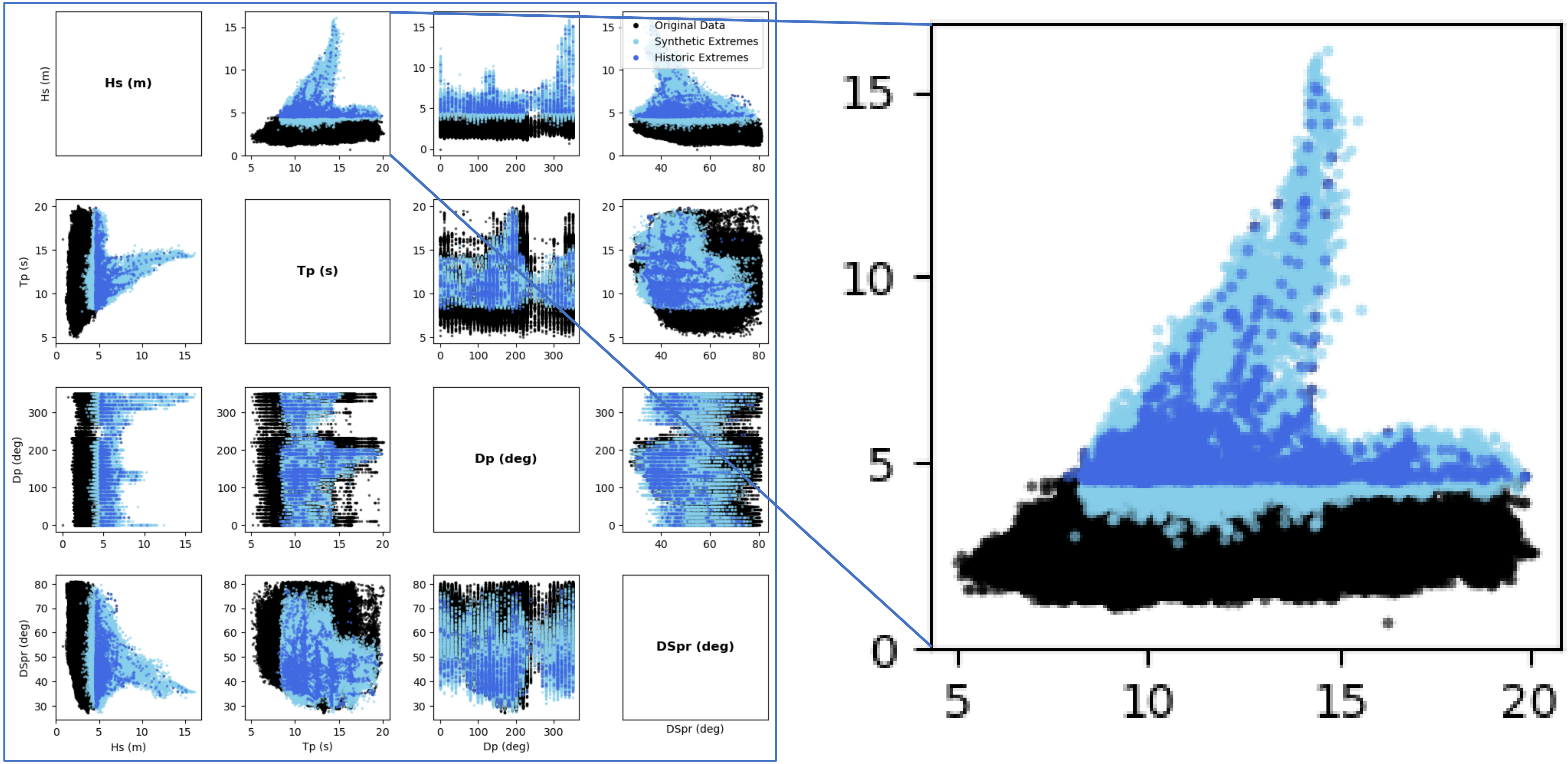


GMM is a probabilistic model that represents data as a weighted combination of several Gaussian (normal) distributions.



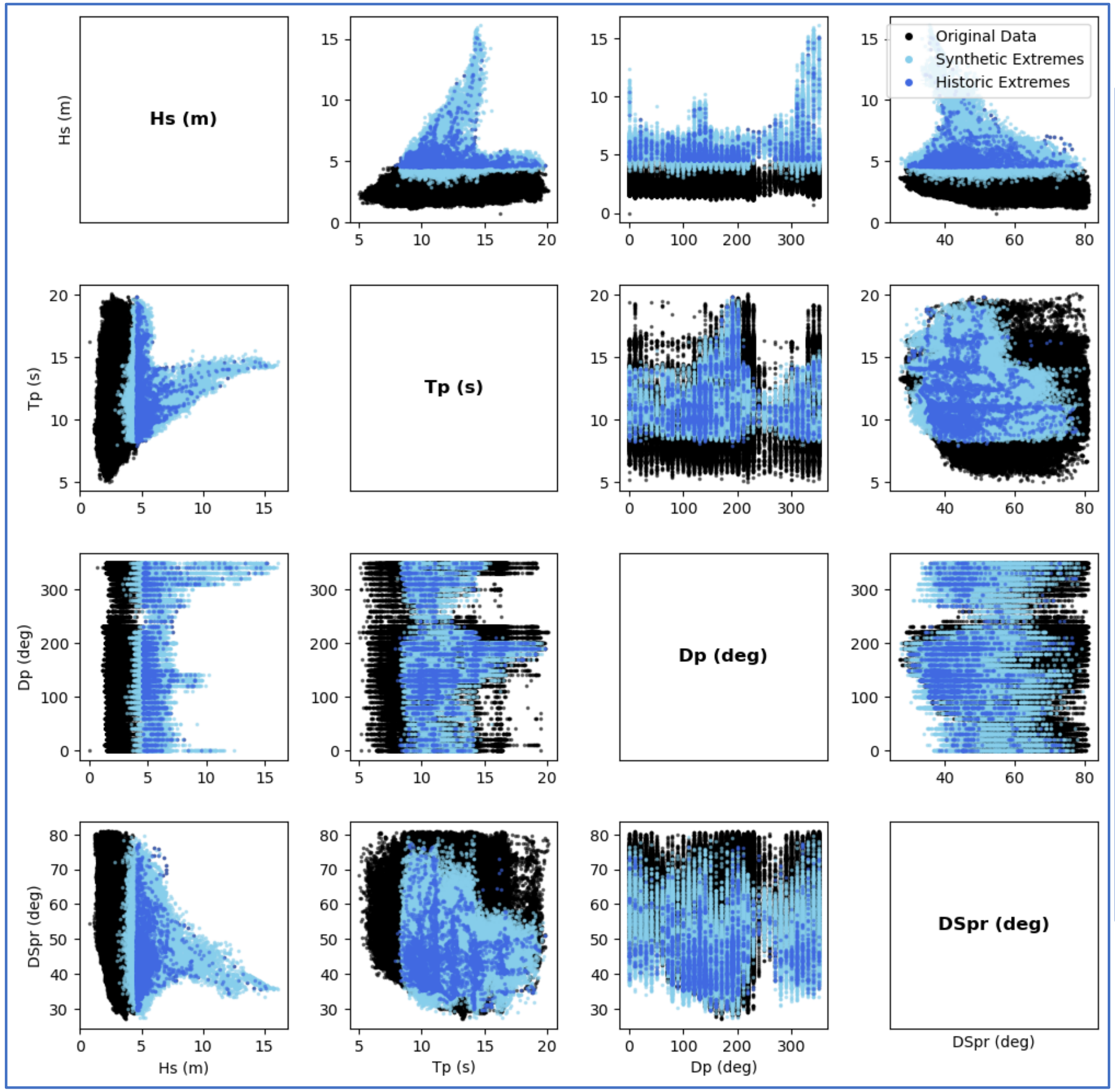
Spectral emulator - Results

Wave parameters



Spectral emulator - Results

Wave parameters



Example spectra

K-means clustering - Results

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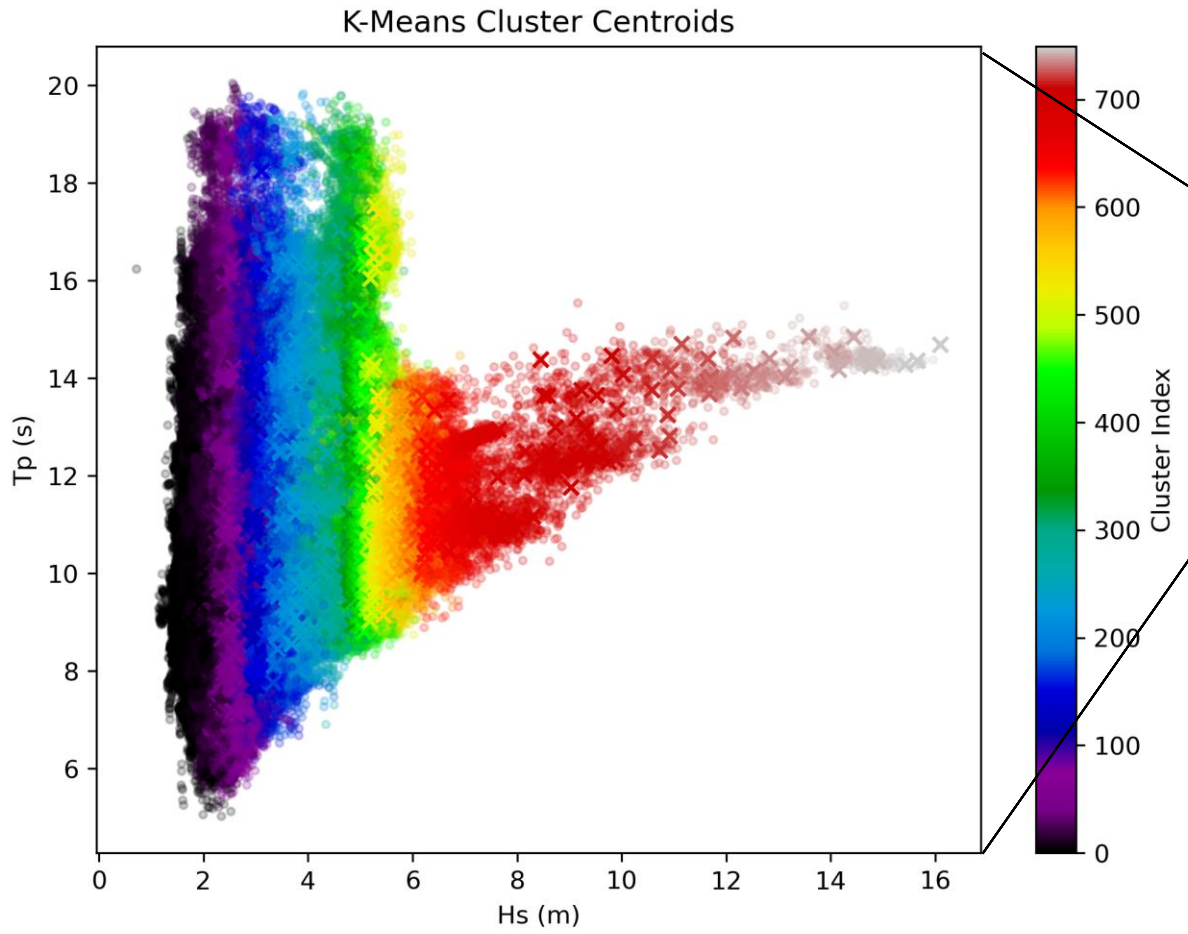
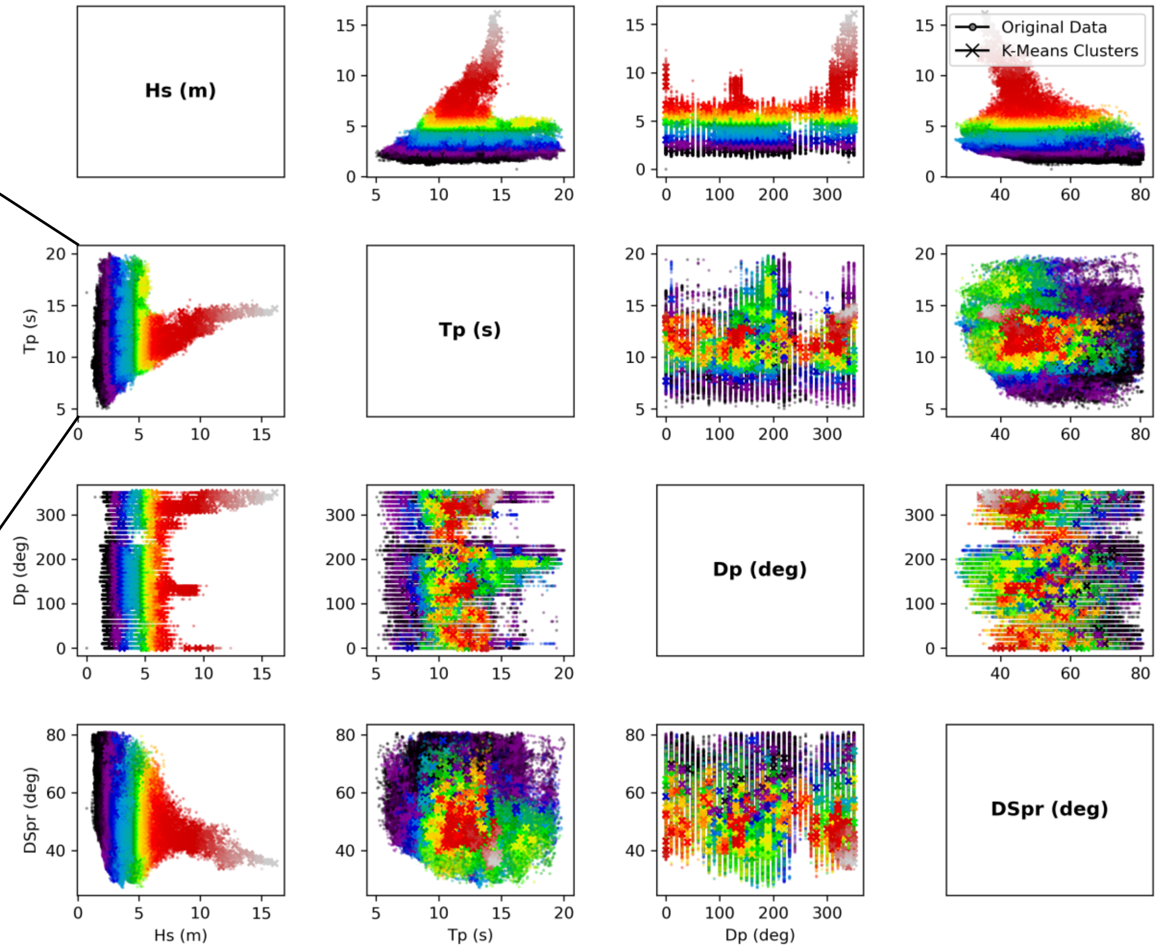


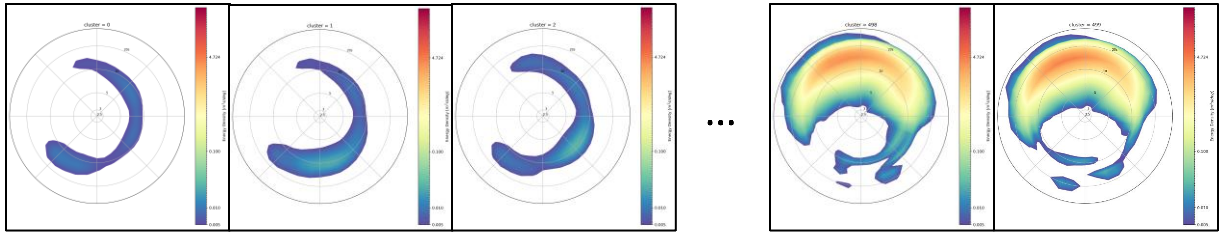


Generate training data

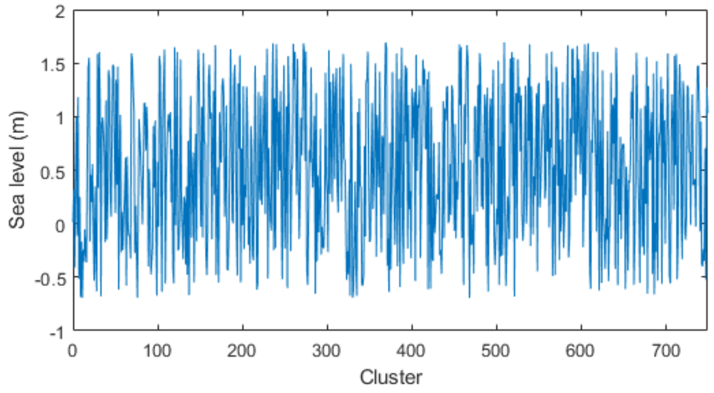
Model input

Superpoint spectra

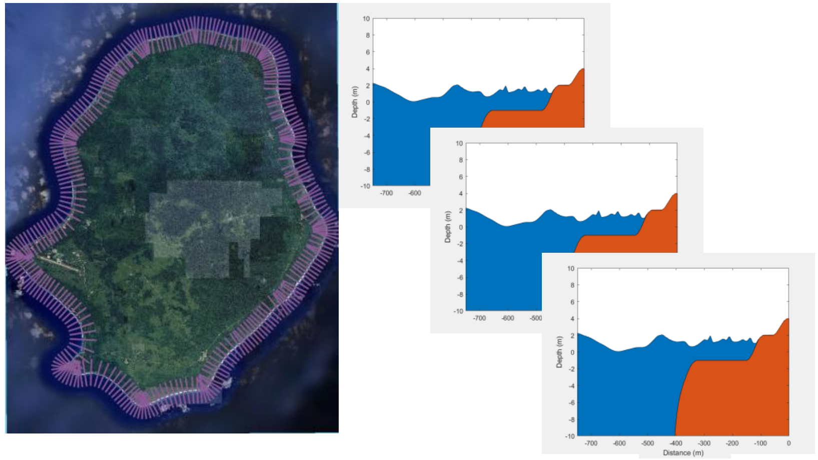
Cluster 0 | Cluster 1 | Cluster 2 | ... | Cluster 748 | Cluster 749



Random sea levels



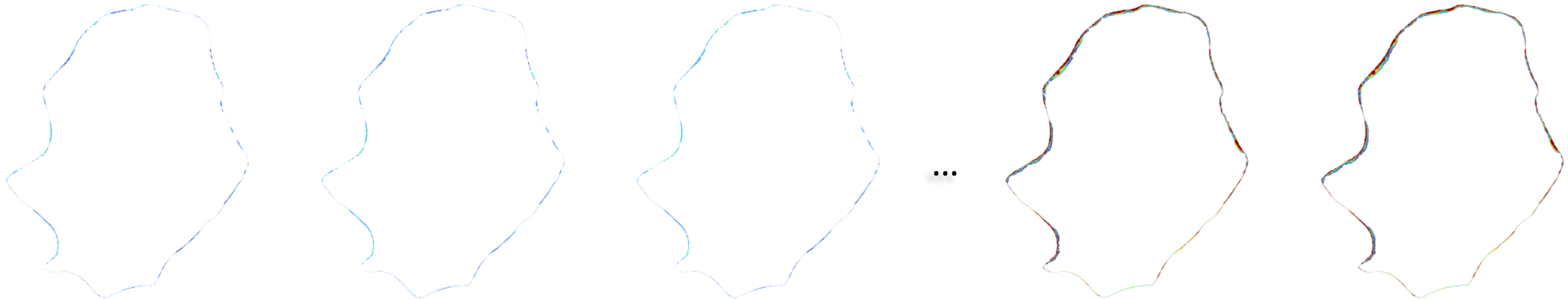
Xbeach NH + SFINCS



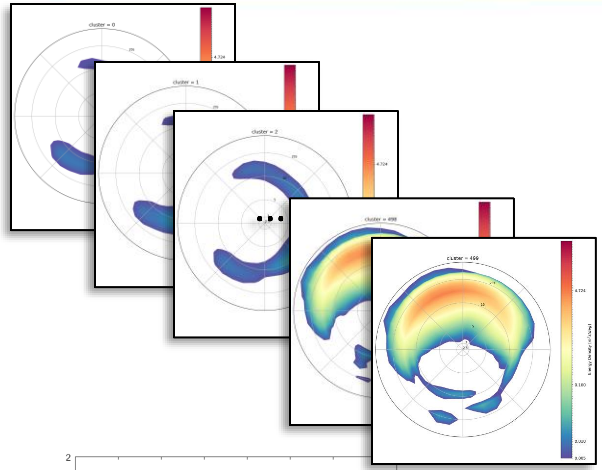
181 transects
750 scenarios
135,750 simulations with XBeach

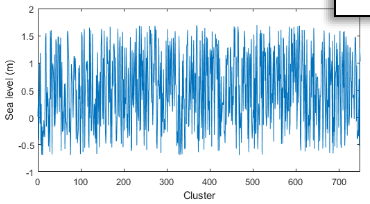
Output

Inundation map 0 | Inundation map 1 | Inundation map 2 | ... | Inundation map 748 | Inundation map 749

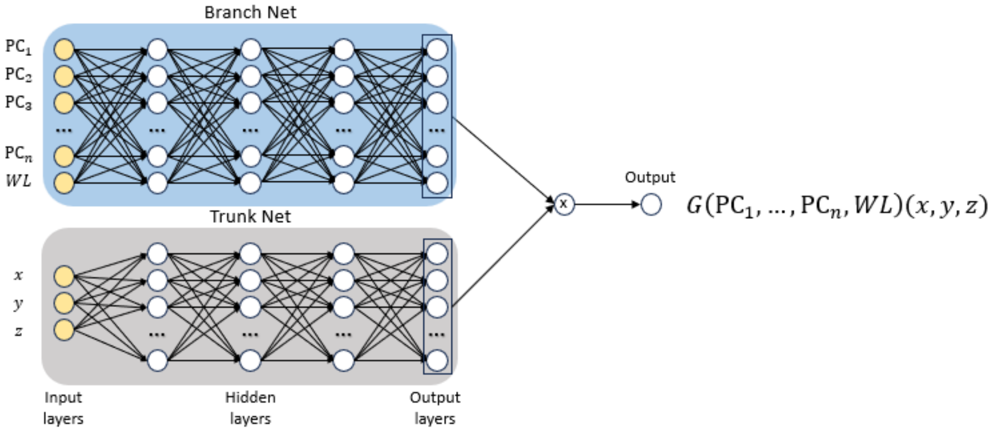


Training DeepONet with 750 scenarios

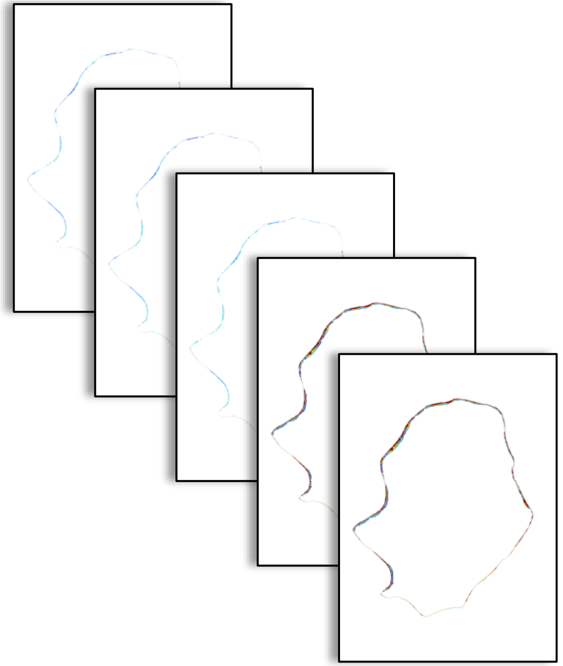


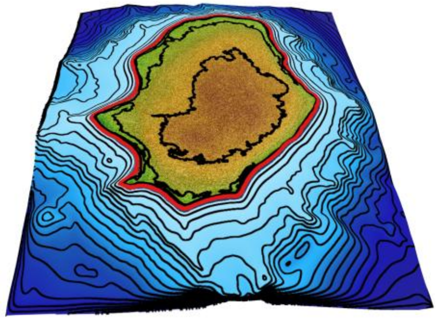


Deep Operator Network*



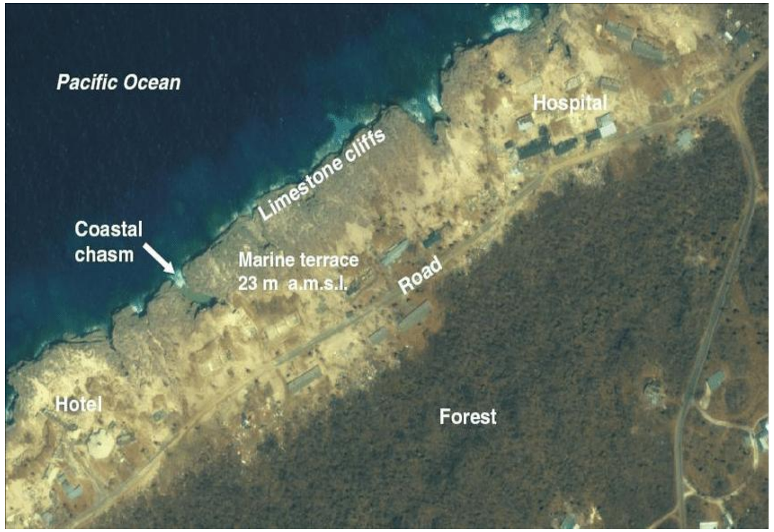
*Lu et al. (2021)



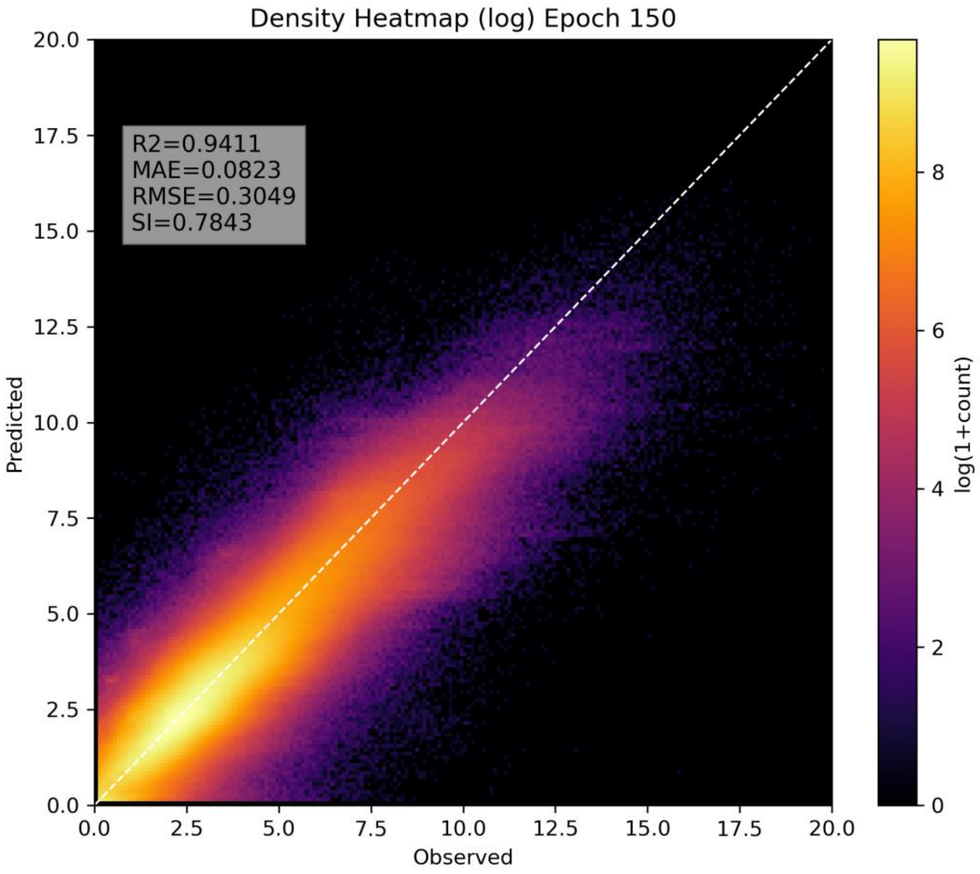


- Learns an operator that takes an *input function* and predicts a scalar output **at each queried location**, by combining the branch embedding of the input function with the trunk embedding of the location.
- DeepONet can reuse the same trained model to predict the scalar at *any* location by just changing the trunk coordinates.

Historical events – TC Heta 2004

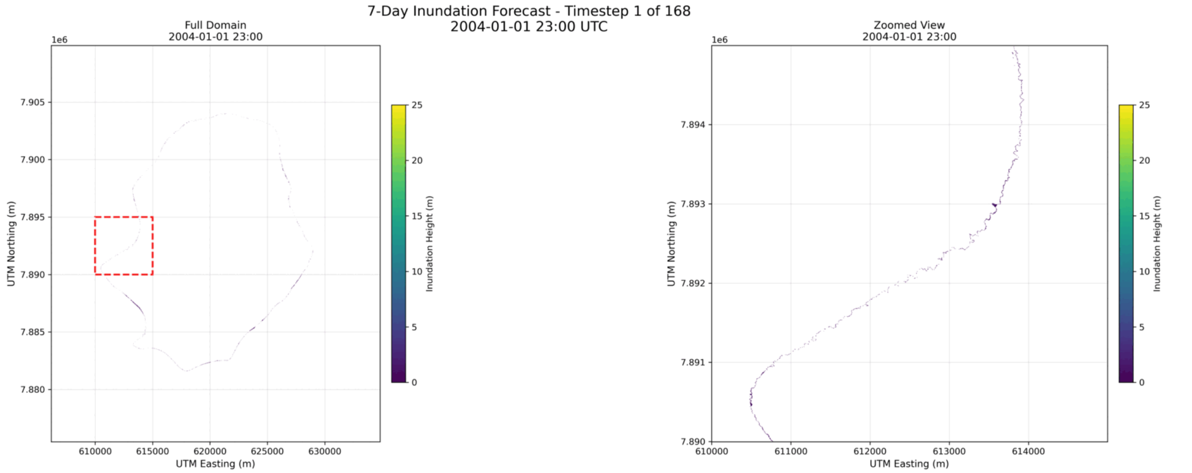



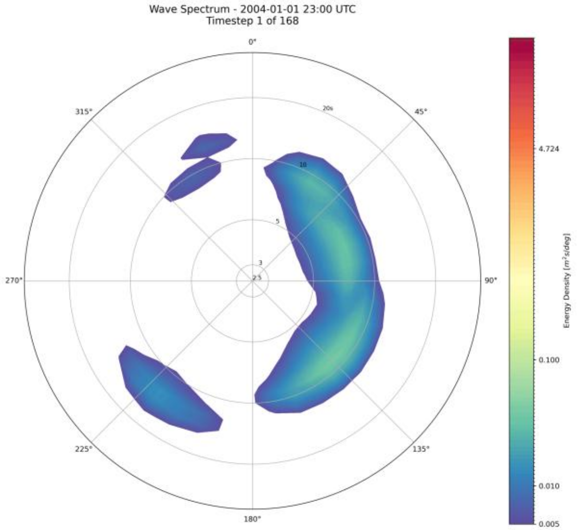
Numerical validation against 100 “unseen” scenarios

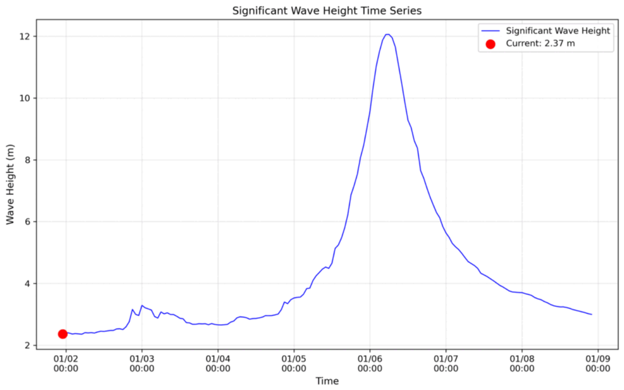


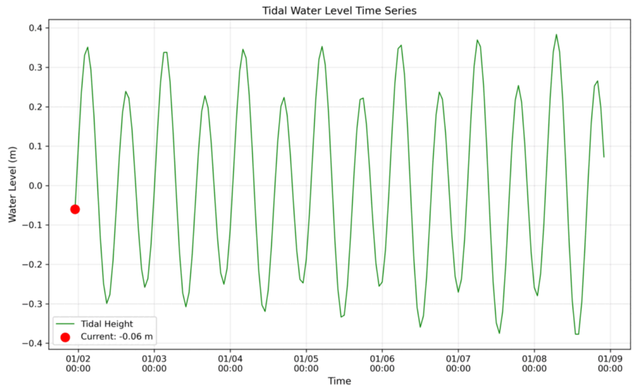
7-day "forecast" run

- 2.5-4 minutes for 7 days (168 time steps) with ~1 million grid points









Conclusion

- By plugging the system into a wave forecast (and storm surge in case of local TCs) we can efficiently predict coastal inundation.
- The methodology allows for domain-wide time-series prediction of inundation levels along with hourly inundation maps (as opposed to event-based maps) allowing for targeted response.
- Coupling the system to a risk model (RISKSCAPE) we can predict impact.
- Ensemble forecasting of inundation is possible (e.g., for TCs using multiple TC tracks).
- Method allows for hindcasting inundation (storage limited).
- System is currently being implemented/operationalized for TV and Niue with further countries in the pipeline.
- Method requires good baseline data to be effective.

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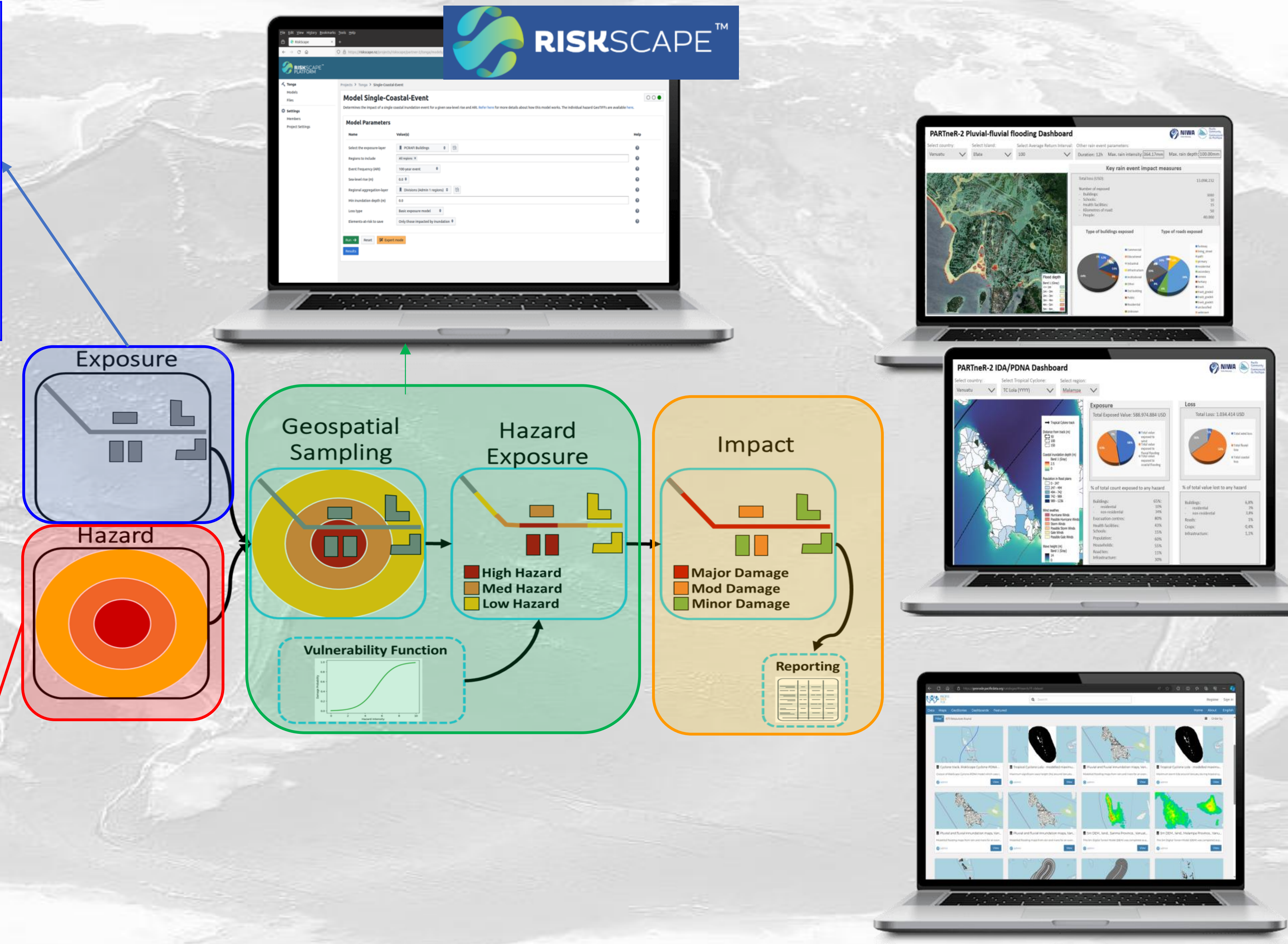
Assets

- Population
- Buildings
- Roads
- Bridges
- Airports
- Port Facilities
- Power
- Water
- Evacuation Centres
- Health Facilities
- Schools
- Villages
- Infrastructure
- Telecommunication
- Crops
- Infrastructure Values



Hazards models

Coastal inundation

- Wave driven inundation

Tropical Cyclone

- Wind speed (incl. topography)
- Storm surge and wave driven flooding
- Rainfall and river flooding (not yet implemented)

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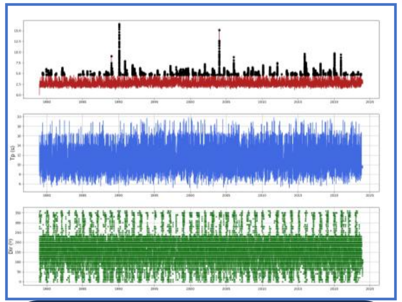
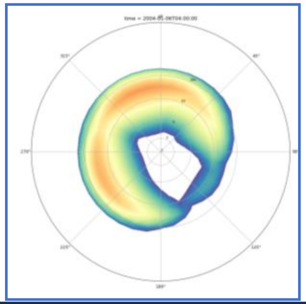
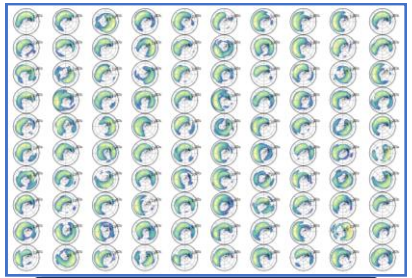
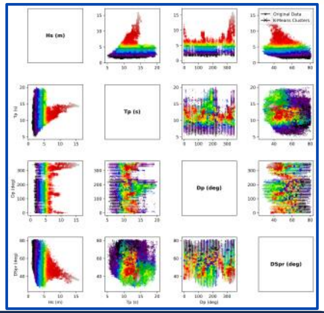
Inundation forecasting



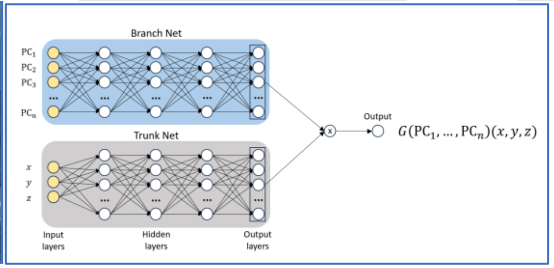


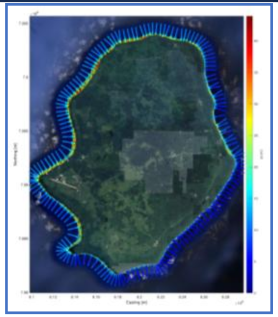




Multi-decadal wave hindcast → Generate superpoint wave spectrum → Monte-Carlo emulator to generate synthetic extreme wave spectra → K-means clustering of wave spectra

→ Simulate clusters with Xbeach-NH and SFINCS → Deep-learning with the simulated clusters → Use neural network to predict inundation





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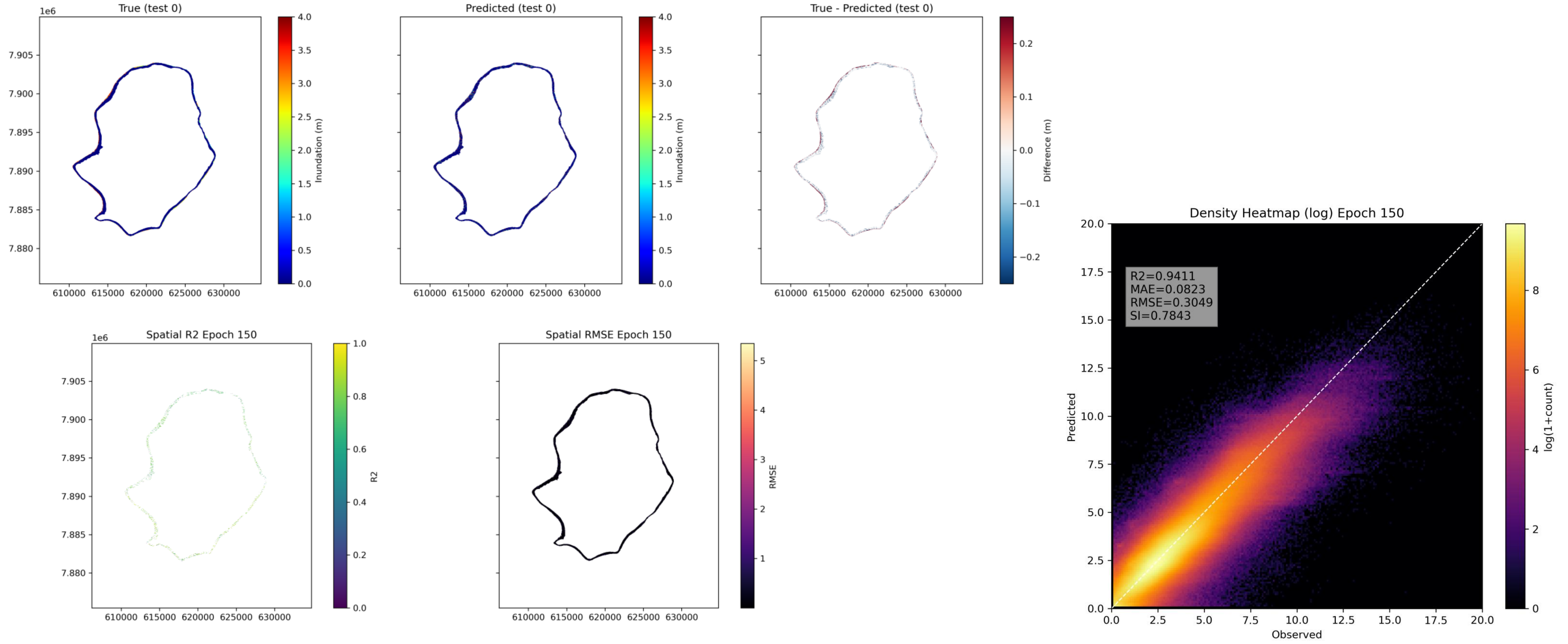
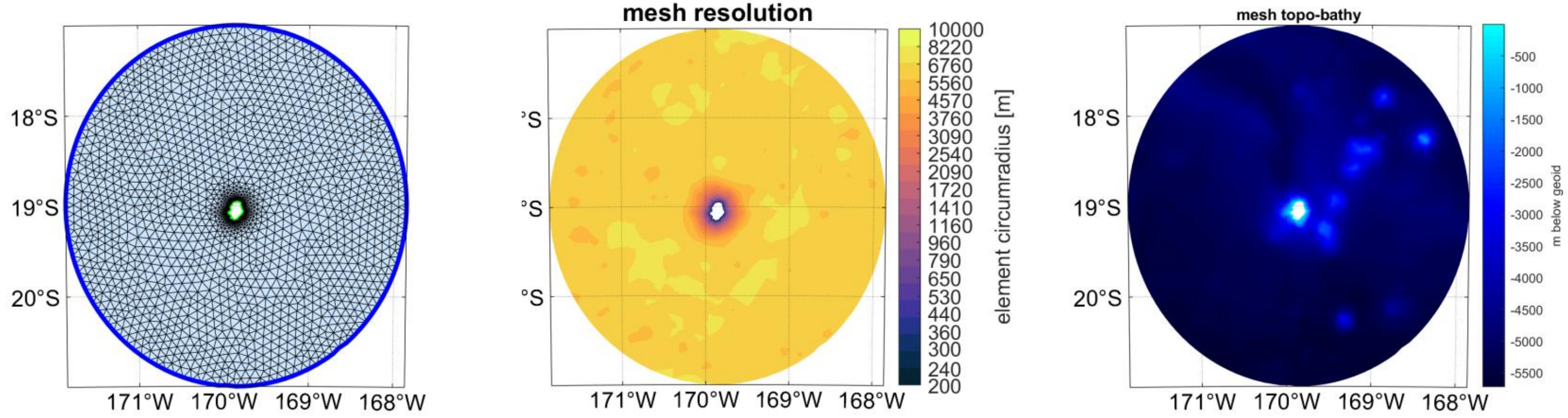
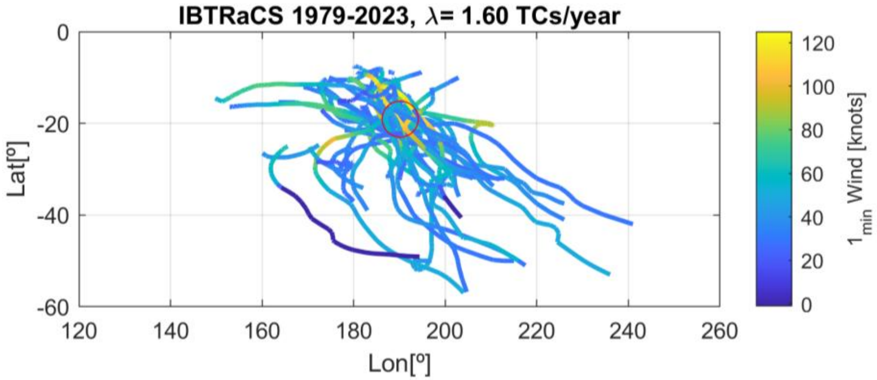


Tropical cyclones

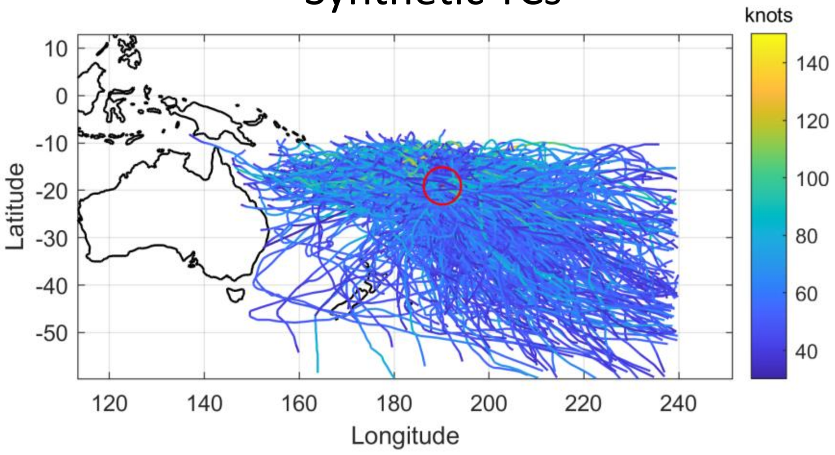
Adcirc + SWAN



Historic TCs



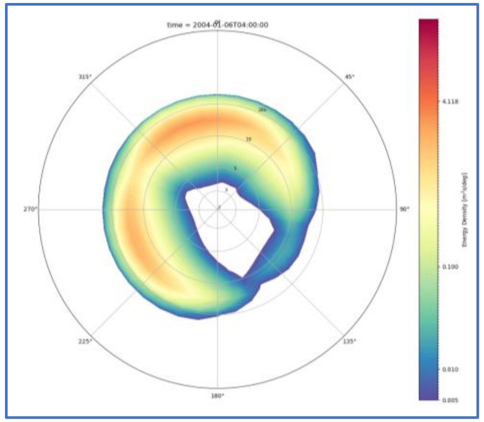
Synthetic TCs*



*Synthetic tracks obtained from Bloemendaal et al. 2020

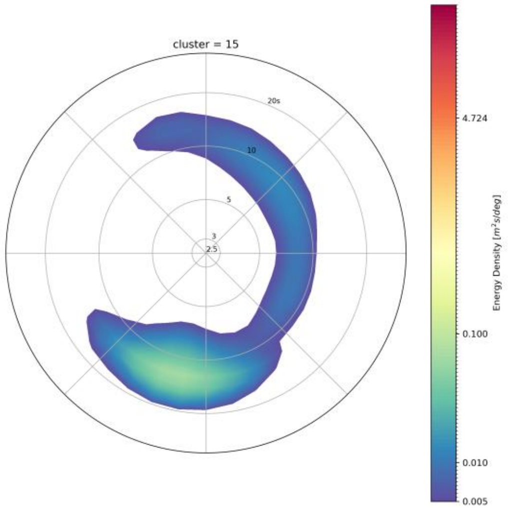
Designing the forecast system

- Explicitly simulating inundation for each wave forecast cycle is computationally expensive
- Xbeach could become numerically unstable resulting in false predictions
- Surrogate models provide a computationally cheap solution
  - Generate 750 representative wave and water level conditions
  - Simulate 750 clustered spectra using Xbeach + SFINCS
  - Train neural network/ML algorithm using the 750 clusters as input and resulting inundation maps as output



K-means clustering - Results

Example centroid for cluster 15



Historic spectra belonging to cluster 15

K-means clustering - Results