HyFlood: A Hybrid Statistical-Dynamical Downscaling Framework for Compound Coastal Flooding

Alba Ricondo[1], Laura Cagigal[2], Curt D. Storlazzi[3], Mark Merrifield[4], Fernando J. Mendez[5] and Peter Ruggiero[1]

[1]Oregon State University, Oregon, United States
[2] University of Cantabria, Santander, Spain
[3] U.S. Geological Survey, California, United States
[4] Scripps Institution of Oceanography, San Diego, California

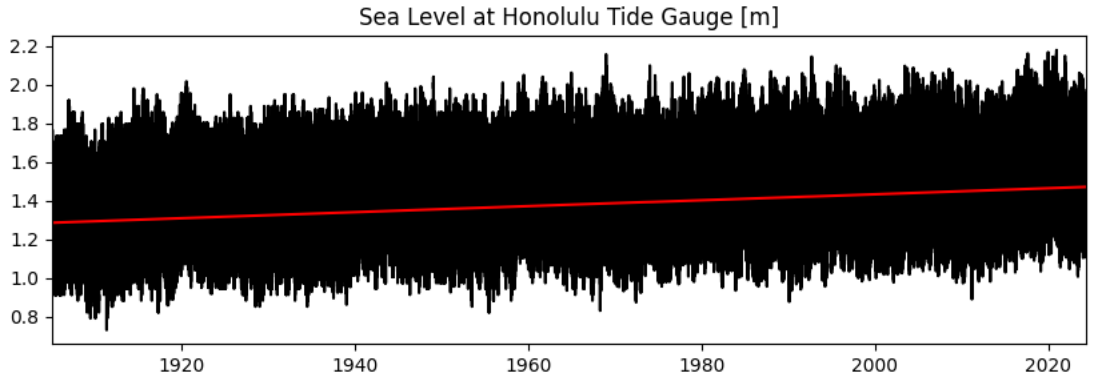
alba.ricondo@oregonstate.edu

4th International Workshop on waves, storm surges, and coastal hazards
incorporating the 18th international waves workshop, Santander, Spain

Motivation for Rapid Assessment of Compound Coastal Flooding

Honolulu, Hawaii on Dec. 7, 2021 – Kona Low

TC Iniki – Sep. 1992

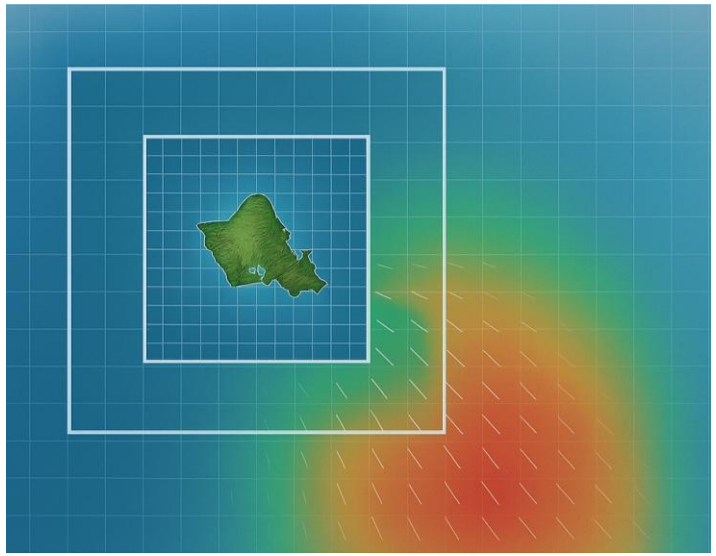


1905-2024 **(20cm)**

Rising sea levels
Groundwater flooding
Change in storm patterns
Vertical Land Motion *(Murray K. et al., 2025)*

Modeling Approach: A Hybrid Statistical-Dynamical Downscaling

Dynamical Downscaling



- ☑ Accurate reproduction of physical processes
- ☒ Computationally expensive

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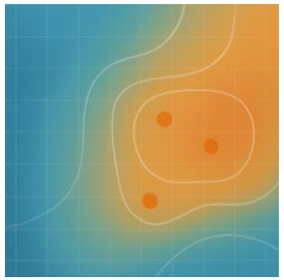
Statistical Techniques



Sampling
Selection
Interpolation

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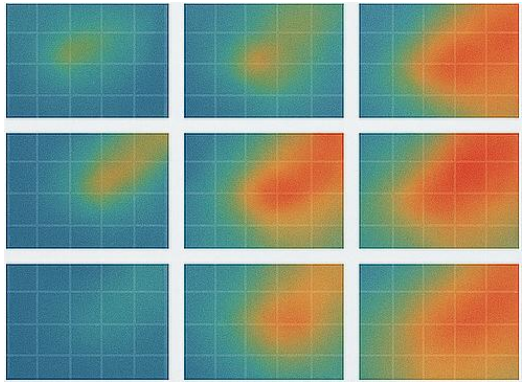
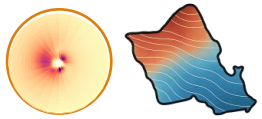
Hybrid Downscaling



- ☑ Accuracy comparable to dynamic models
- ☑ Fast and efficient

Downscaling of Wave & Water Level Climate

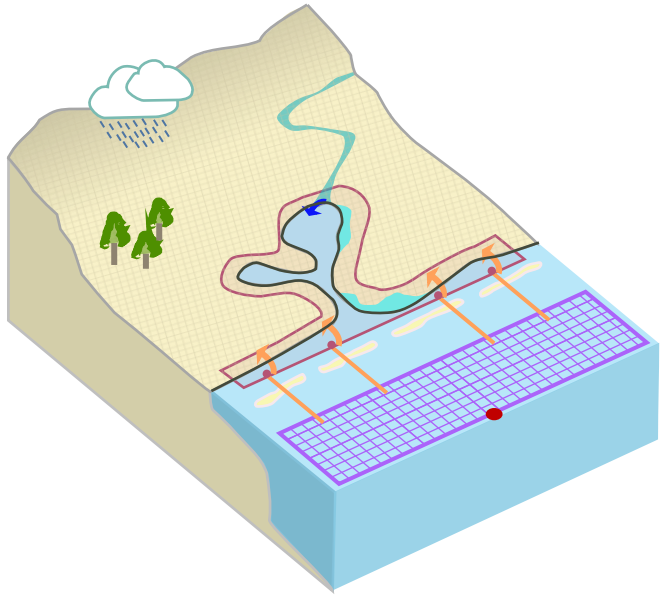
Application to Southern O'ahu



INPUT
Offshore Wave Spectra
Rainfall

CONVEX
(N=1,000,000)
MDA (M=10,000)

SAMPLE GENERATION



NUMERICAL MODELING

Offshore Waves

BinWaves
(Cagigal et al,. 2024)
Nearshore Wave Spectra

AT SS

HySwash *(Ricondo et al., 2024)*
IG energy
Mean Wave Setup

Filter reflected IG

SFINCS-GPU *(Leijnse et al,. 2021)*
Inland Water Depths

Rainfall

SURROGATE PREDICTION

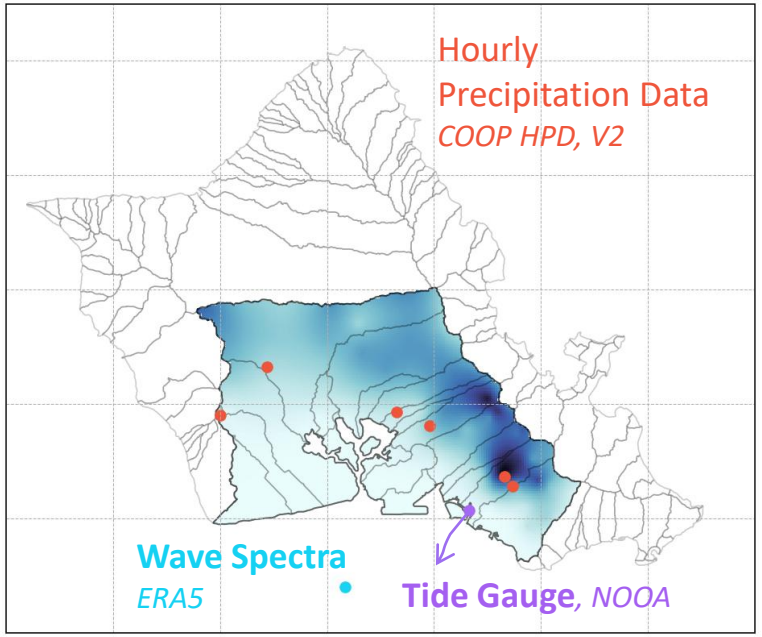
Random Forest (RF)
Radial Basis Functions (RBF)

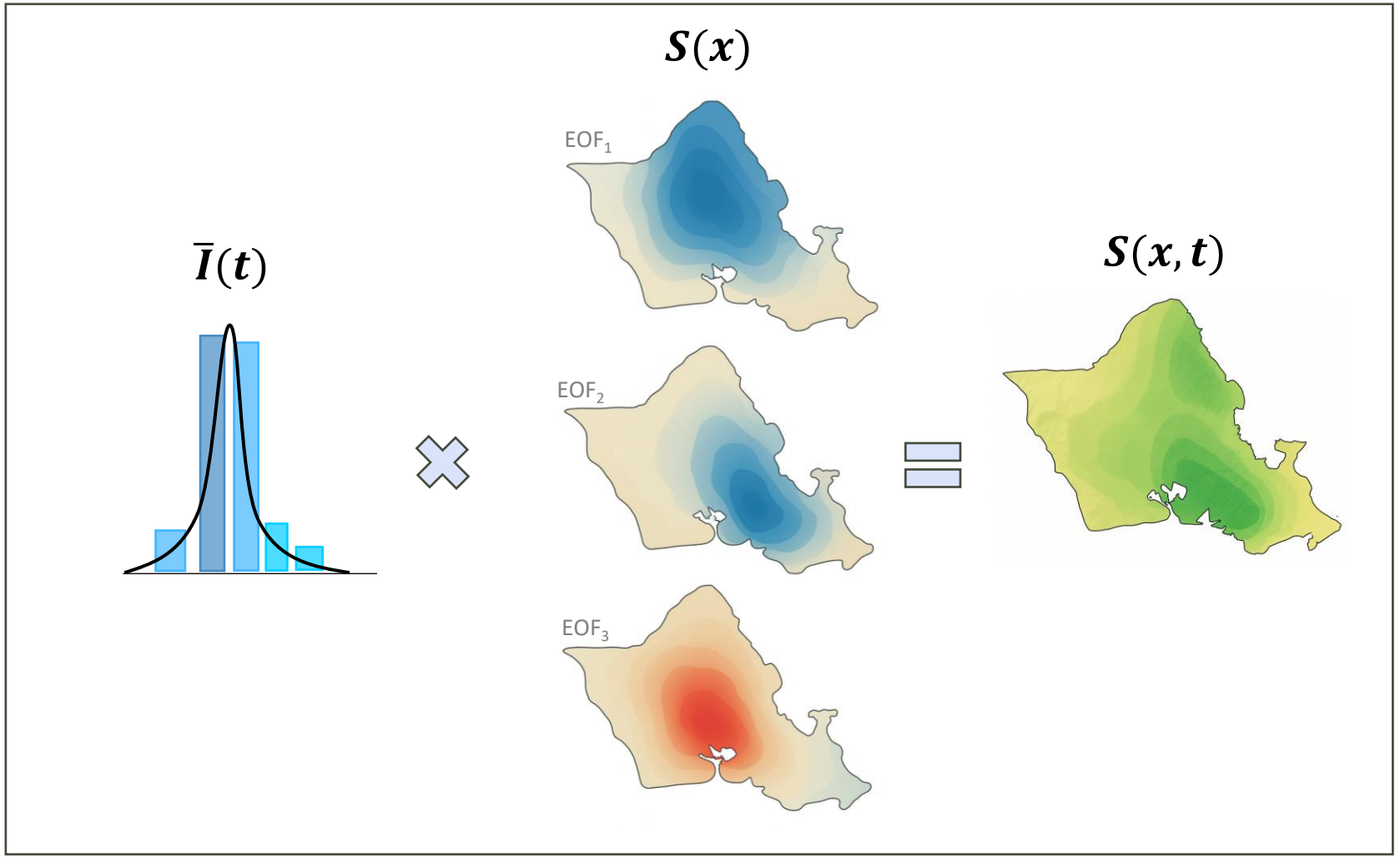
OUTPUT
Inland Water Depths

Characterizing Storm Evolution through Spatial-Temporal Modes

Pozo et al., 2024, 2025

Data Sources





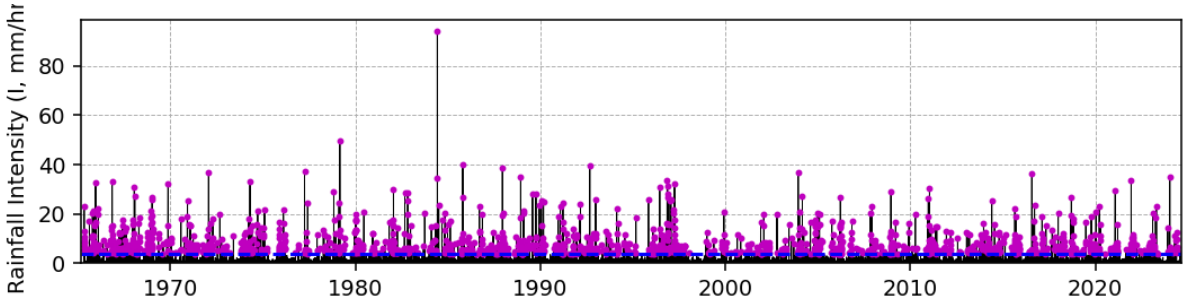
HyFlood: **Parameterization of Compound Events**

Characterizing Storm Evolution through Spatial-Temporal Modes

Pozo et al., 2024, 2025

TEMPORAL → $\bar{I}(t)$

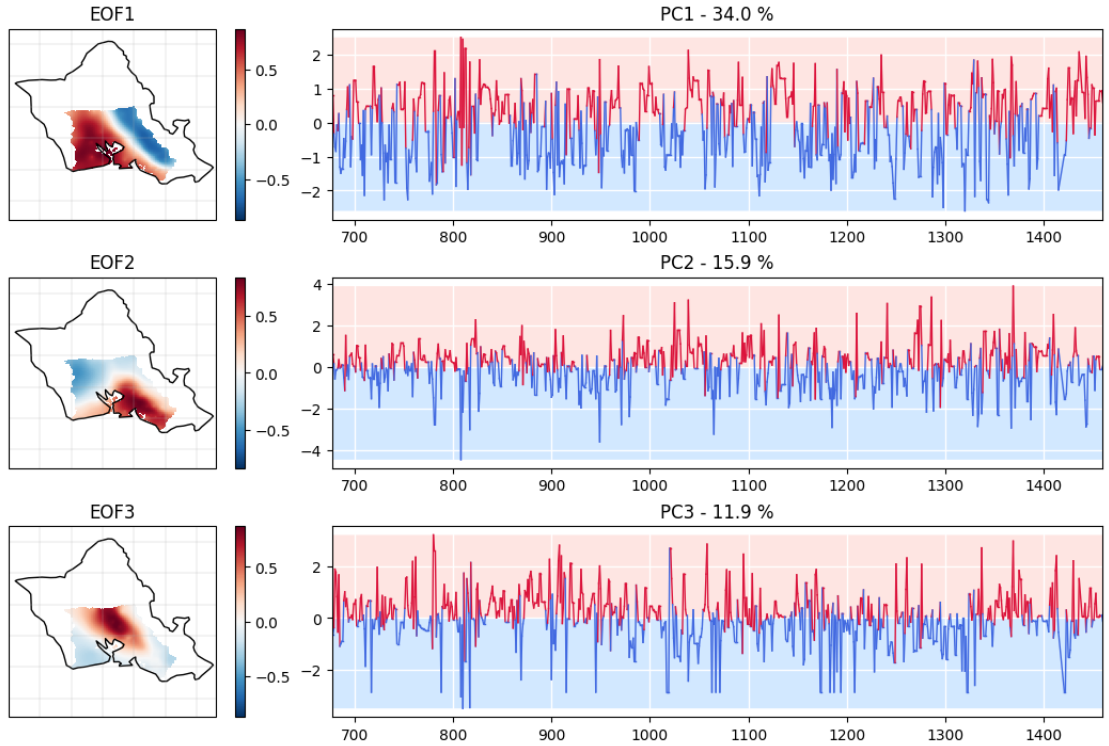
Peak Over Threshold
(POT)
Hourly Rainfall



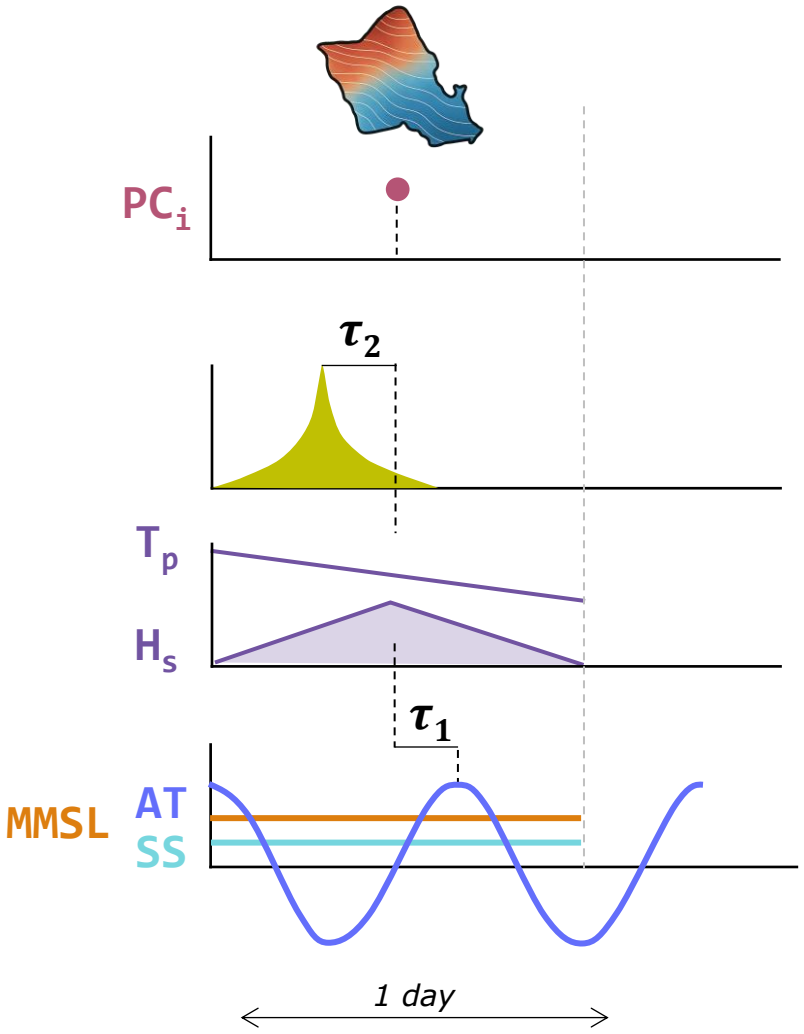
$$I(x_i, t) = \bar{I}(t) \cdot S(xi)$$

SPATIAL → $S(xi)$

Principal Component
Analysis
(PCA)
Daily Rainfall



HyFlood: **Daily Parameterization of Compound Flood Drivers**



Oceanic Drivers

- MMSL: Monthly Mean sea level
- AT-TR: Tidal range
- $SS_{\{min,max\}}$: Storm surge
- $H_{s\ \{min,max\}}$: Significant wave height
- $T_{p\{min,max\}}$: Peak Period
- Dp: Peak Direction

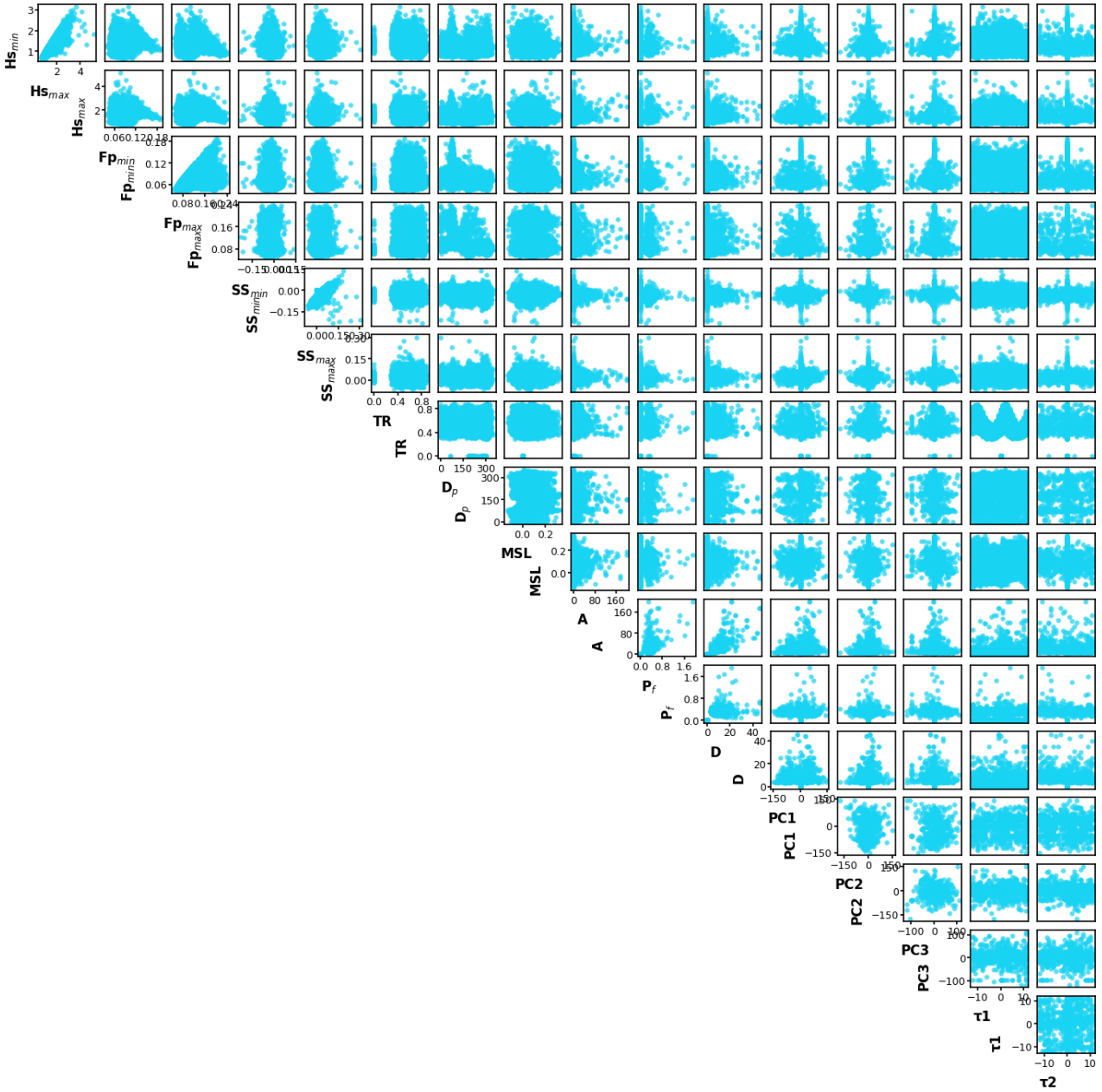
Precipitation Drivers

- D: Duration
- A: Area
- Pf: Peak Factor
- $PC_{\{1\ldots3\}}$: Principal Component Mode
- τ_1: Time Lag between peak Hs and peak AT
- τ_2: Time Lag between peak Hs and peak Rainfall

17
Dimensions

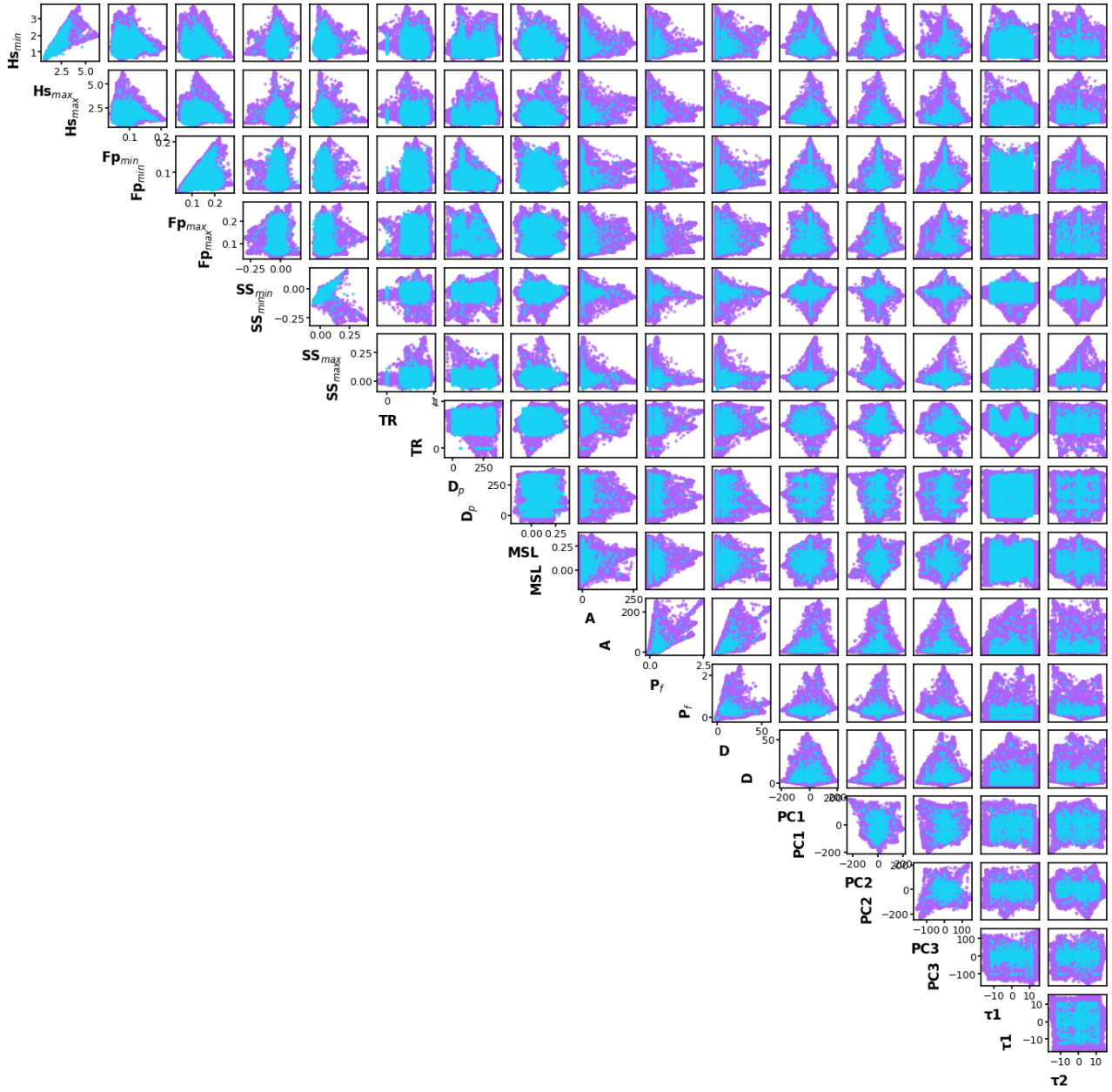
HyFlood: **Sampling Compound Drivers**

- Historical Parameter Space



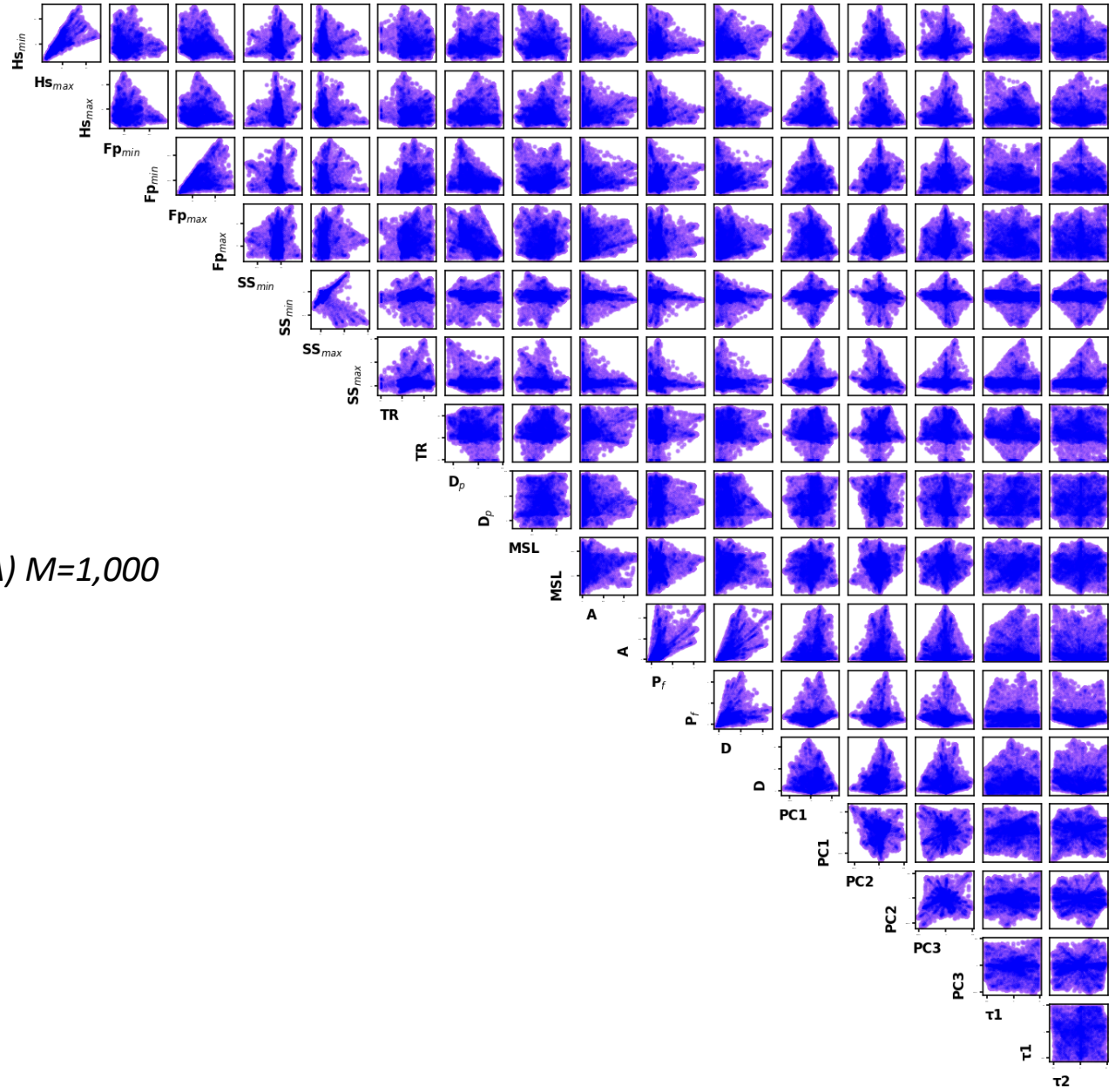
HyFlood: **Sampling Compound Drivers**

- Historical Parameter Space
- Synthetic Samples
  Convex Sampling N=10,000

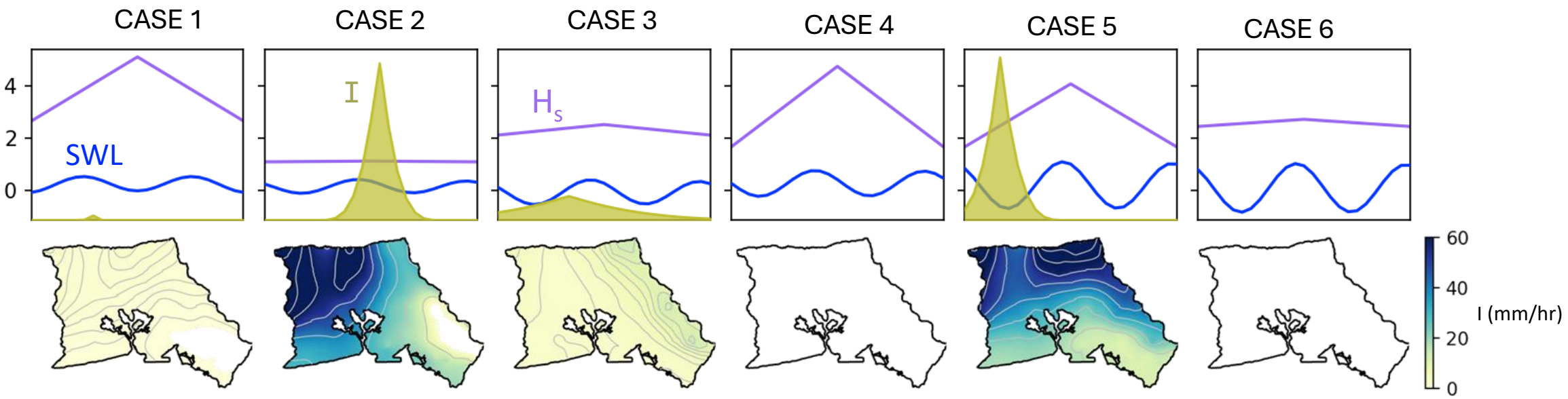


HyFlood: **Selecting Representative Events**

- Historical Parameter Space
- Synthetic Samples
  Convex Sampling N=10,000
- Selection Algorithm
  Maximum Dissimilarity Algorithm (MDA) M=1,000
- Representative Events



HyFlood: **Library of Compound Flooding Scenarios**

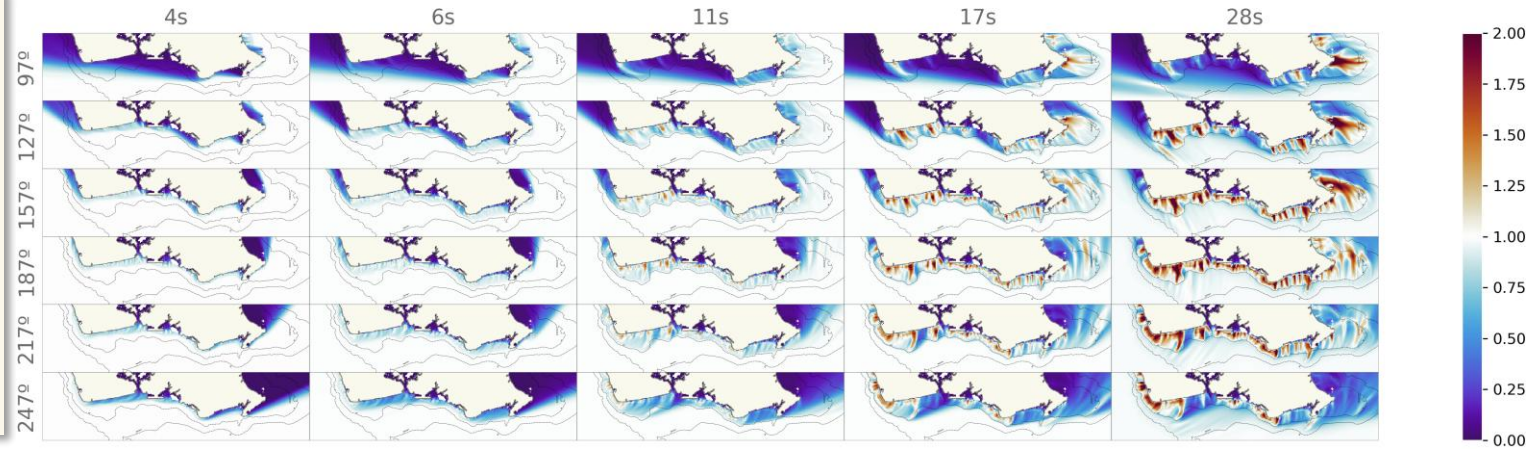


BinWaves: **From Offshore to Nearshore Waves**

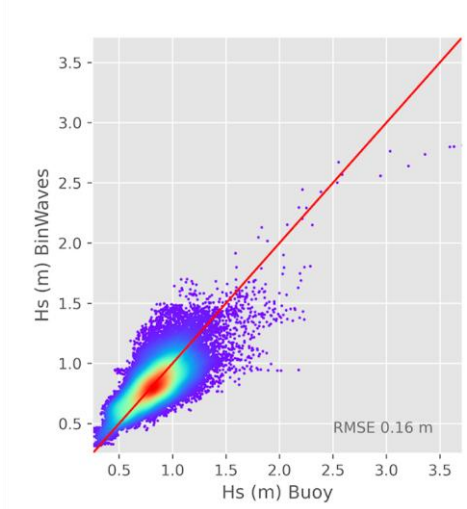
BinWaves (Cagigal et al., 2024)

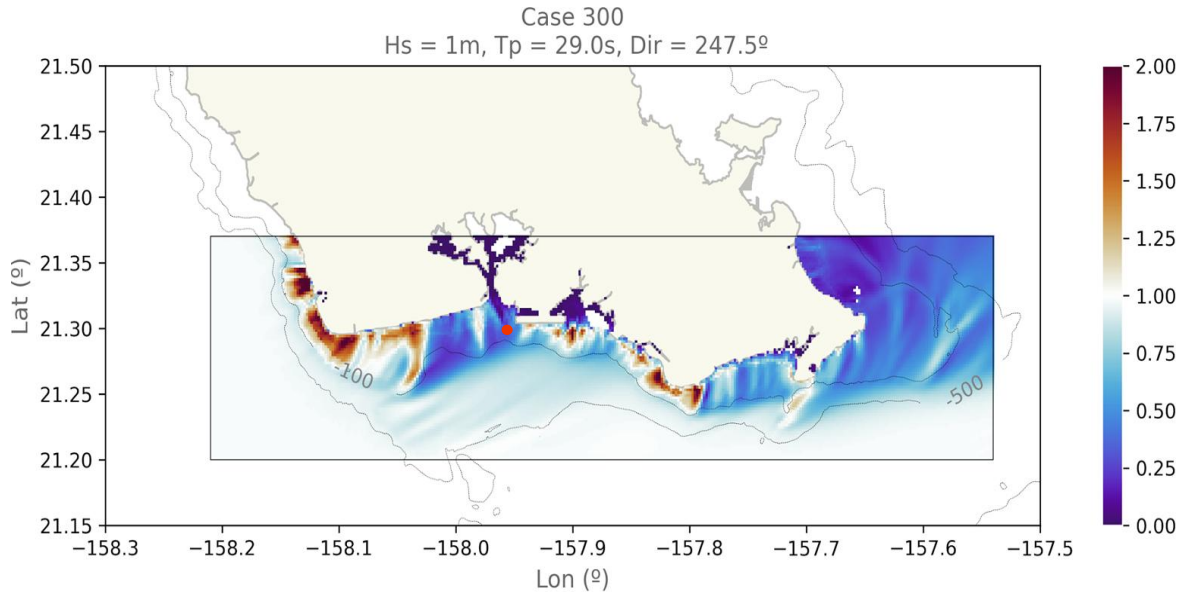
Solve: Nearshore wave propagation
Spatial Scale: ~ 200 m
Model: SWAN Stationary (*Booij et al., 1999*)
Input: Offshore Wave Spectra
Output: **Nearshore Wave Spectra**

Library of Monochromatic SWAN Cases



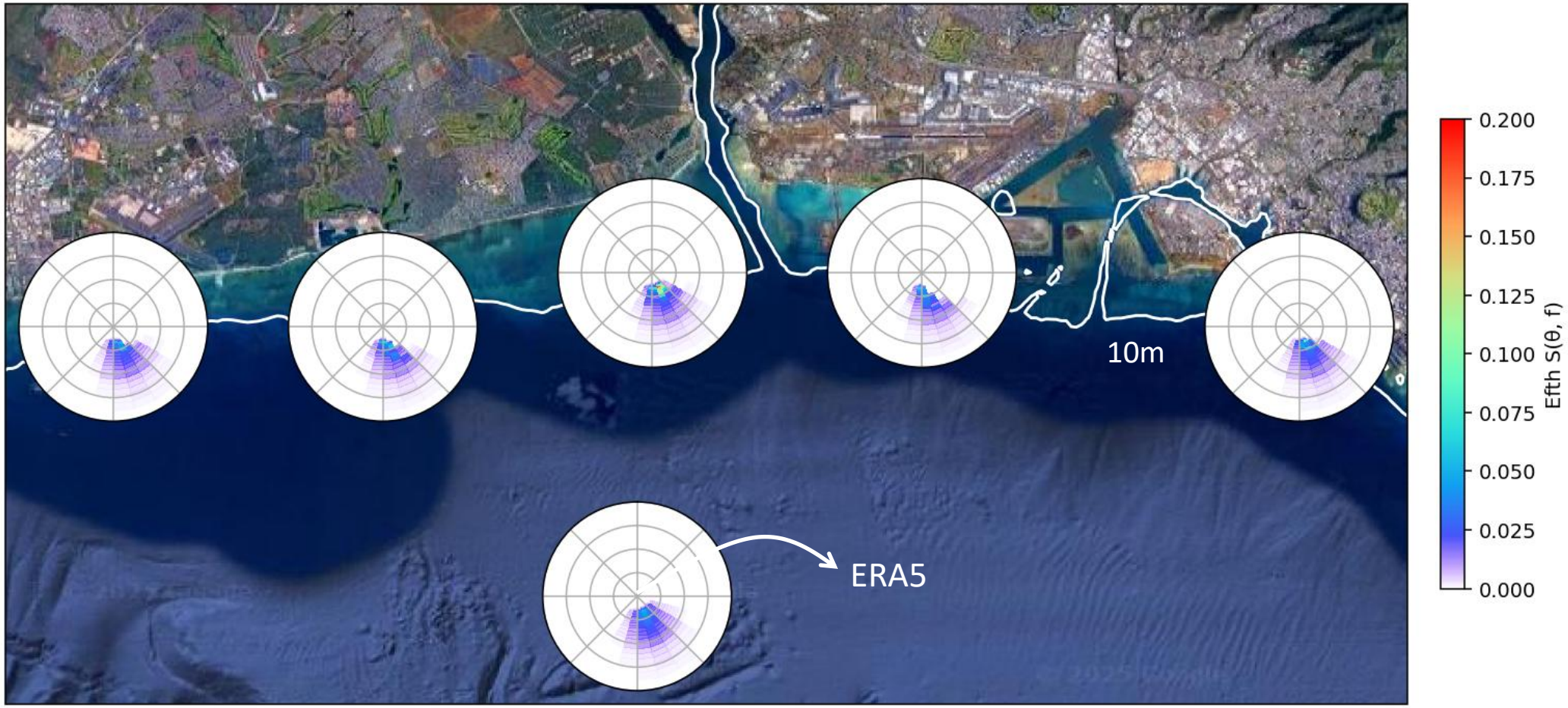
Validation with Pearl Harbor Wave Buoy





BinWaves: **From Offshore to Nearshore Waves**

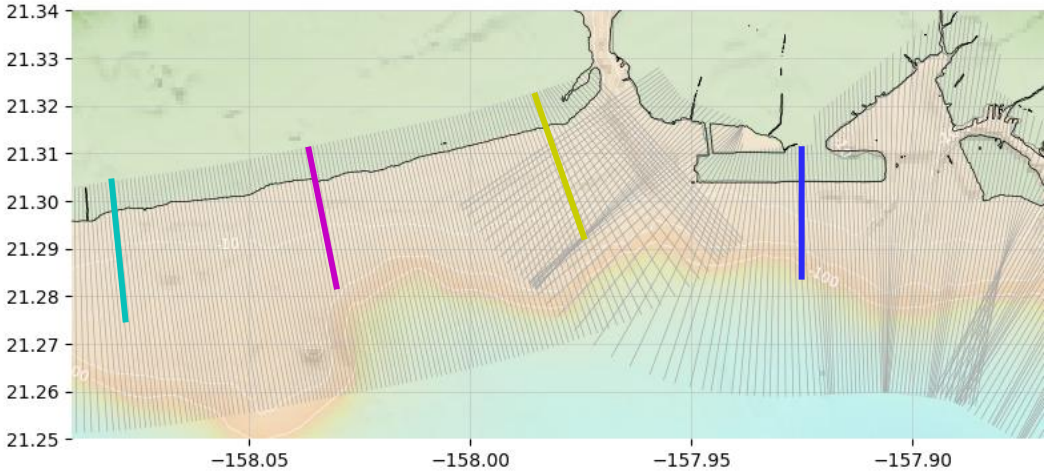
CASE 1

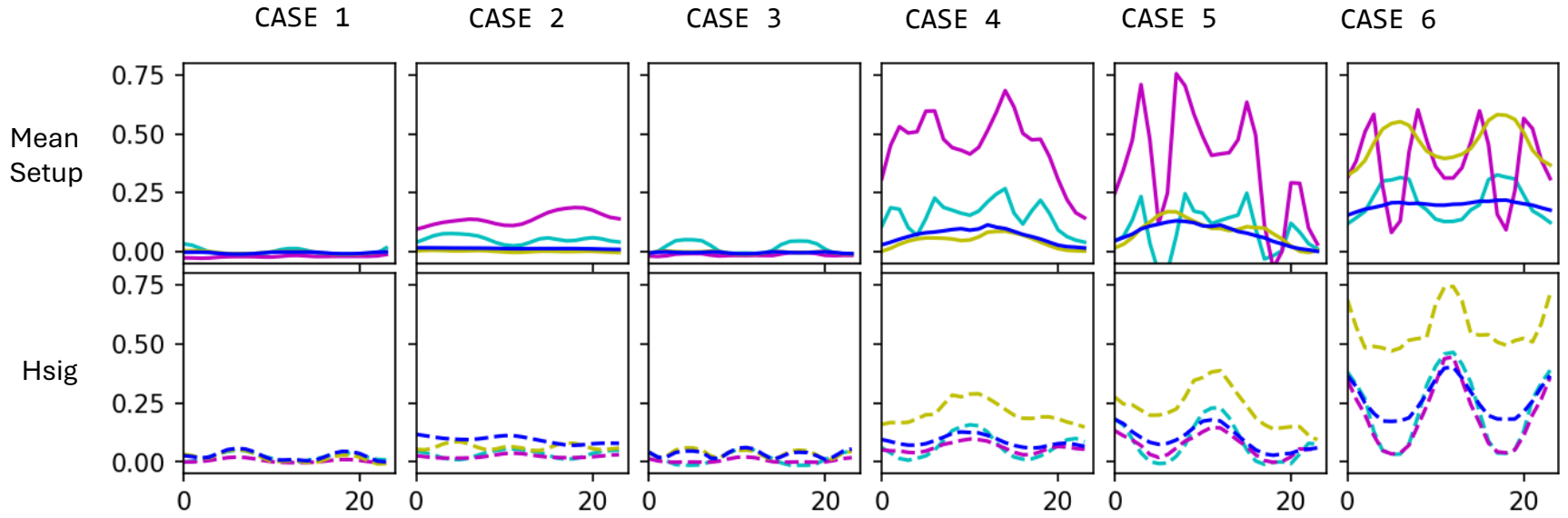


HySwash: **Modeling Surf-Zone Hydrodynamics**

HySwash (Ricondo et al., 2024a, 2024b)

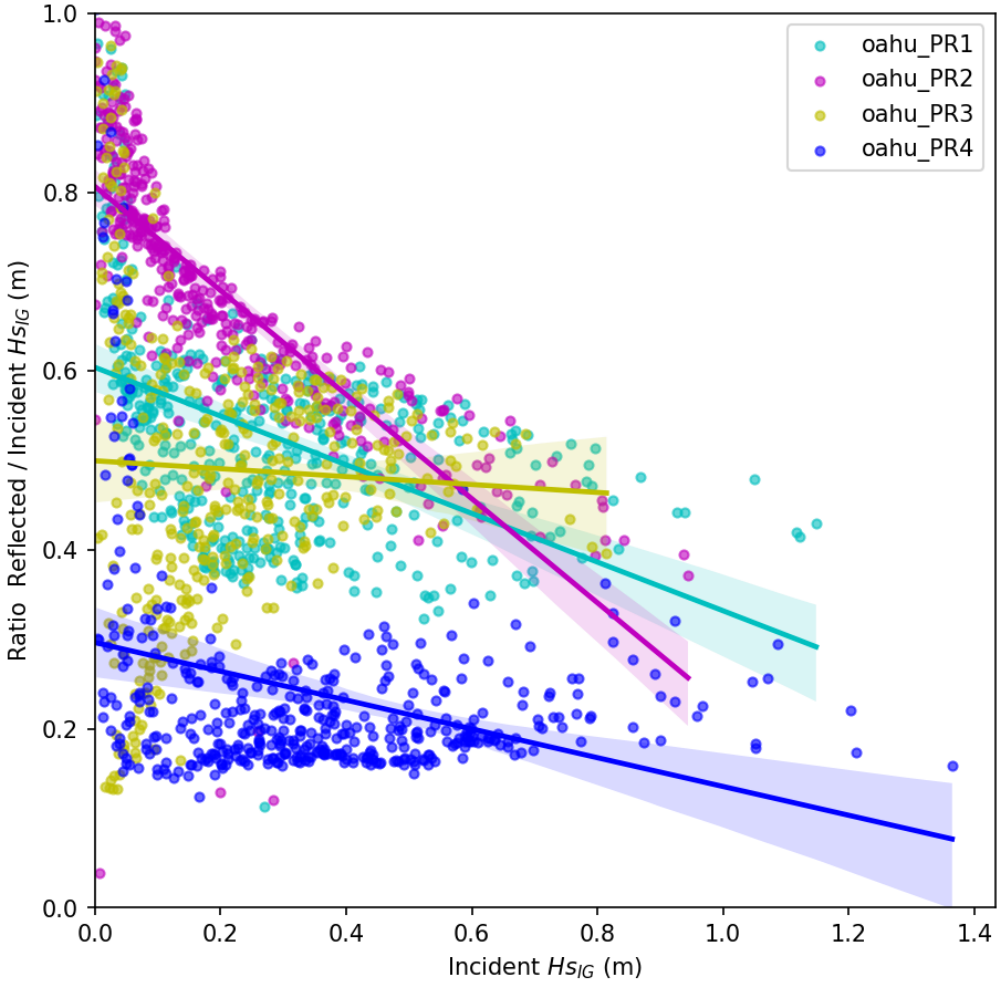
Solve: Surf-zone hydrodynamics along cross-shore profiles
Spatial Scale: ~ 1 m
Model: SWASH 1D (*Zijlema et al., 2011*)
Input: Water surface elevation at 10 m depth
Output: **Mean Setup and IG energy at -1.5 m depth**

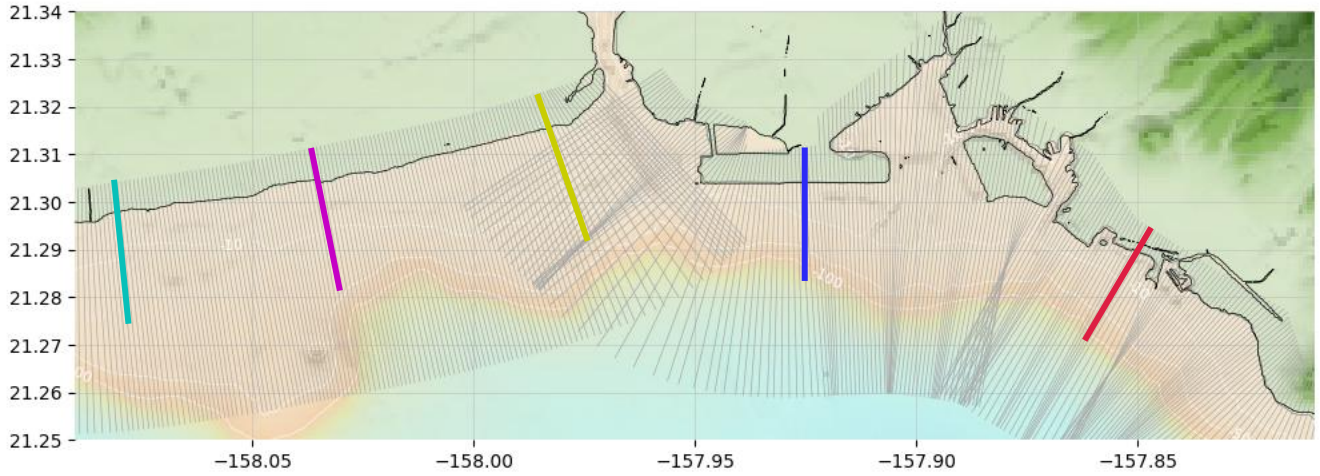


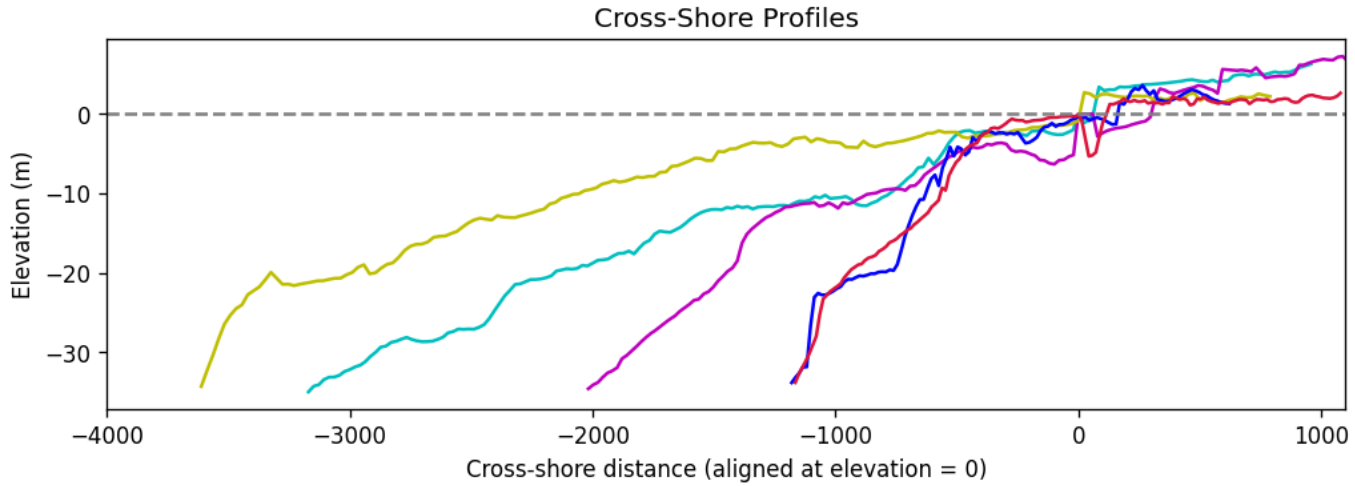


Modeling Surf-Zone Hydrodynamics

Subtracting the Reflected IG Component



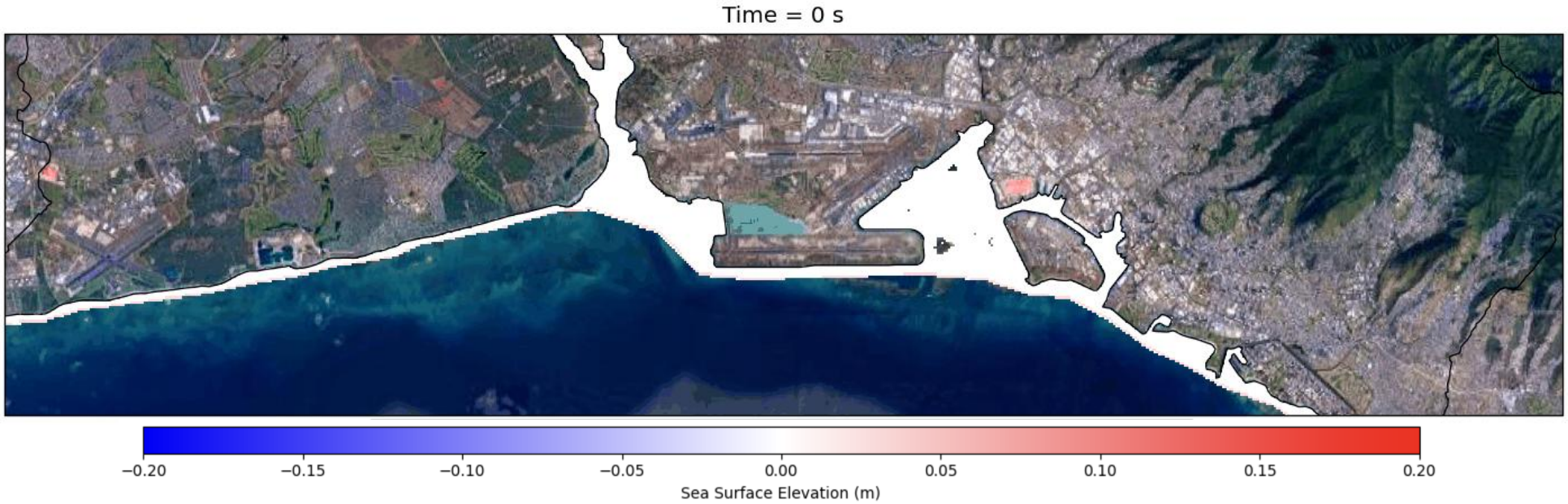




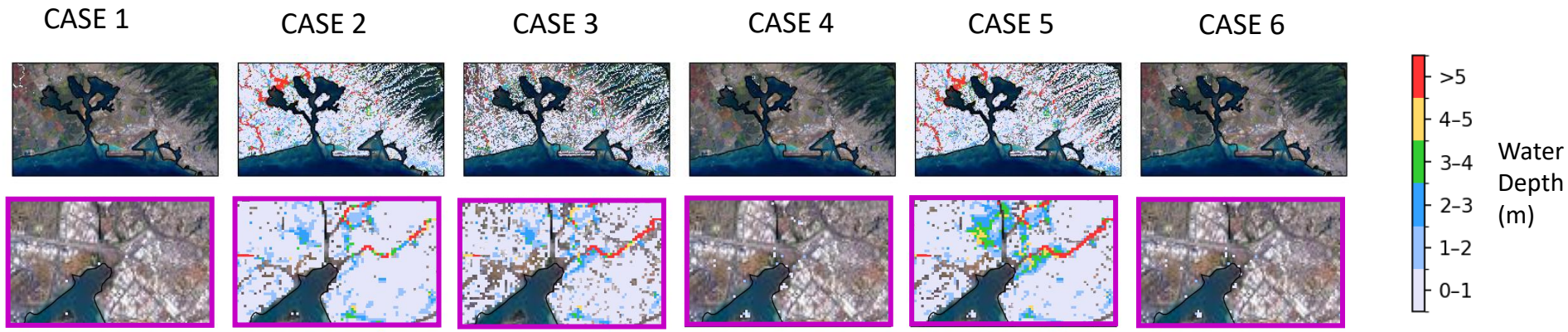
HyFlood: **Modeling Compound Flooding**

SFINCS-GPU

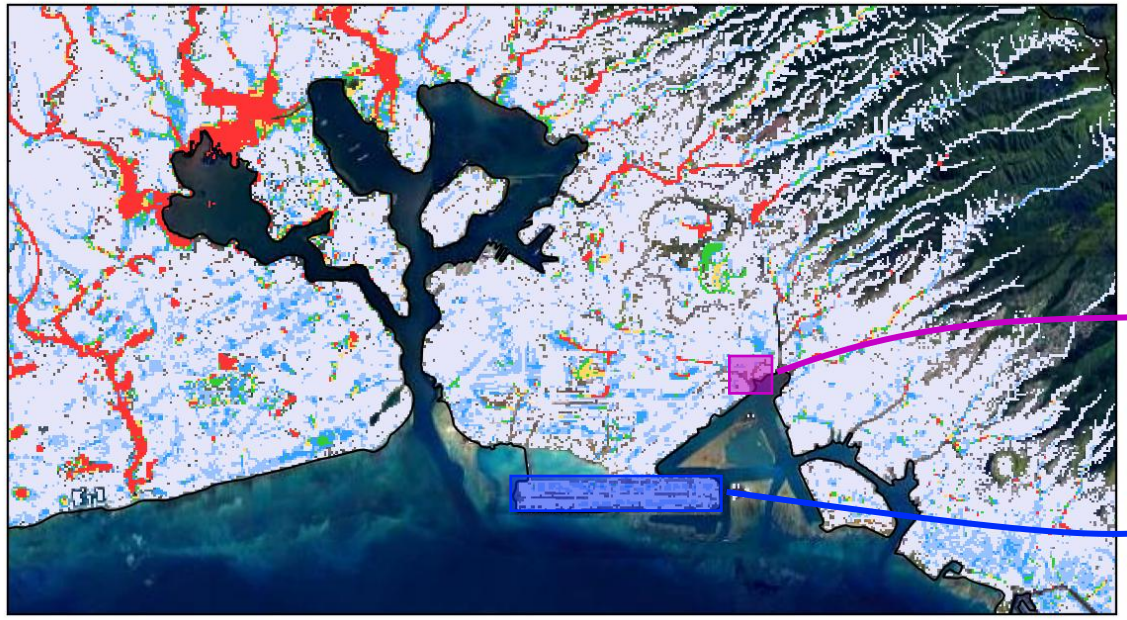
Solve: Surf-zone hydrodynamics along cross-shore profiles
Spatial Scale: ~ 10 m
Model: SFINCS-GPU *(Leijnse, T., et al 2021)*
Input: Slowly-varying Mean Setup
Varying IG (200s period)
Precipitation
Output: **Maximum Water Depth**



HyFlood: **SINFCS-modeled Flood Extents**

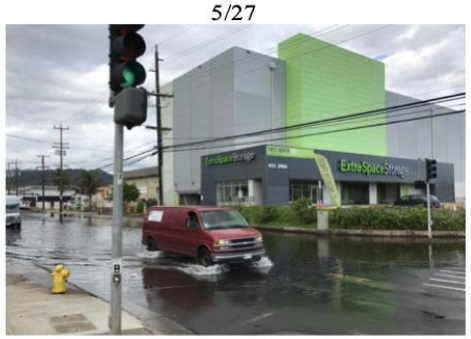


Zoom to CASE 5



Defining Proxies for Inundation
Proxy = max water depth

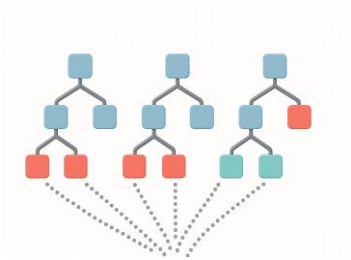
Runway



Mapunapuna, Honolulu

HyFlood: **Reconstructing Flood Proxies**

Training the Surrogate Prediction

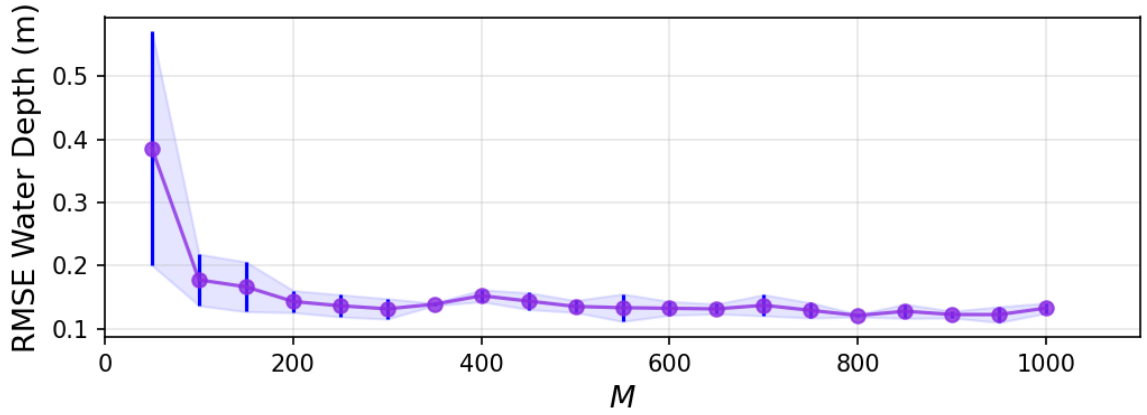


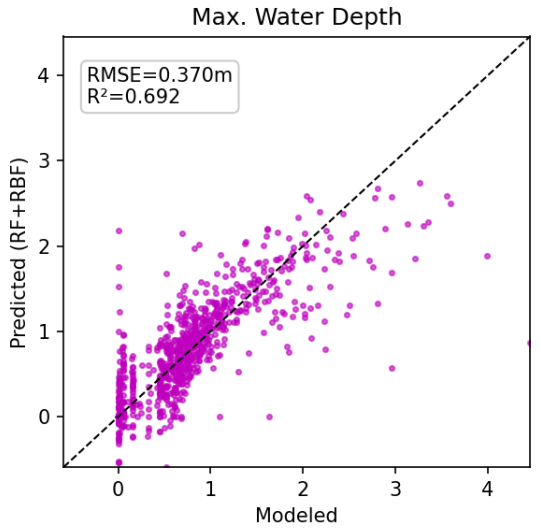
Dry-wet Prediction with
Random Forest

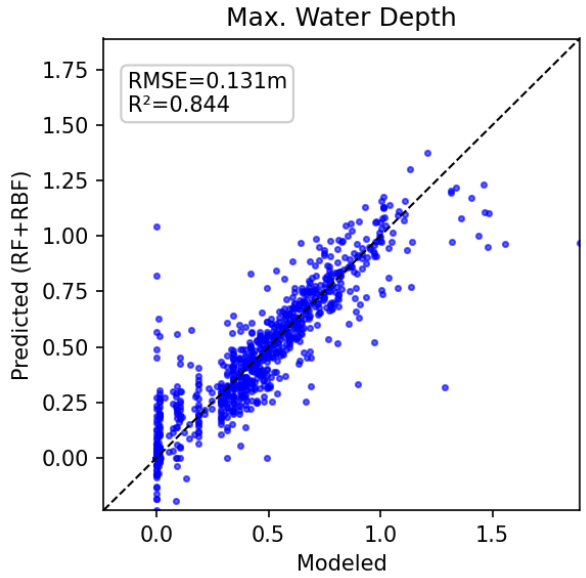
NO

YES → Data Interpolation with
Radial Basis Functions
RBF

K-fold Cross Validation K = 5







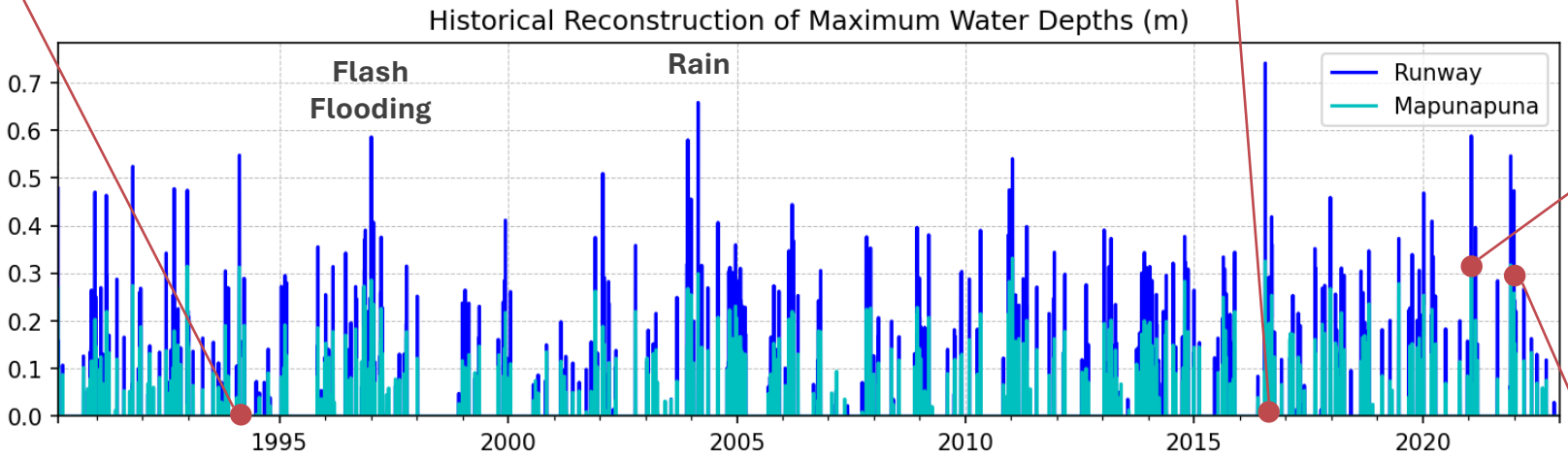
HyFlood: **Reconstructing Flood Proxies**

Historical Reconstruction of Inundation Proxies

TC Iniki, Sept 1992

Tropical Storm Darby, Jul 2016

Heavy Rains, Jan 2021



Rain, Dec 2021

Thank you!

Alba Ricondo
alba.ricondo@oregonstate.edu

ONR MURI | Sea-Level Rise in the Indo-Pacific Region: Building a Framework for Interdependent Resilience

ESTCP | Defense Regional Sea Level (DRSL) Database Transformation and Update

BlueMath

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Historical Drivers of Compound Flooding