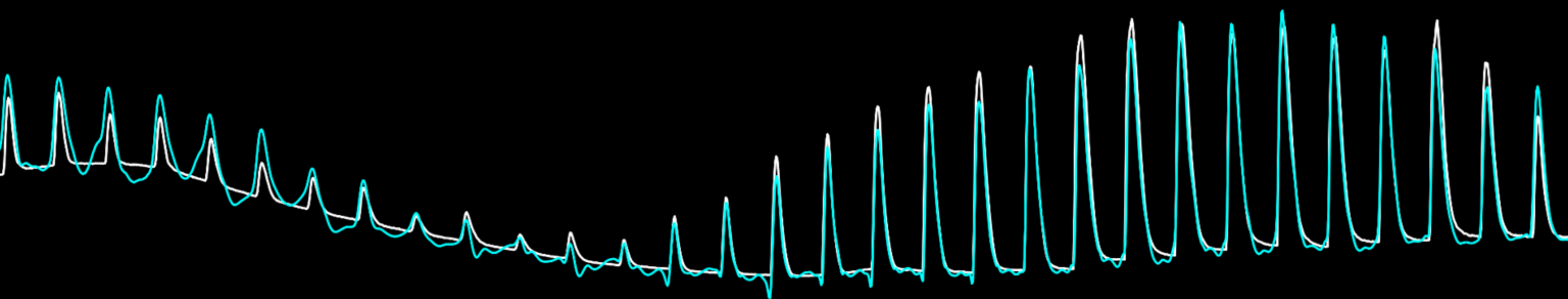
Global Operational storm surge forecasting in ungauged regions with scientific machine learning

Thomas Monahan, Tianning Tang, Stephen Roberts, Thomas Adcock



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Eric and Wendy Schmidt
AI in Science Postdoctoral Fellowship,
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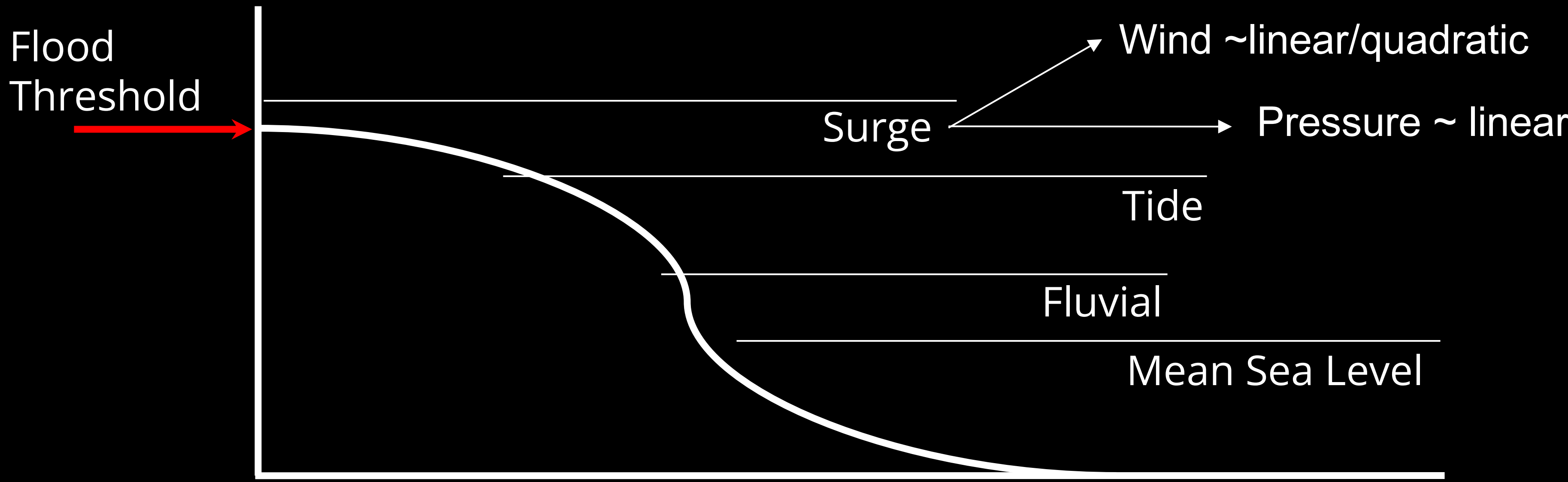
Objective: Predict the total sea level and human vulnerability—anywhere in the world, at any time.*

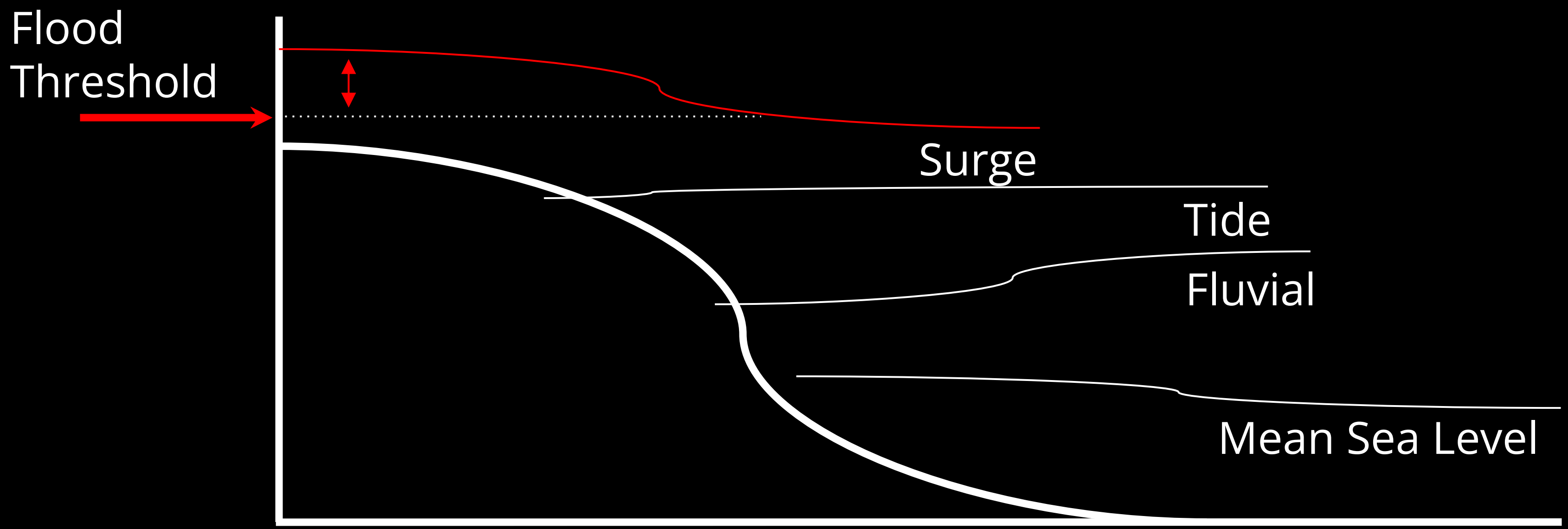
Basic Model:

Sea-Level = MSL + Fluvial + Tide + Surge

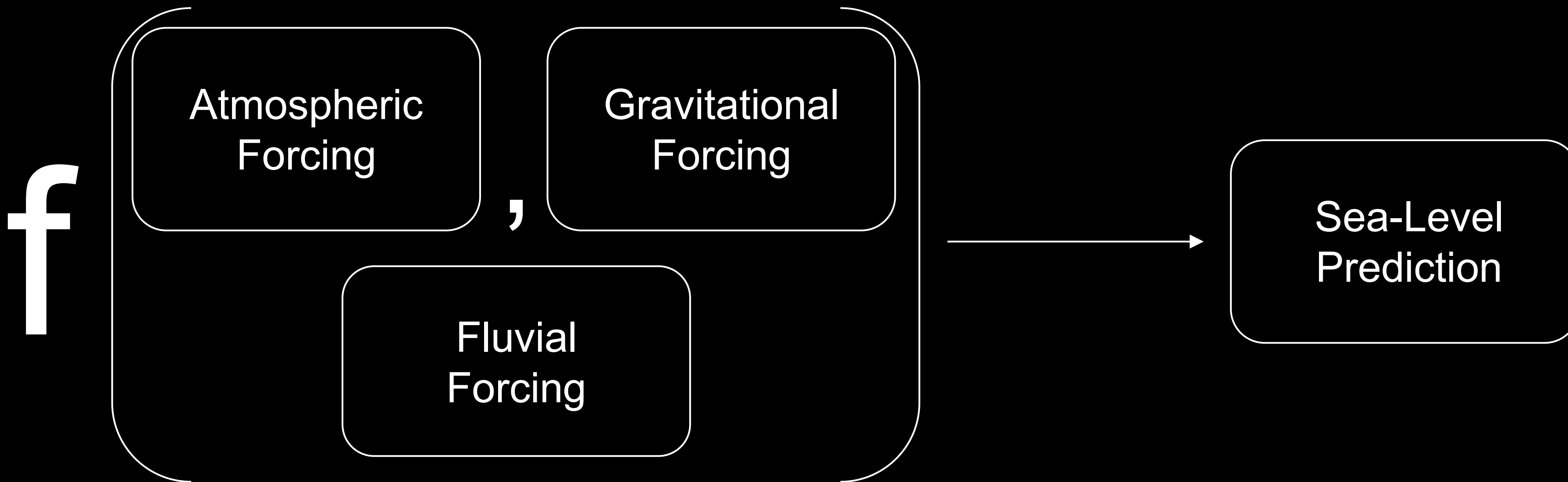


Correct Model:

Sea-Level = MSL + Fluvial + Tide + Surge + f(MSL,Fluvial,Tide,Surge)



Basic Problem



***Compound Sea-Level --** the total sea-level under multiple types of forcing.*

Numerical Modelling

Atmospheric Model

Oceanic Boundary Conditions

Observational Data??

Discretized Domain

Shallow Water Eqs

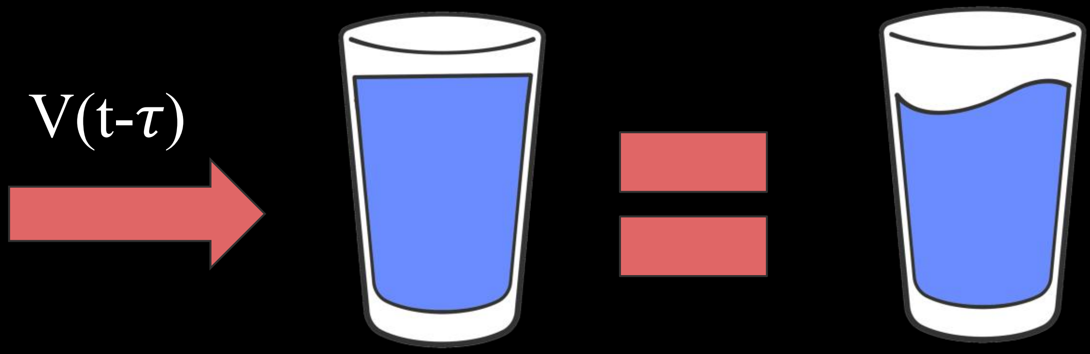
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} + \frac{\tau}{\rho_w h}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial (uh)}{\partial x} = -\frac{P - P_0}{\rho_w g}$$

$$\tau = \rho_a C_D u^2$$

Time Stepping

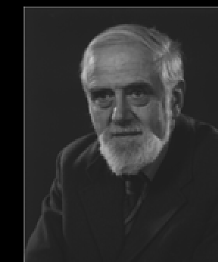
Impulse-Response Theory



TIDAL SPECTROSCOPY AND PREDICTION

By W. H. MUNK† and D. E. CARTWRIGHT‡
Institute of Geophysics and Planetary Physics, University of California, La Jolla

(*Communicated by Sir Edward Bullard, F.R.S.—Received* 21 *June* 1965)



Key Observations:

- Oceanic response to forcing is ***time-invariant*** and ***weakly nonlinear***.
- Can be completely described by a finite set of past, present values of the tidal input potential.
- Tidal input potential is readily computed using Kepler-Newtonian mechanics.

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Impulse-Response

$$\hat{\zeta}(t) = \sum_{m,n} \sum_{s} [u_n^m(s) a_n^m(t - \tau_s) + v_n^m(s) b_n^m(t - \tau_s)]$$

Volterra Series!

$\mathscr{R}(\hat{\zeta}) =$ predicted sea-level

$s =$ number of time-lags

$\tau =$ time-lag

$w = u + iv =$ response weights

$c_n^m(t) = a_n^m + ib_n^m =$ input potential

$n, m =$ spherical harmonic degree and order

Nonlinear Responses

$$x^{th} \text{order response} = \sum_i \cdots \sum_x \sum_s \cdots \sum_{s'} w(i, \ldots, x, s, \ldots, s')(c(t-\tau_s))(\ldots)(\ldots)(c(t-\tau_{s'}))$$

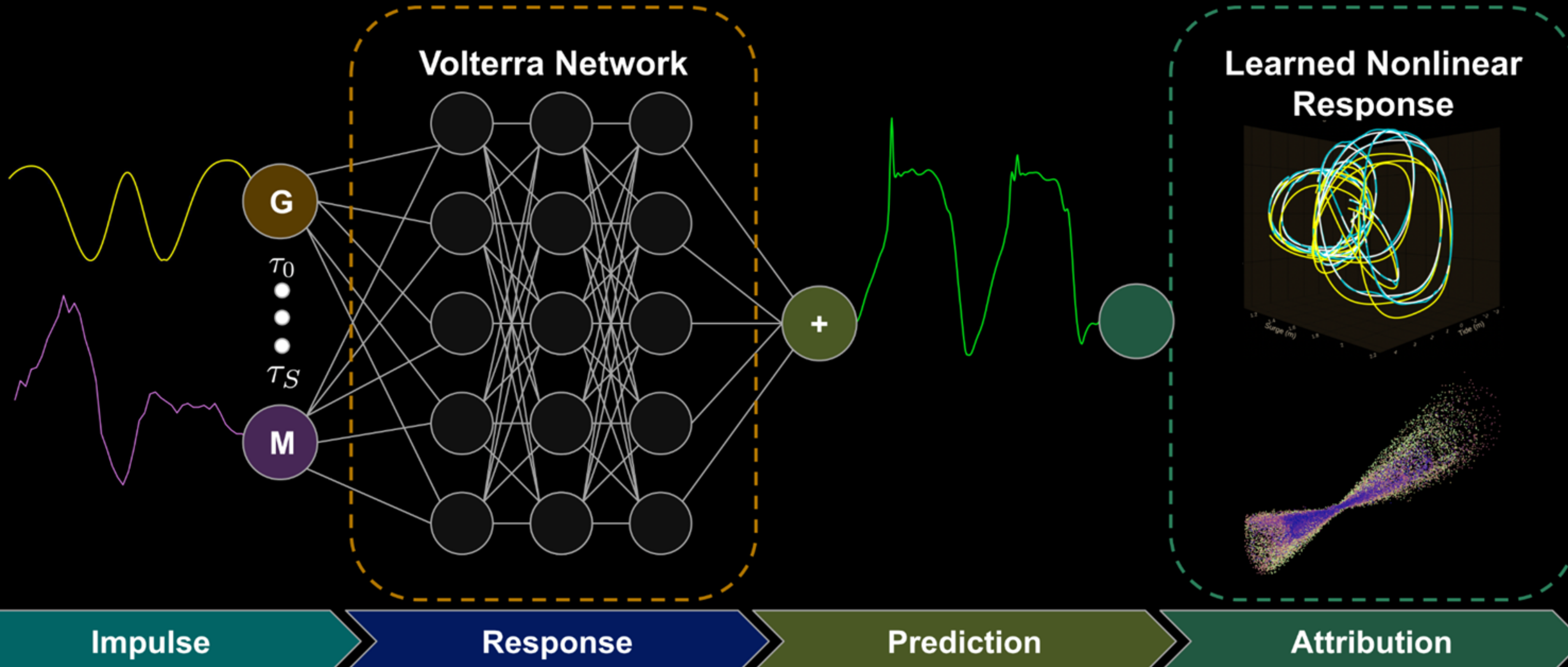
- Exponentially more terms as the “order” of nonlinear interactions increases.

Problem:

- In a conventional response analysis we must define these terms beforehand making the inference of higher order nonlinearities extremely challenging.
- This renders the automated application of the conventional method to strongly nonlinear tides and surges impossible.

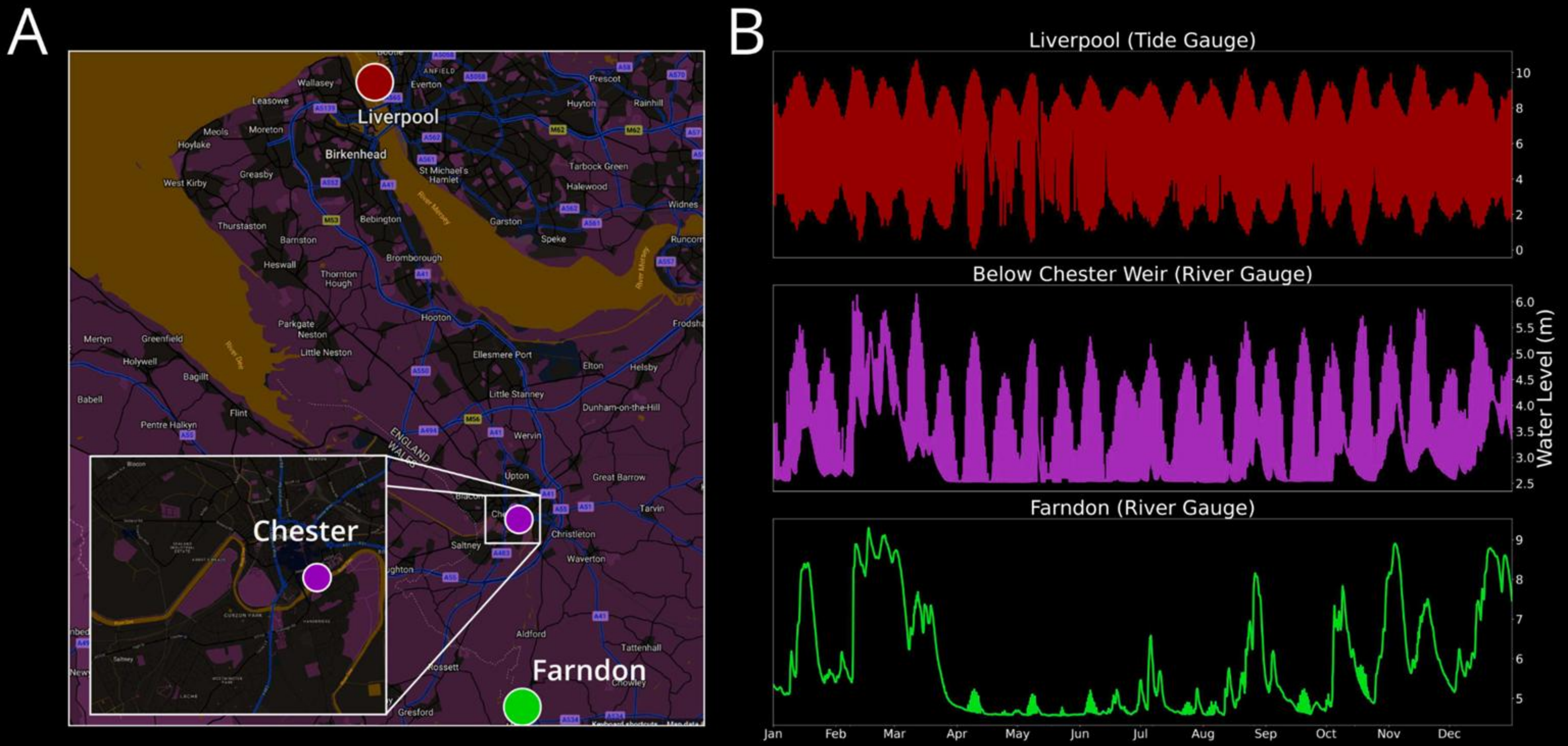
RTide

$$V_G, V_M \longrightarrow f(V_G, V_M) \longrightarrow \hat{\zeta}(t) \approx g = p_0 + \sum_{|F|} p_i^T$$



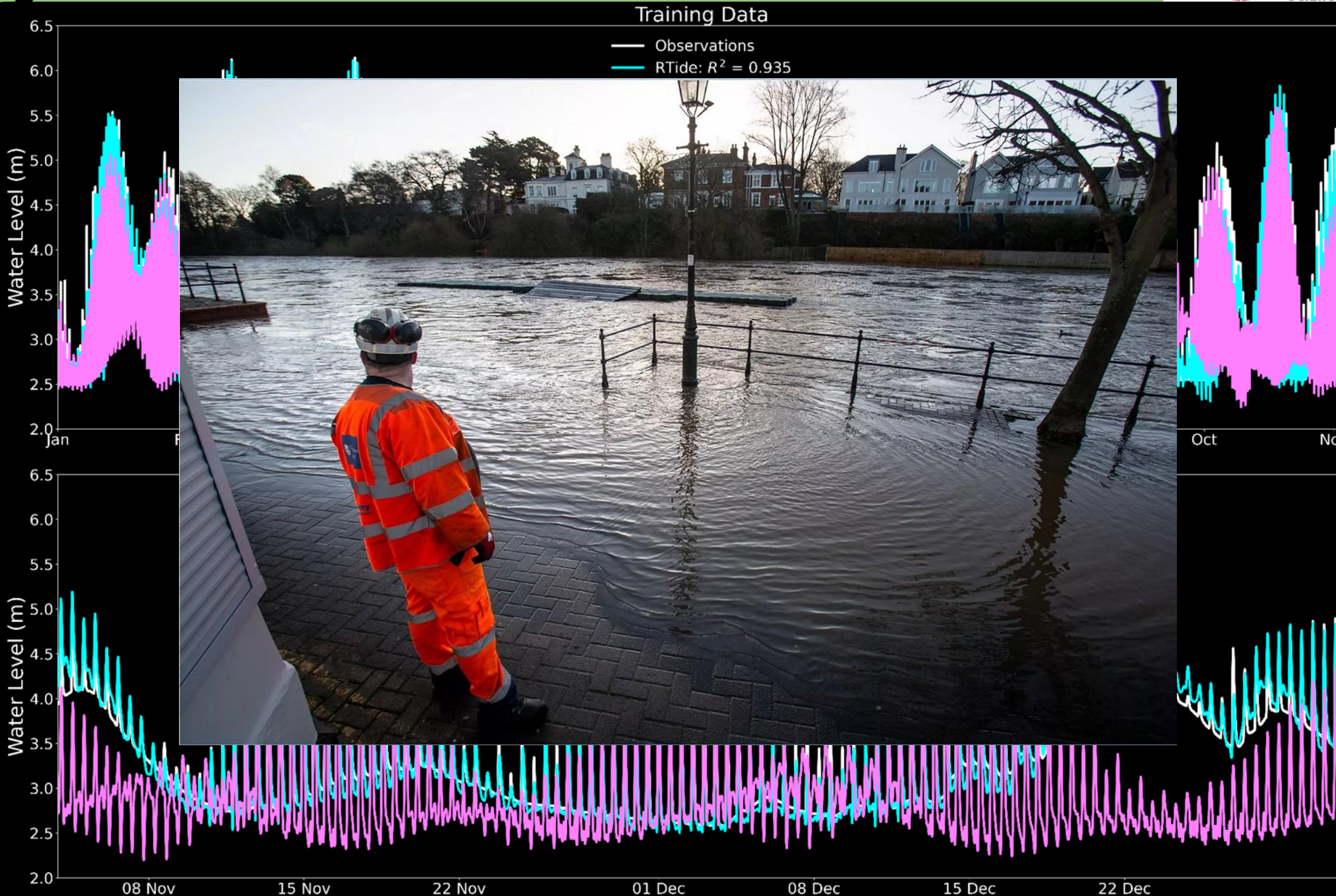
[1] Monahan et al. RTide: Automating the tidal response method (JGR: Machine learning and computation)

Tidal Rivers

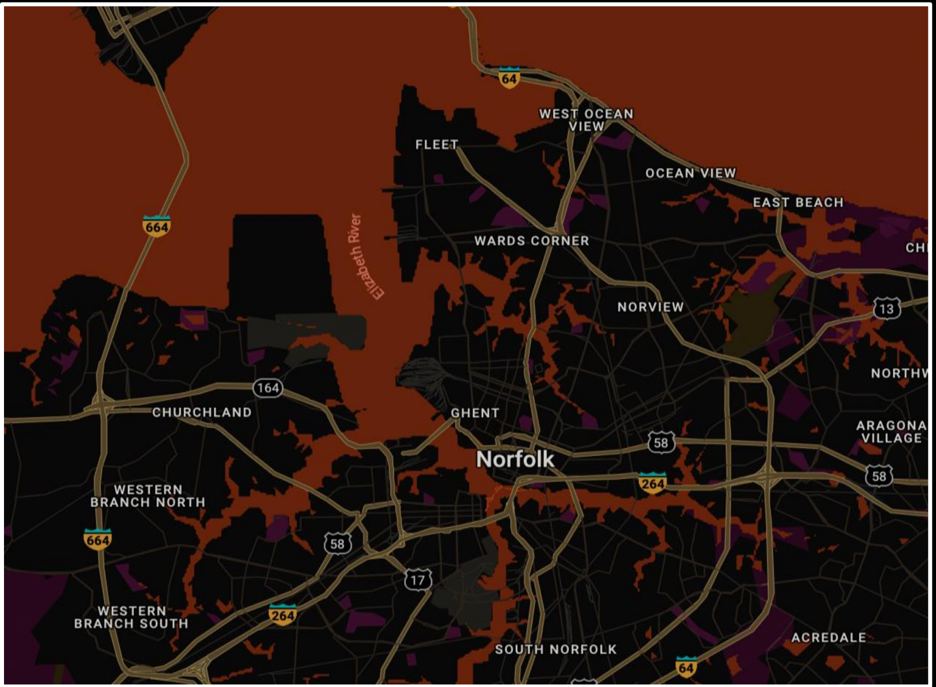


f(gravitational + fluvial)

1.8 Tidal Rivers



Meteorological Forcing



f(gravitational + meteorological)

1.10 Meteorological Forcing

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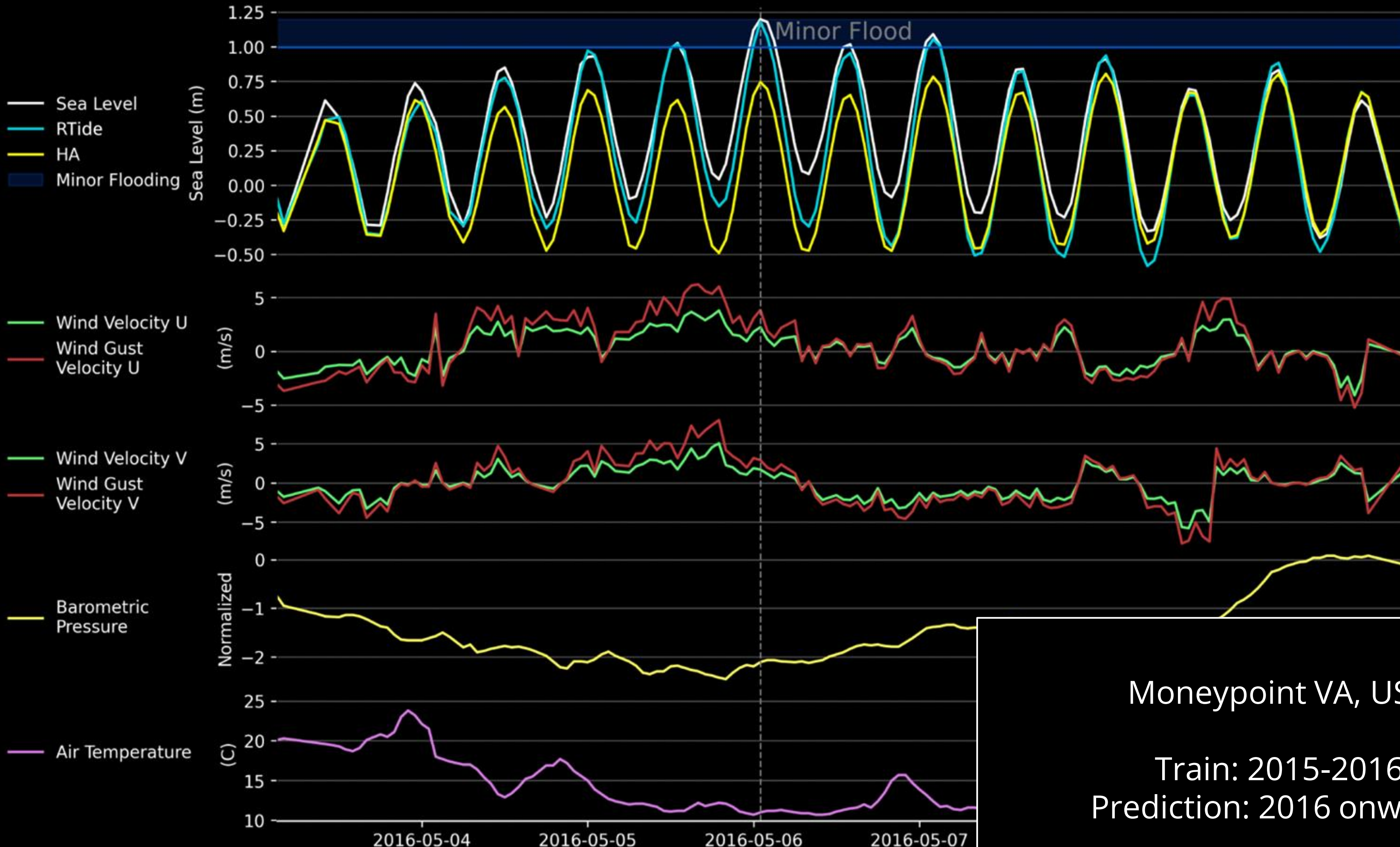
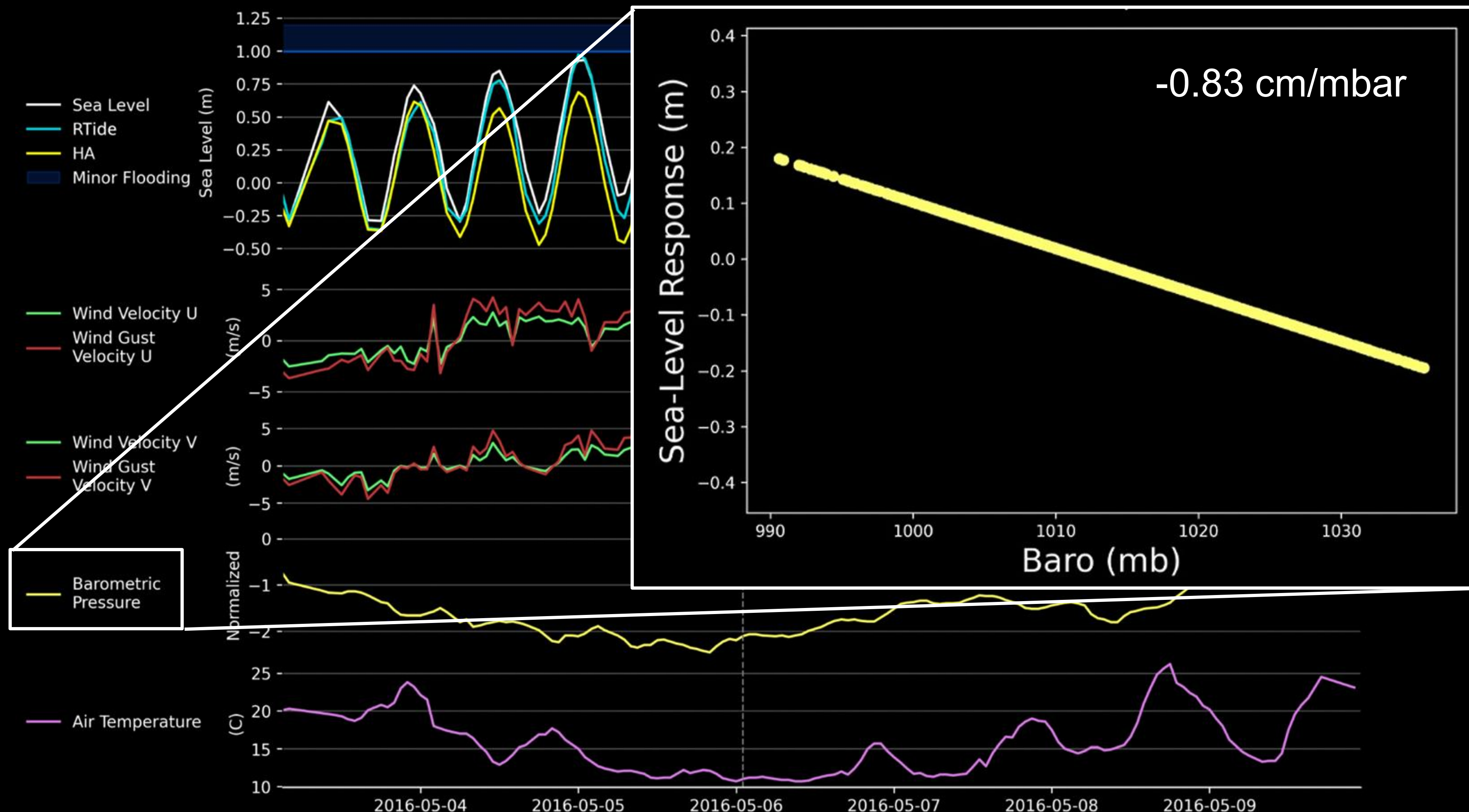
University of Oxford



Moneypoint VA, USA

Train: 2015-2016
Prediction: 2016 onwards

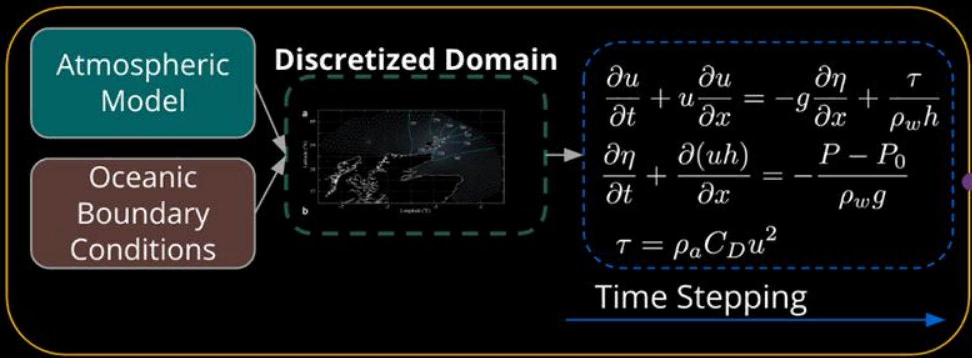
1.10 Meteorological Forcing



How can this be used *with* operational storm surge forecasts?

Operational Usage

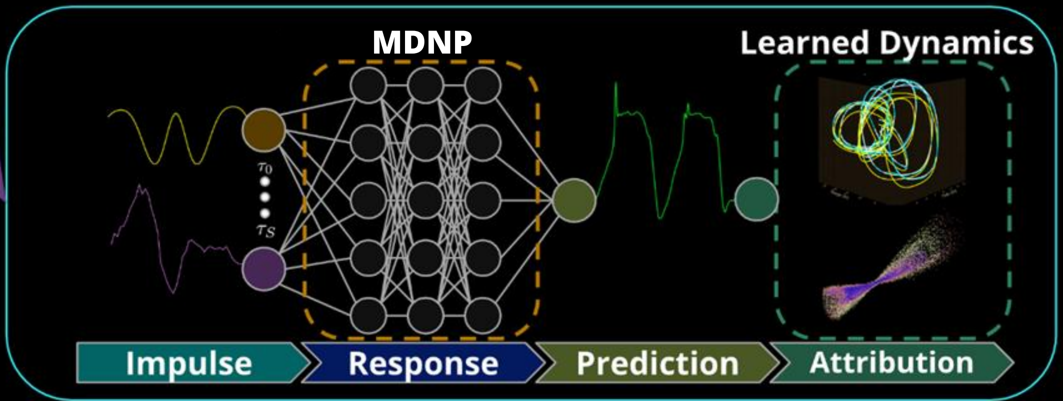
Numerical



- ✖ Resolution is limited by computational expense.
- ✖ Accuracy is dependent on boundary conditions, especially **bathymetry**.
- ✔ Great atmospheric surge
- ✖ Poor oceanic response.

RTide

- ✔ Learns response directly from data —> no need for bathymetry!
- ✔ Can capture localized nonlinearities.
- ✔ Provides insights into dynamics.
- ✖ **But**, cannot account for externally generated surges.



Operational Usage

Numerical

Atmospheric Model

Oceanic Boundary Conditions

Discretized Domain

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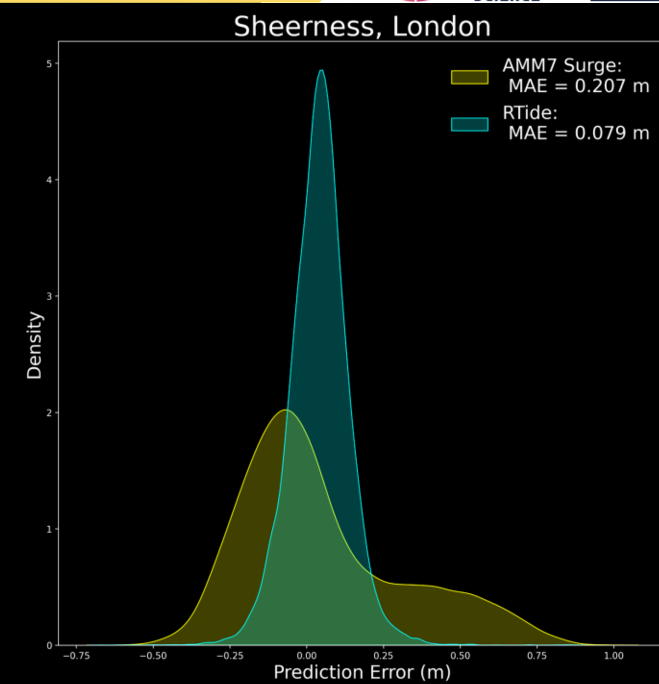
Time Stepping



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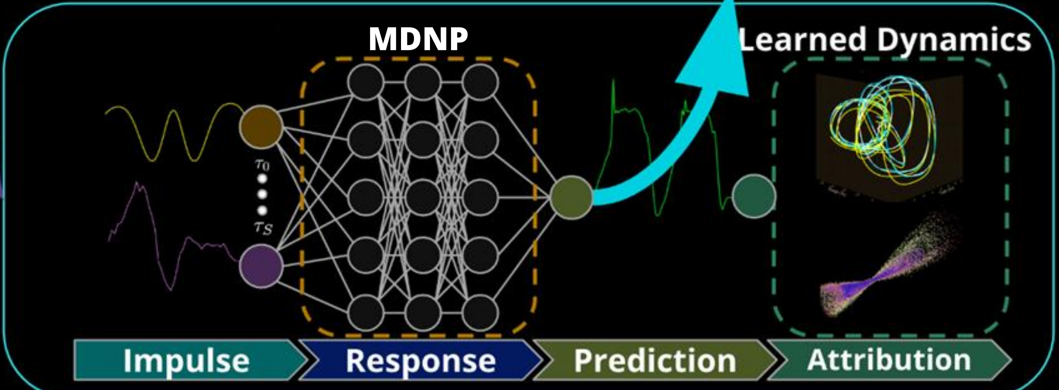

2.3 Operational Usage

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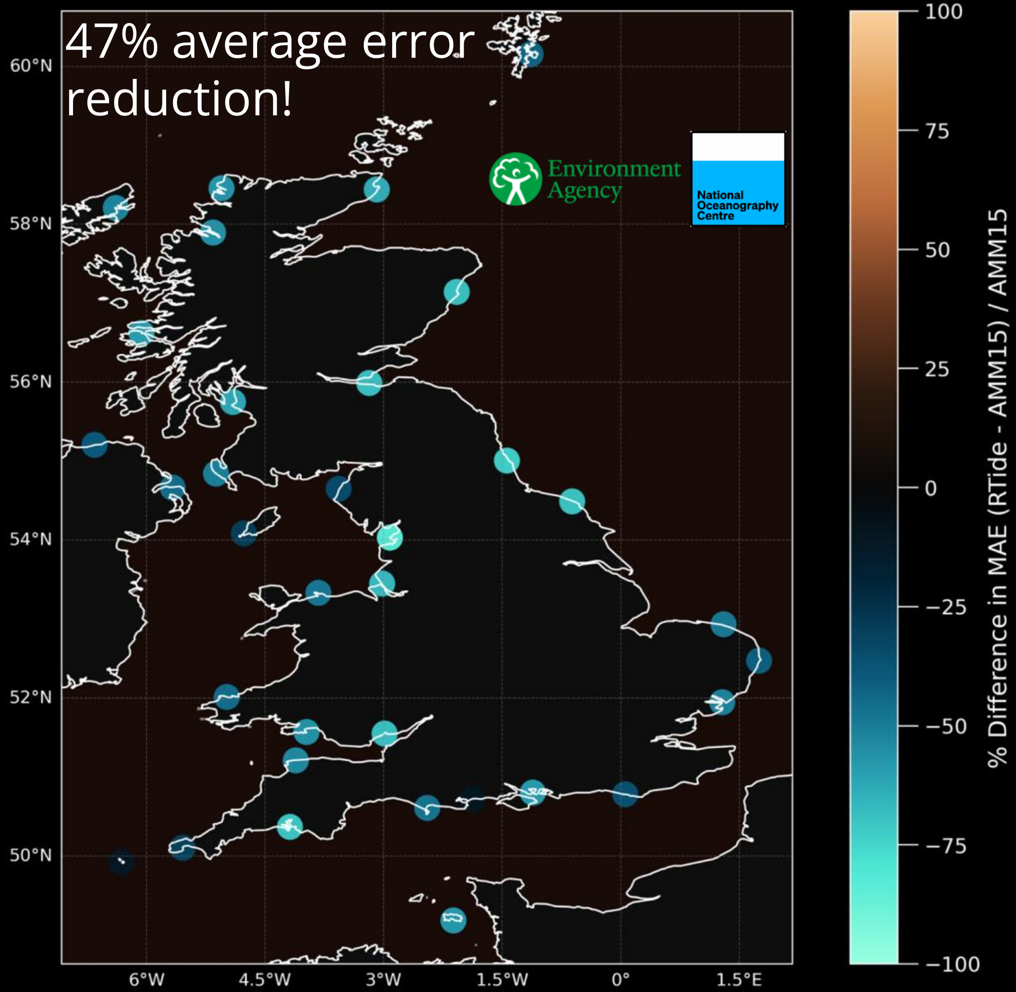


Ministry of Infrastructure and Water Management

Training 2022-2023 and Forecast 2024

DCSM7 + RTide: 36% lower error

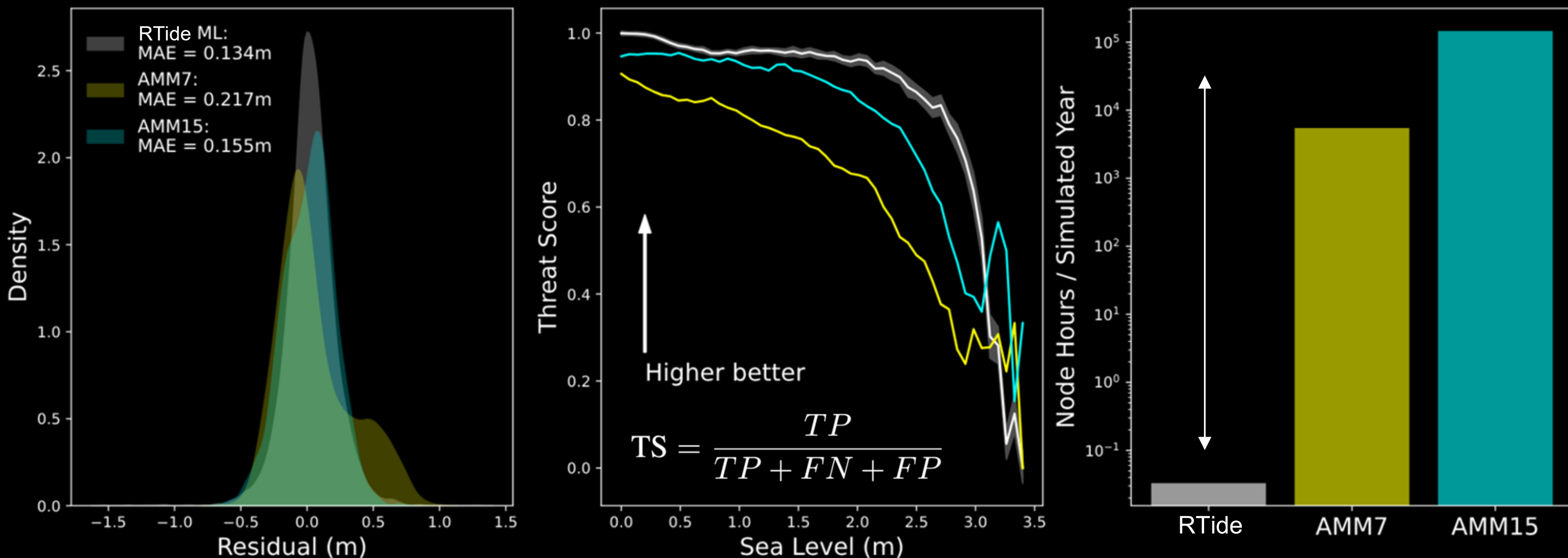
Model	MAE	Brier Score (99th percentile)
AMM15	.155m	.0009
AMM15 + RTide	.063m	.0002

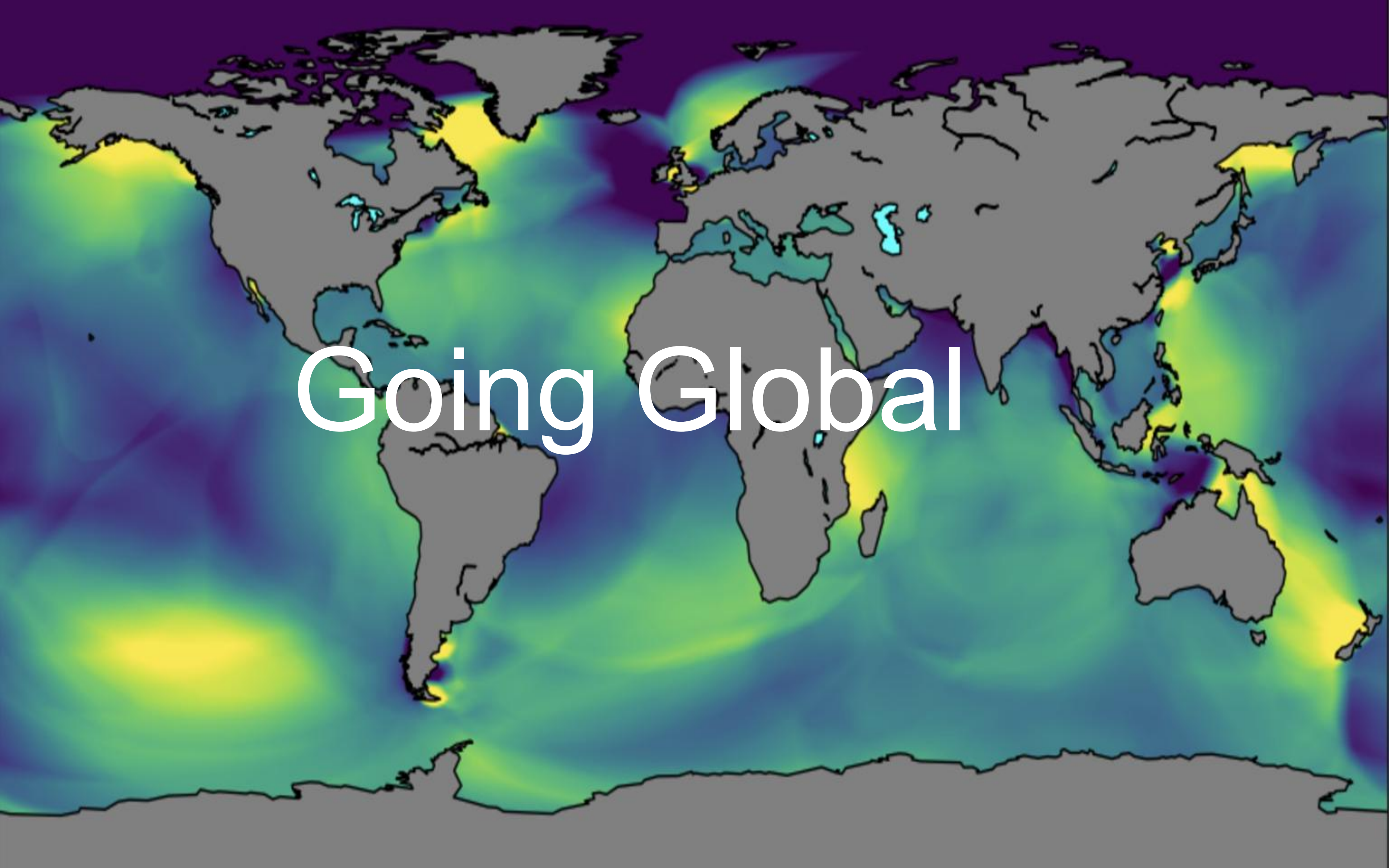
$$\mathrm{BS} = \frac{1}{N}\sum (f_i - o_i)^2$$

Operational Usage

Do we need the numerical model at all?

>4 million times more efficient!

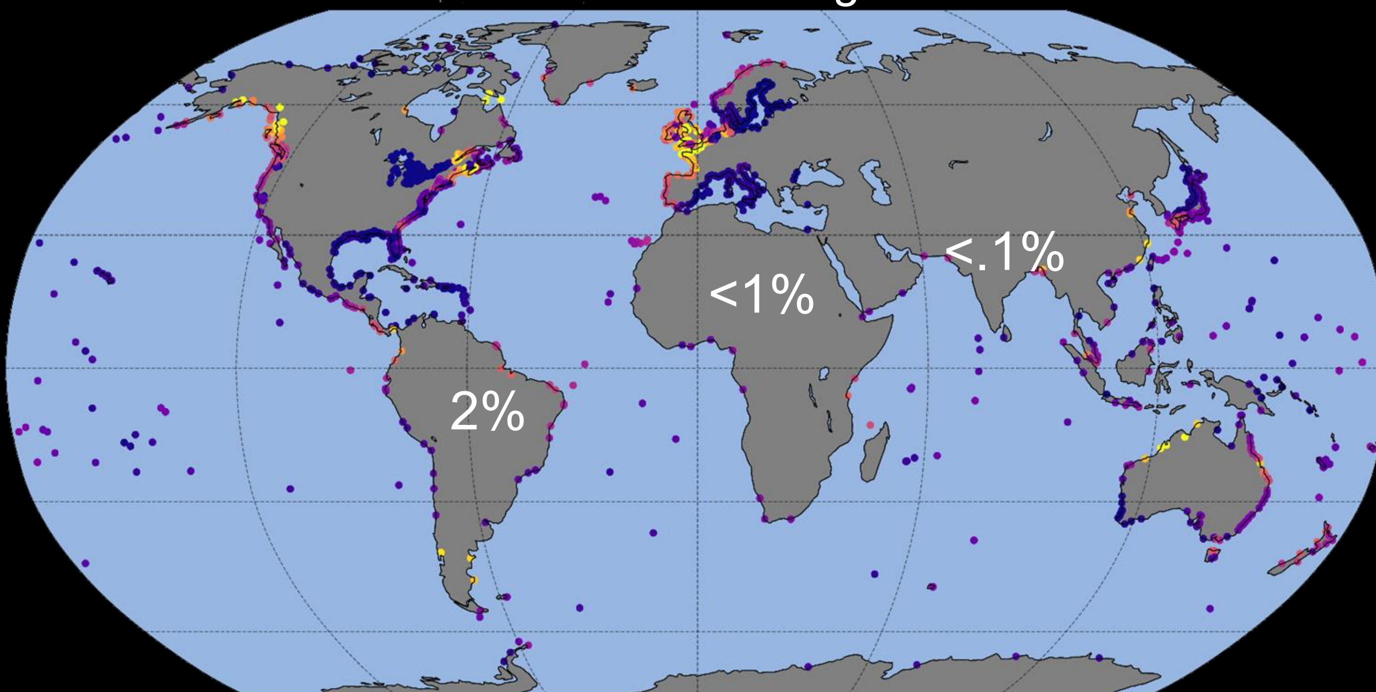



Going Global

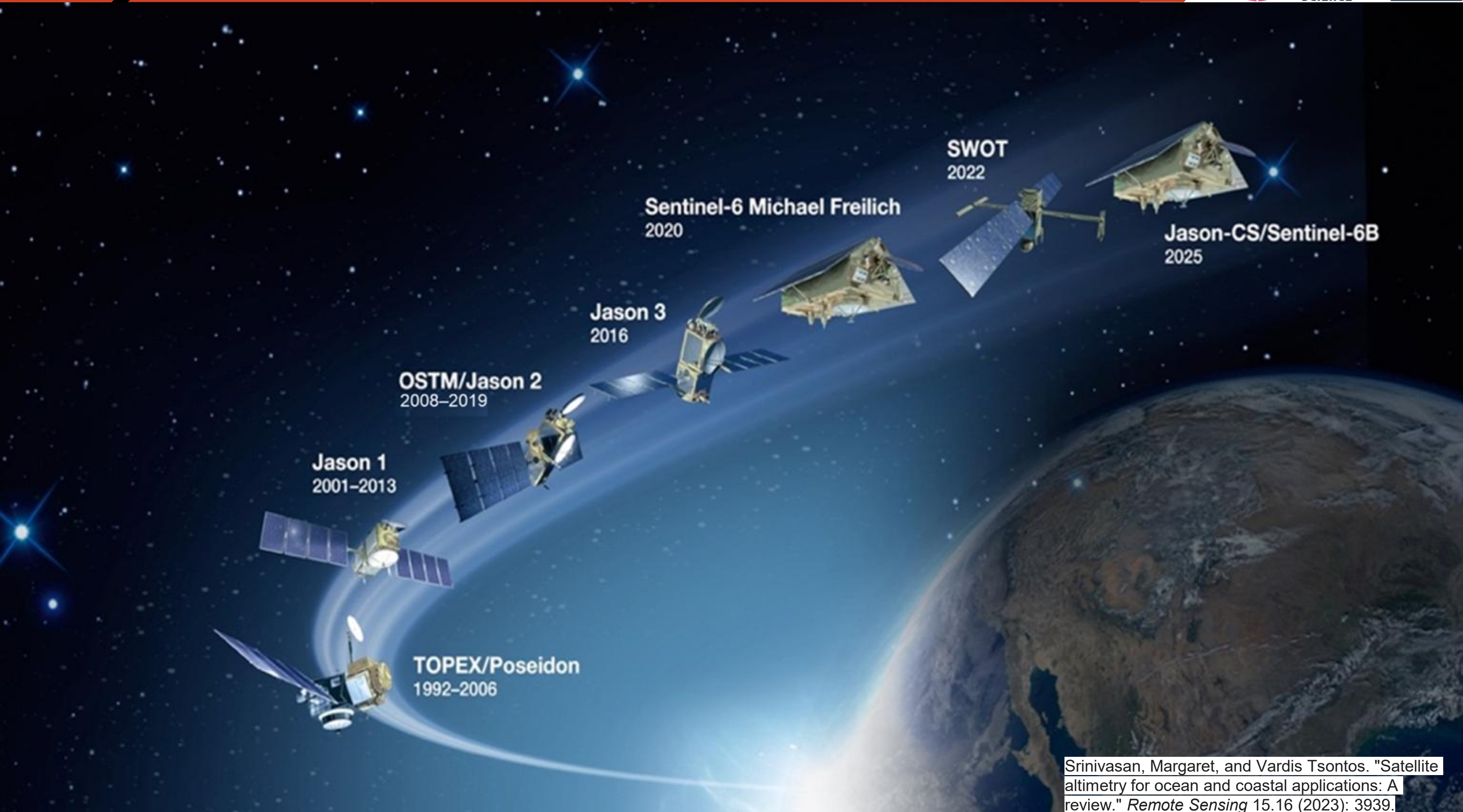
Going Global

1. What do we do if there are NO in-situ observations?
2. What if there is not a numerical model to post-process?

Global Tide Gauges



Going Global



Srinivasan, Margaret, and Vardis Tsontos. "Satellite altimetry for ocean and coastal applications: A review." *Remote Sensing* 15.16 (2023): 3939.

Going Global

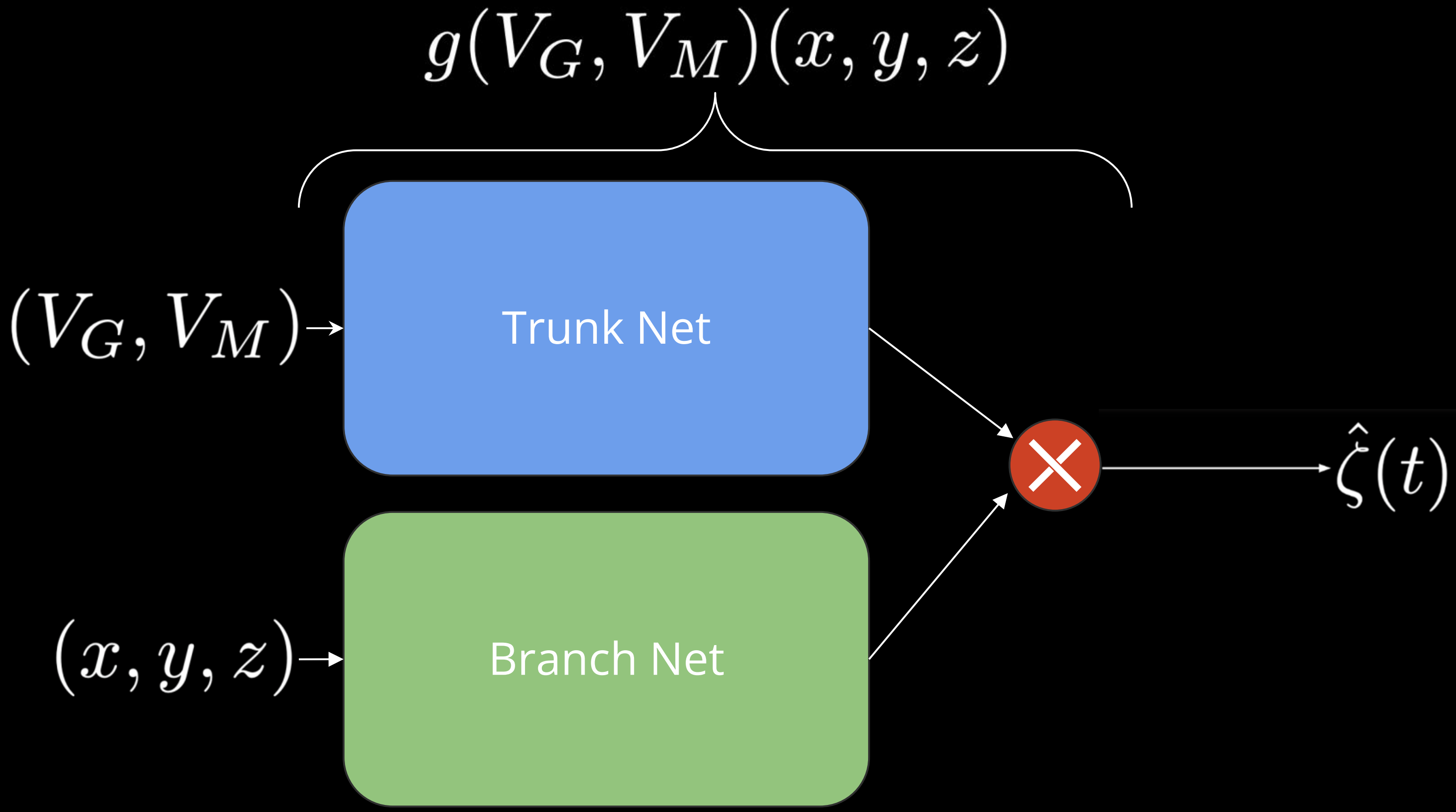
Single Location:

$$f(V_G, V_M) \longrightarrow \hat{\zeta}(t)$$

Multiple Locations:

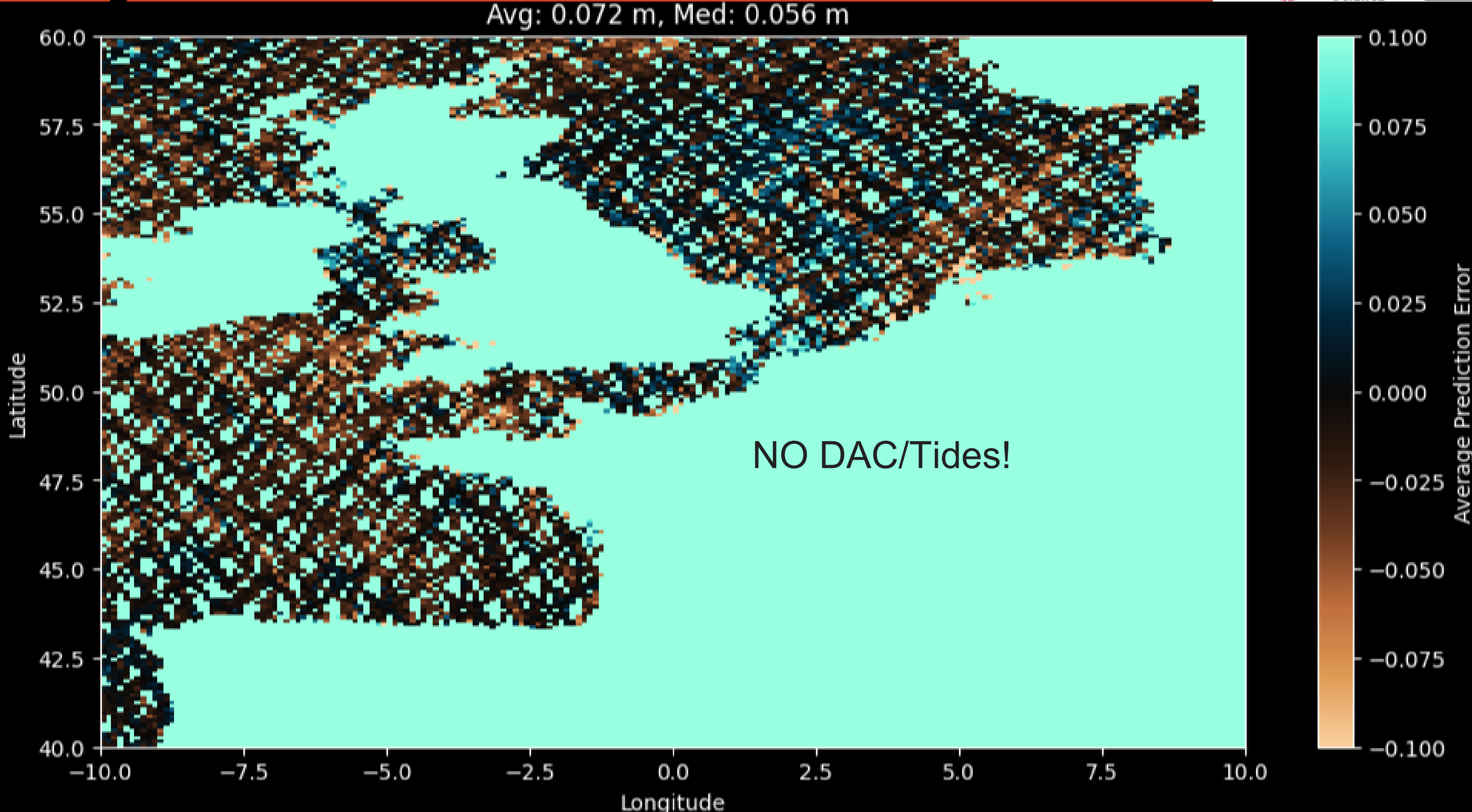
$$g(V_G, V_M)(x, y, z) \longrightarrow \hat{\zeta}(t)$$

Going Global

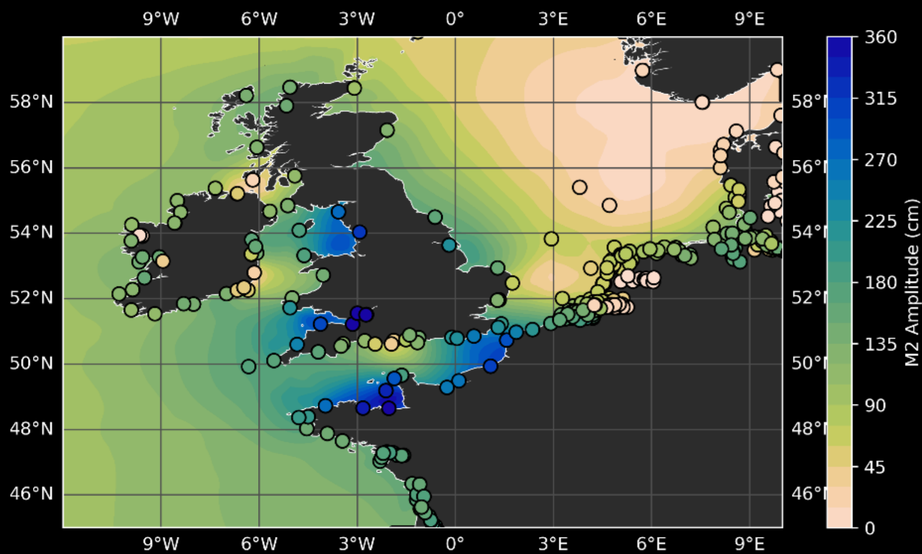


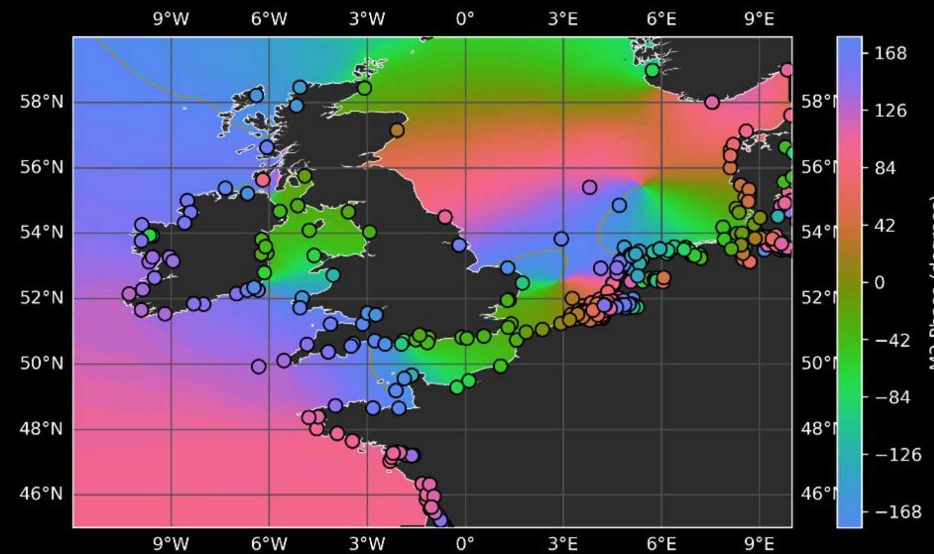
Lu, Lu, et al. "Learning nonlinear operators via DeepONet based on the universal approximation theorem of operators." ***Nature machine intelligence*** 3.3 (2021): 218-229.

3.4 Going Global (Tides)



Going Global (Tides)





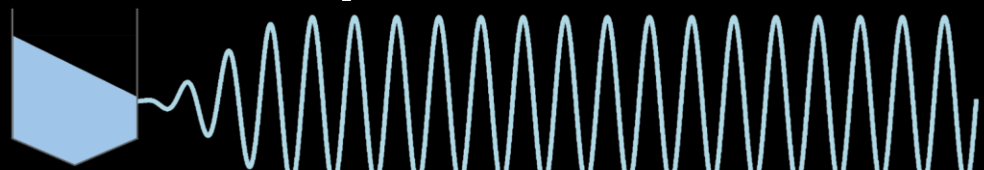
Future Outlook

1. Accurate empirical global surge forecasts are not far away…
2. Response-based post-processing can dramatically improve predictive accuracy and uncertainty quantification.
3. Response approach is the first approach which does NOT require bathymetric data, or observational data at test-time which opens the door for truly global forecasts.
4. Inference is incredibly fast, making more comprehensive and physical assessments of future flood risk tractible.

RTide

Special thanks to supervisors and collaborators:
Thomas Adcock, Tianning Tang, Stephen Roberts, and Jeff Polton

Questions?



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