RTide: Physics-informed ML for ocean water levels and currents

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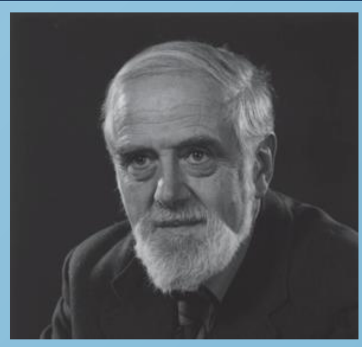
History

The tidal Response Method was developed in the 1960s by Walter Munk (sometimes called the Einstein of the oceans) and David Cartwright, FRS [1]. Whilst widely cited, the method has not been widely adopted due to the expertise needed to use the model. Despite the potential of the method, until now, no generalized empirical approach has existed for the analysis and prediction of general tidal processes.



The Response Method

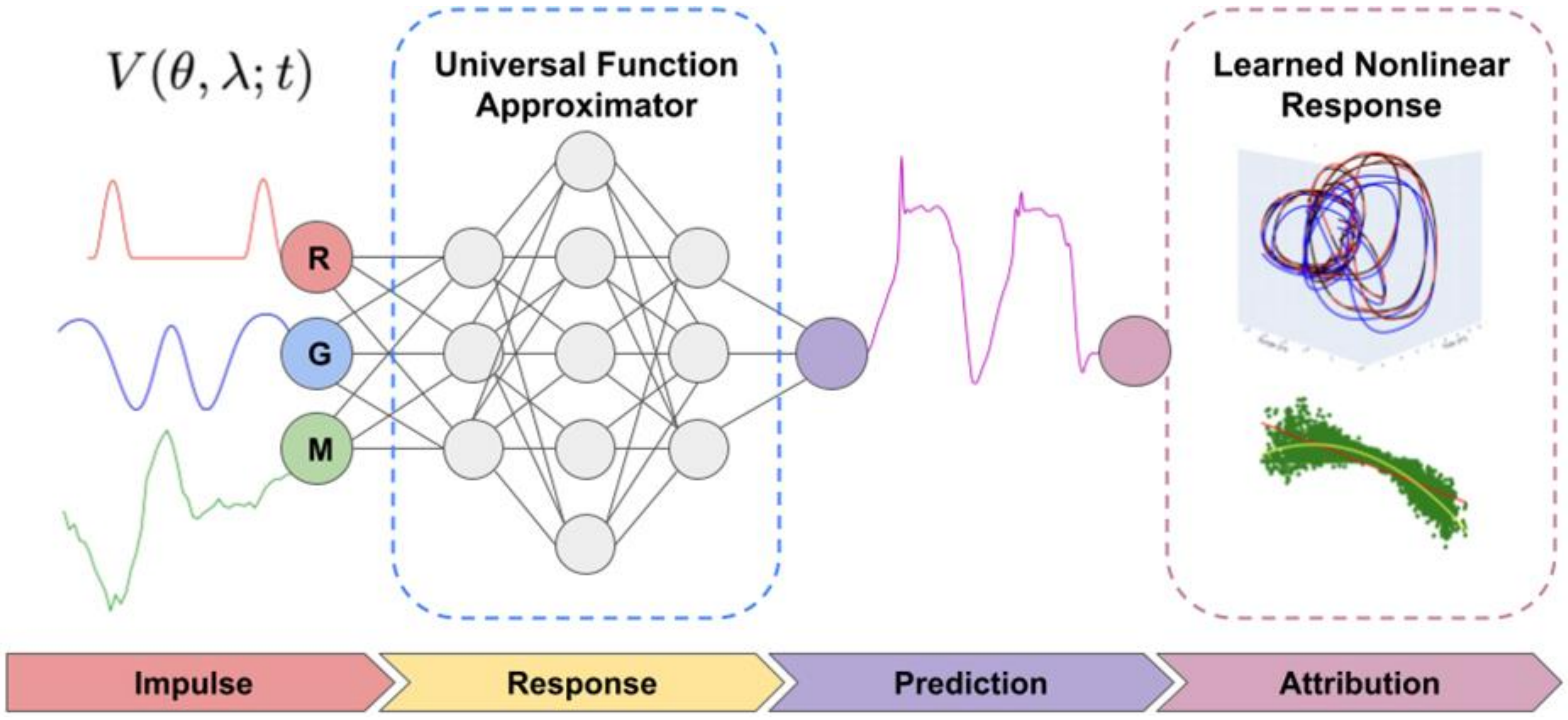
The Response Methods establishes a physical connection between the force applied to the ocean (e.g. astronomical forces) and the resulting ocean movement by assuming this connection to be both time-invariant and weakly nonlinear. While this framework was developed for tides, our work proves that this assumed relationship holds for a wide range of processes, including fluvial and meteorological. In this framework, the sea-level is related to learned weights w(s) and associated forcing V(t-s) at time-lag s, such that

$$\hat{\zeta}(t) = \sum_{s} w(s)V(t-s)$$

While this linear form is sufficient for open-ocean tides, high order nonlinear interactions dominate coastal processes. Deriving the weights associated with these higher order interactions becomes intractable in the classic approach due to the exponential explosion in terms.

RTide

RTide overcomes the challenge of estimating higher-order interactions by exploiting an equivalence between the Volterra series (the basis of the response method), and a class of constrained neural networks [3, 4]. An alternative probabilistic model using *Neural Processes* moves away from this equivalence but allows for faster training and the inclusion of confidence intervals. Typically RTide requires an order of magnitude less data than Harmonic Analysis for comparable performance.



Application to currents

The original method has only been used on water levels which are generally less non-linear than tidal currents. We have extended the approach to predict currents by developing a simple but novel coupled framework which predicts currents in multiple spatial directions using a shared set of weights [5]. Our model has been used to predict currents at the MeyGen site, largest site for tidal stream turbines in the world, outperforming their operational flow model used to predict yield [6].

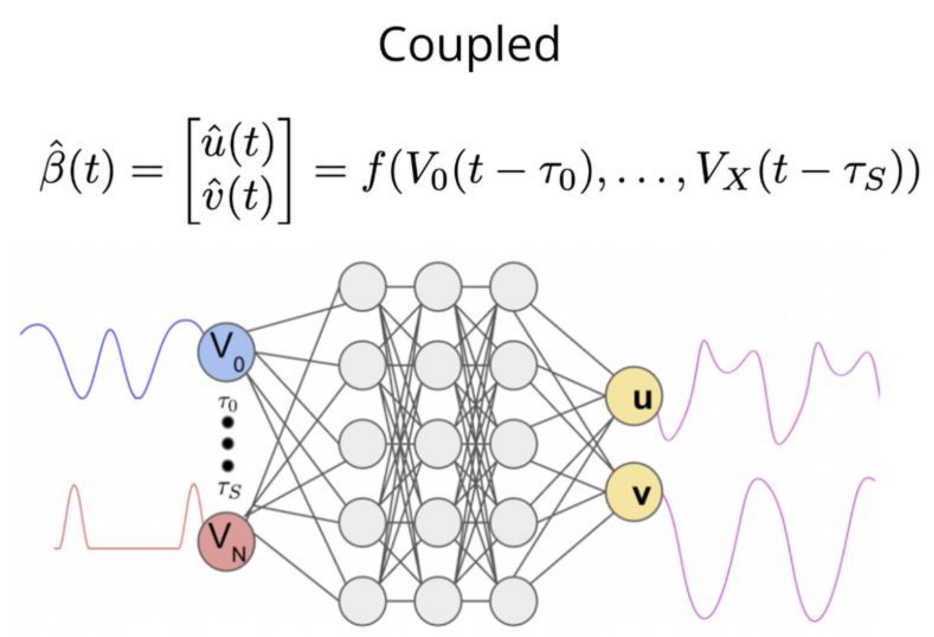


FIG 1: Example of coupled RTide architecture with shared weights for orthogonal u and v velocities.

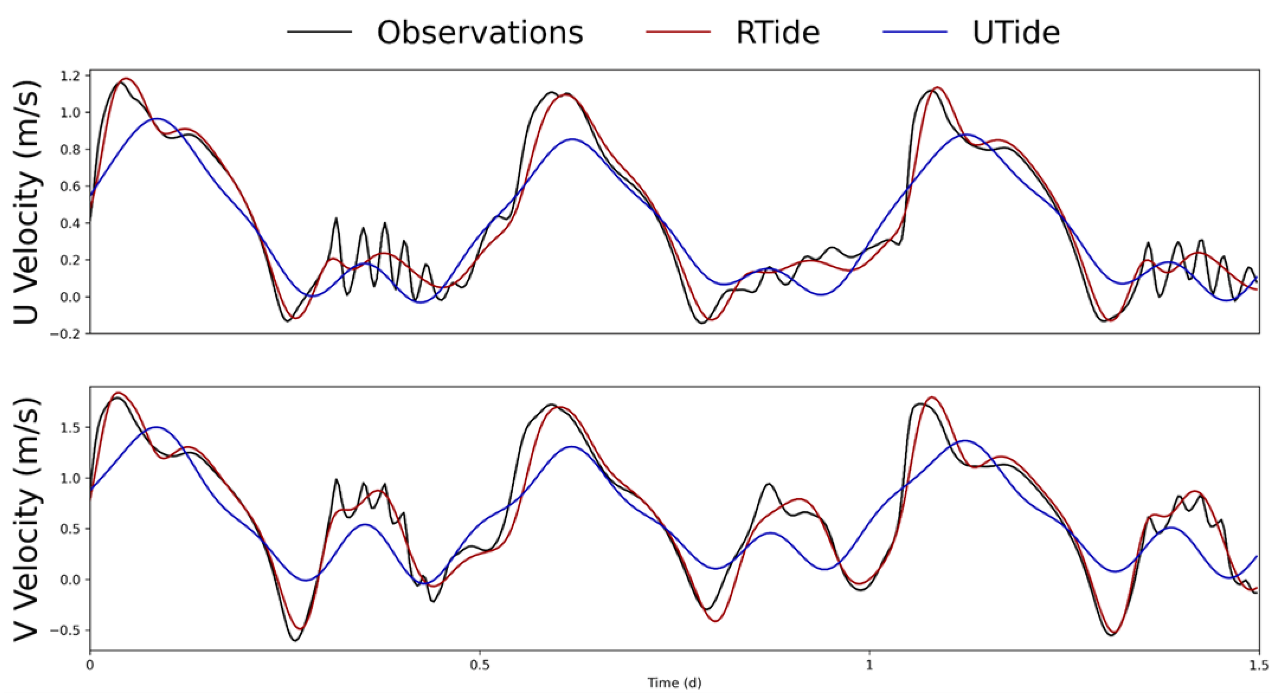


FIG 2: Predictions of principle current at MeyGen site. Black observations. Red: RTIde (MAE 0.624 m/s); Blue: Harmonic Analysis (MAE 1.296 m/s); Red: Flow model (MAE 0.785 m/s)

Application to storm surge

A criticism of pure machine learning models is that they struggle with extremes which is important for surges and coastal flooding. RTide, however, learns a physical time-invariant response function. It can therefore *extrapolate to* unseen extremes by virtue of the fact that it has learned (*interpolated)* the coupled time-invariant response function which governs such events – outperforming SOTA numerical models.

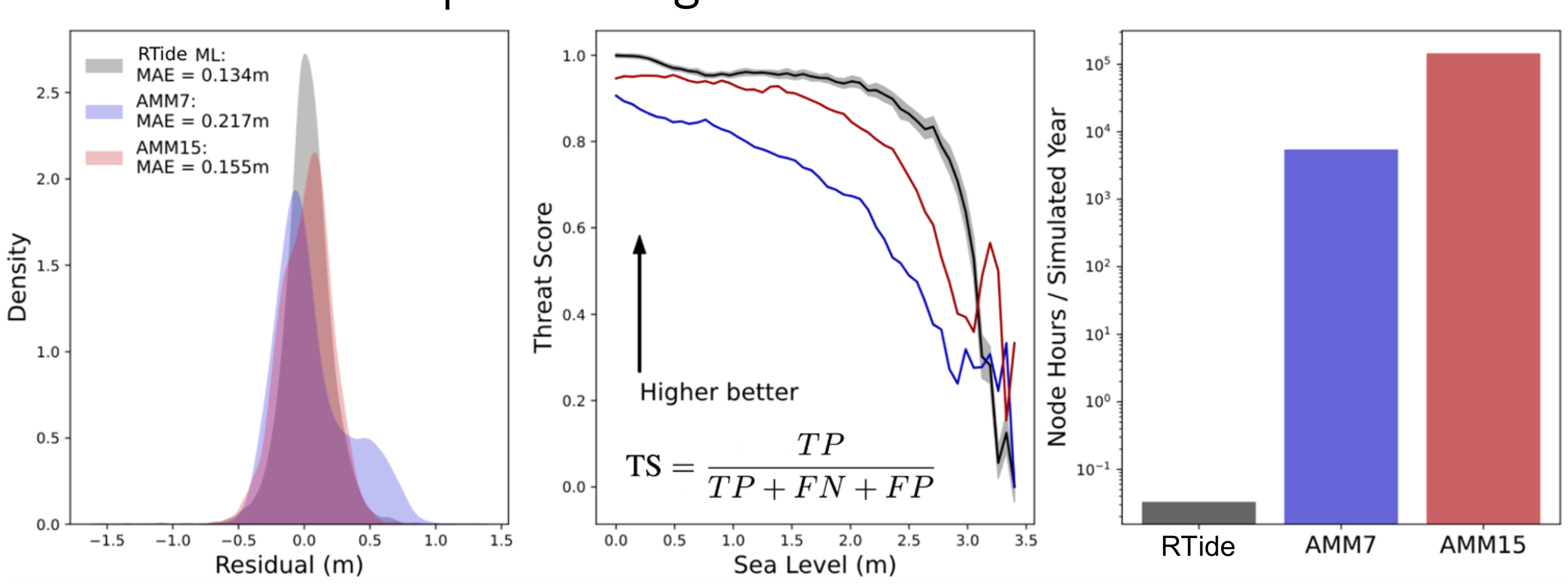
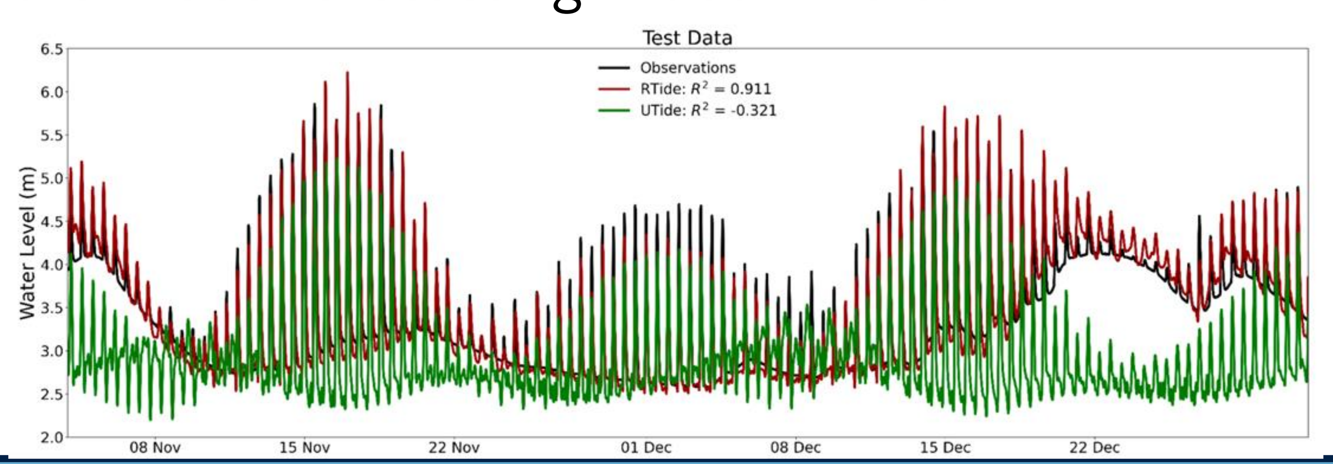


FIG 4: Comparisons of RTide forecasts for the year 2021-2022 at Sheerness, UK against operational UK surge models (AMM7 = 7km resolution), (AMM15 = 1.5 km resolution).). Left panel shows the distribution of forecast residuals compared to actual tide gauge observations. Middle panel shows the threat score (TS) at various water-levels. Right Panel shows the associated run-time in node hours for each model per simulated year.

RTide with other inputs

RTide can take inputs other forcings other than astronomical and atmospheric. For instance, it can take upstream river water levels which is important for flood forecasting in tidal rivers.

FIG 3: Prediction of water levels at Chester Weir. UTIde is a standard Harmonic Analysis package



References

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2. Marmarelis, V.Z. and Zhao, X., 1997. Volterra models and three-layer perceptrons. IEEE Transactions on neural networks, 8(6), pp.1421-1433.
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