Enhancing tidal analysis and prediction using physics informed machine learning

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Abstract:
Worldwide, tidal flows pose significant operational and engineering challenges to numerous industries and are critical drivers of many biological, chemical, and geophysical processes. Accurate tidal predictions are important for modelling these phenomena at both global and regional scales. While tides in deep oceans are essentially linear, classical methods of tidal analysis breakdown in estuarine and coastal zones where nonlinearity, non gravitational tides, and nonharmonic forcing 'contaminate' the tidal continuum. Furthermore, new coastal altimetry missions present unique challenges in tidal analysis due to the severe aliasing generated by infrequent sampling. Despite this, tidal predictions in these regions are important as they serve as the nexus between anthropogenic activities and the greater ocean. The methods developed in this work look to augment the classical harmonic and response methods of tidal prediction using machine learning to improve the study and prediction of these "messy" tidal regions. We develop two complementary approaches: a variational bayesian harmonic analysis (HA) capable of harmonic inference for satellite altimetry missions, and a modified machine learning Response Framework

Case Study 1: Empirical Mean Sea Surface and Tidal Correction From SWOT
The NASA Surface Water Ocean Topography mission (SWOT), launched on 15 December 2022, will provide the highest spatial and temporal altimetric measurements of coastal oceans to date. While SWOT presents unprecedented spatial resolution, the temporal sparsity renders the applications of conventional tidal analysis methods useless. The need for new methods of tidal analysis are made even more salient by the fact that the variance in the derived sea surface anomaly due to mean sea surface and tidal prediction errors can be in excess of 30 percent for each data product respectively. We apply our variational bayesian tidal analysis to simultaneously correct the mean sea surface and tidal correction errors present in SWOT data. Our results indicate that the variational harmonic analysis can significantly reduce the global error in both the estimated M2 constituent and sea surface height. Thus, we expect that these improvements can significantly improve our understanding of the global tidal energy budget, and be used to derive new high resolution estimates of the global mean sea surface. These empirically corrected data products will also help to facilitate the study of many other submesoscale processes which are of high interest to SWOT researchers.

Case Study 2: Response Nuisance Flood Prediction and Analysis
As sea levels continue to rise, coastal nuisance flooding, storm surges will become more frequent. The drivers of nuisance floods are generally more subtle and are a result of the confluence of astronomical tides, wind, and weather. Conventional methods make use of computationally expensive hydrodynamic models whose coarse resolution and simplifying assumptions often prevent the accurate prediction of these events. We illustrate the ability of the Response Framework to learn the nonlinear role of both tidal and non-tidal forcing in driving nuisance flood events using both simulated and real data. Furthermore, we illustrate how the learned response models can be used to recover novel analytic descriptions of the interactions between forcing inputs.

Discussion:
The revised harmonic and response paradigms presented in this work provide two complementary approaches to tidal analysis. Collectively, these methods enable the study of several phenomena which heretofore could not be accounted for. These include non-gravitational forcing, storm surges, tidal rivers, anthropogenic climate change, and tidal analysis and prediction from satellite altimetry. We show that in addition to outperforming classical methodologies in predictive accuracy, these frameworks actually retain more physics and provide greater interpretability. This constitutes an important paradigm shift; in addition to quantifying how tides are behaving we can now ask why. There is strong evidence that tides are changing as a consequence of anthropogenic climate change. Furthermore, relatively little is known as to how tides are impacted and impact sea level rise, storm surges, and estuarine dynamics. Thus, it is imperative that work is undertaken to understand, predict, and adapt to these changing risks. It is our hope that this work can help to enable these efforts through the release of an open-source Python package (OTide) which will be released in early spring.