Using stochastic models to improve predictions of internal tide-driven currents and temperature

Forum for Operational Oceanography

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Oceans Graduate School
University of Western Australia

ARC Research Hub for Transforming energy Infrastructure through Digital Engineering

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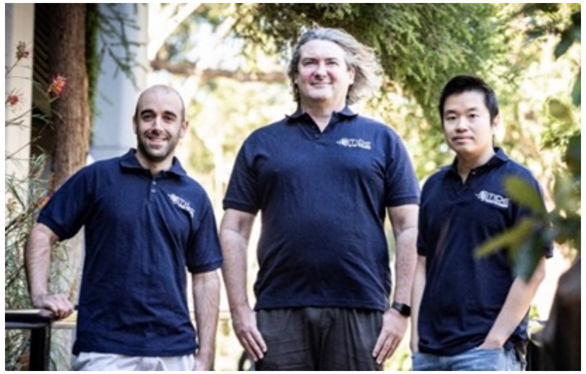
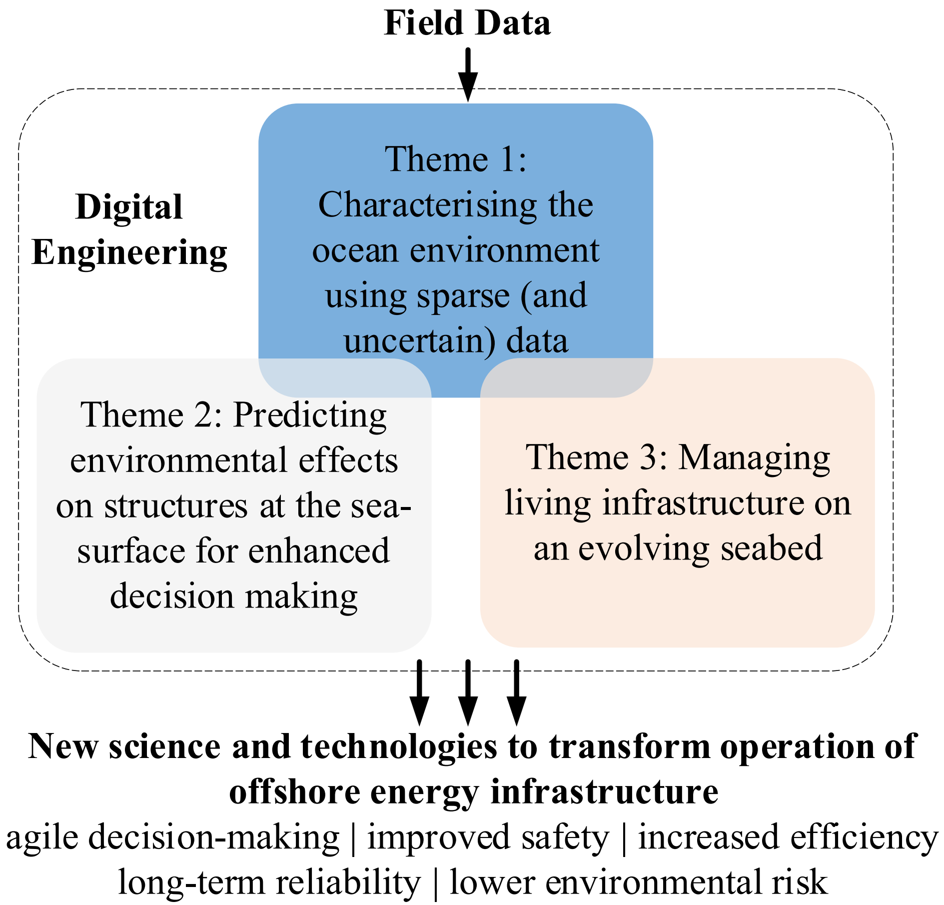
Transforming energy Infrastructure through Digital Engineering Research Hub

Development of new science and technology through ***digital engineering*** to optimise the management of offshore energy infrastructure – thereby making this activity cheaper and yet more reliable.

Digital Engineering is the creation, use and embedment of data in engineering.

Oceanography focus: Prediction of nonlinear internal waves and submesoscale eddies using "traditional" physical models and new "data science" methods





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Setting the scene

- **Tidal harmonic analysis** is useful for predicting water level in coastal regions
- It is also useful for predicting ocean currents and water temperature in some offshore locations where internal waves are active
- The utility of tidal predictions (i.e. their *useability* for decision-makers) is usually judged from some **bulk measure of residual properties** (rmse, skill, etc.)
- Threshold for a "good fit" is usually left to the decision-maker... resulting in ad-hoc decisions

What should decision-makers (operators) do with the model residual?

Example 1: Broome sea-level

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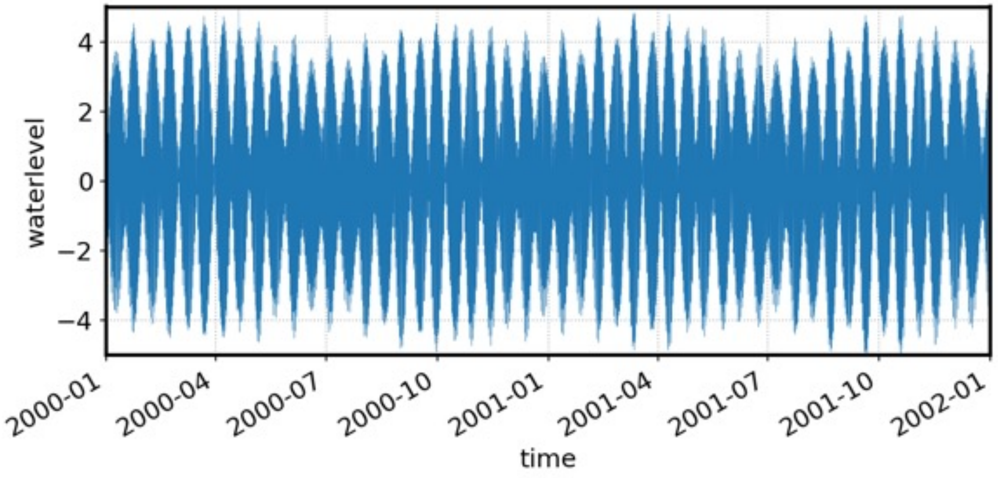
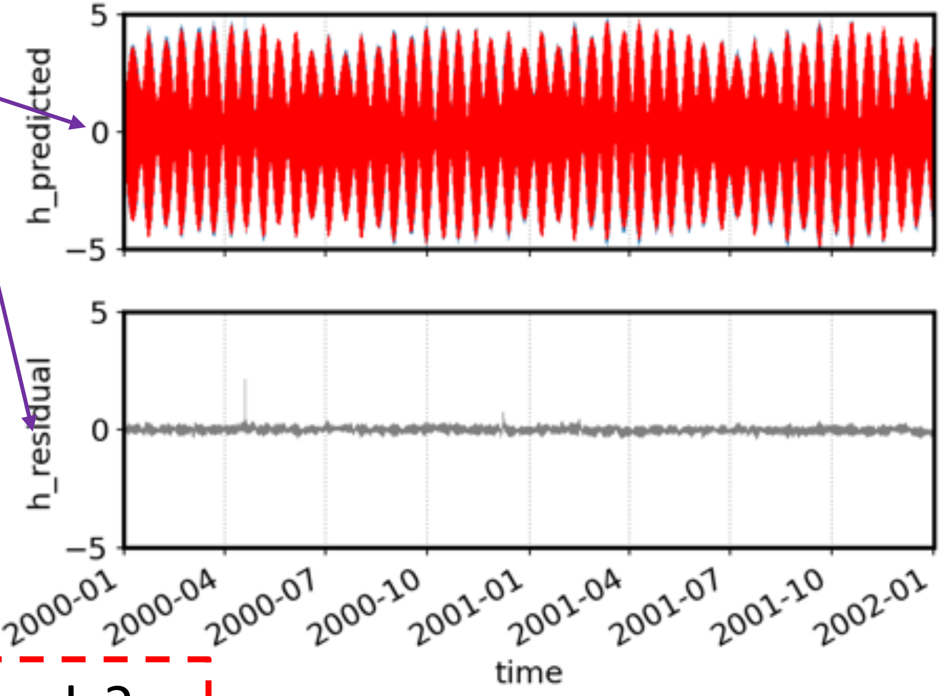
$$y = \sum_j A_j \cos(\phi_j) + B_j \sin(\phi_j) + \varepsilon$$



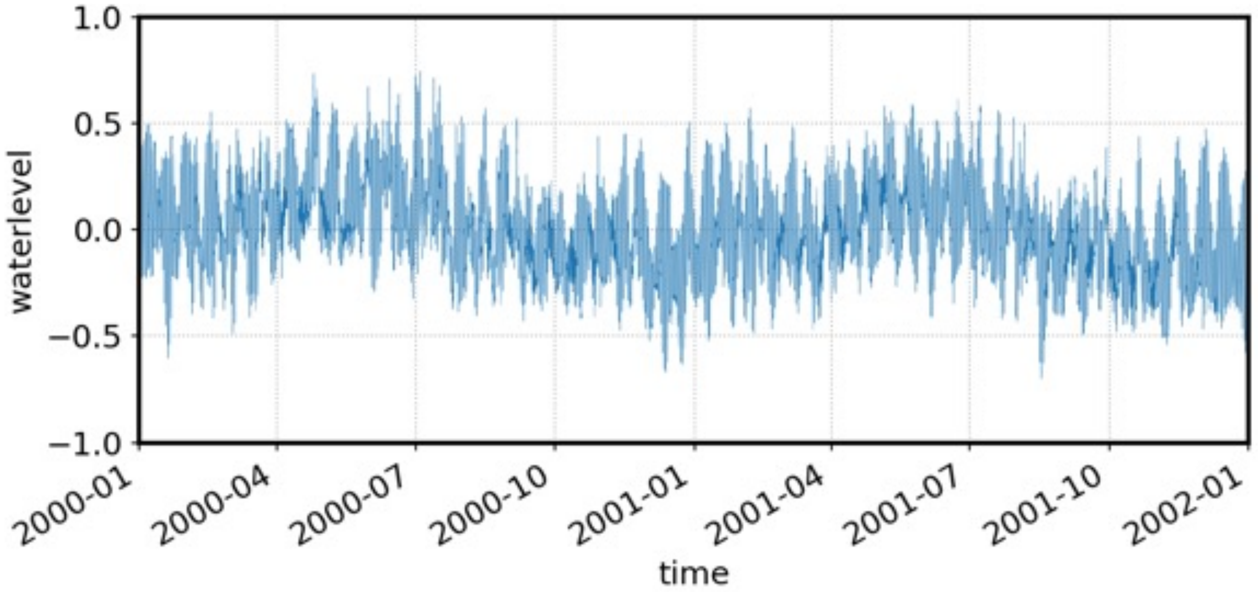


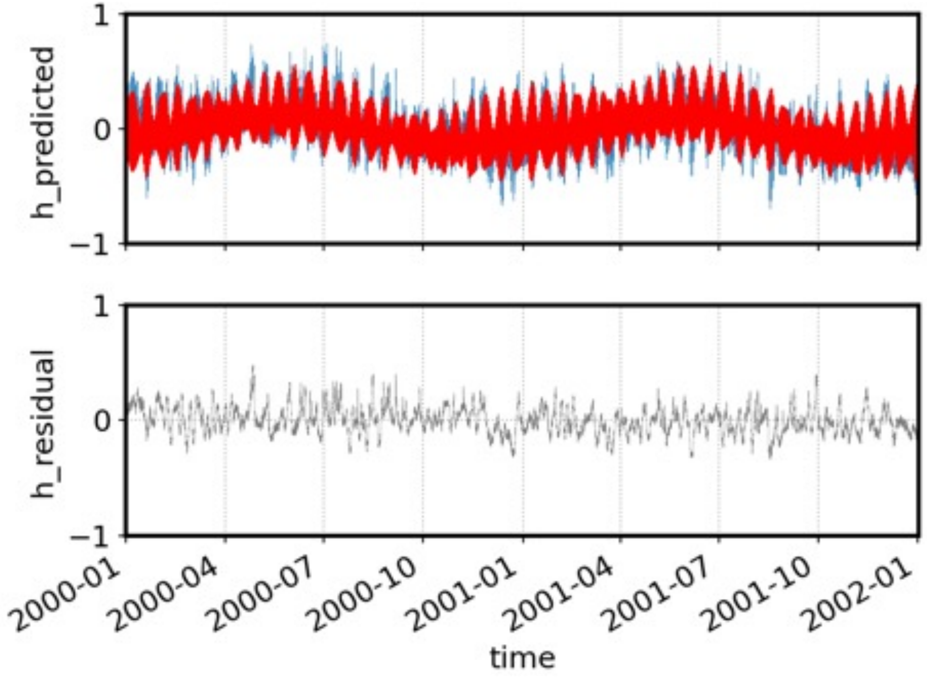
Question: Is the residual OK for my needs?

Data source: Australian Baseline Sea Level Monitoring Project (BoM)

Example 2: Hillarys sea-level

$$y = \sum_j A_j \cos(\phi_j) + B_j \sin(\phi_j) + \varepsilon$$



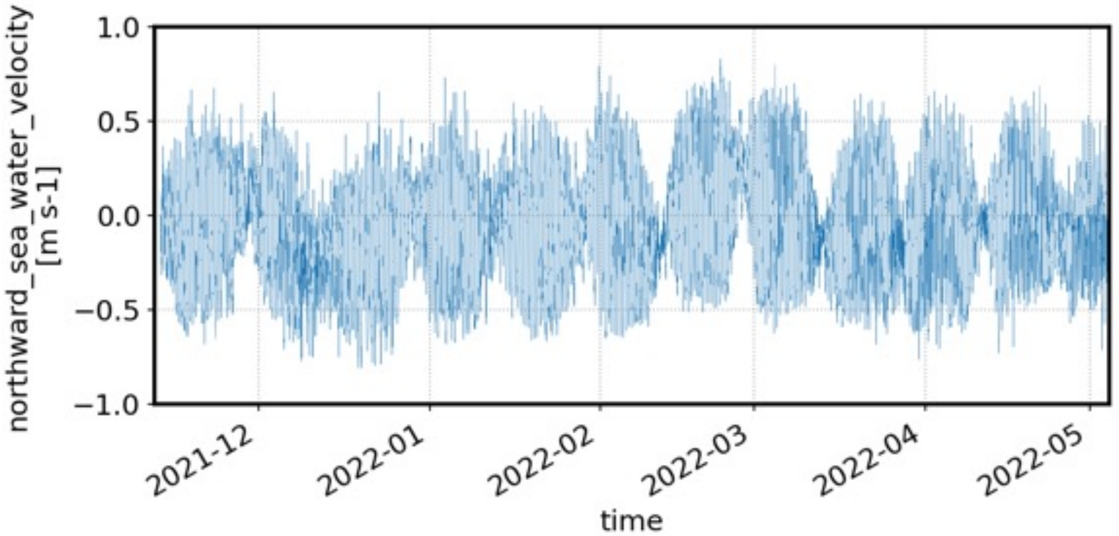


Question: Is the residual OK for my needs?

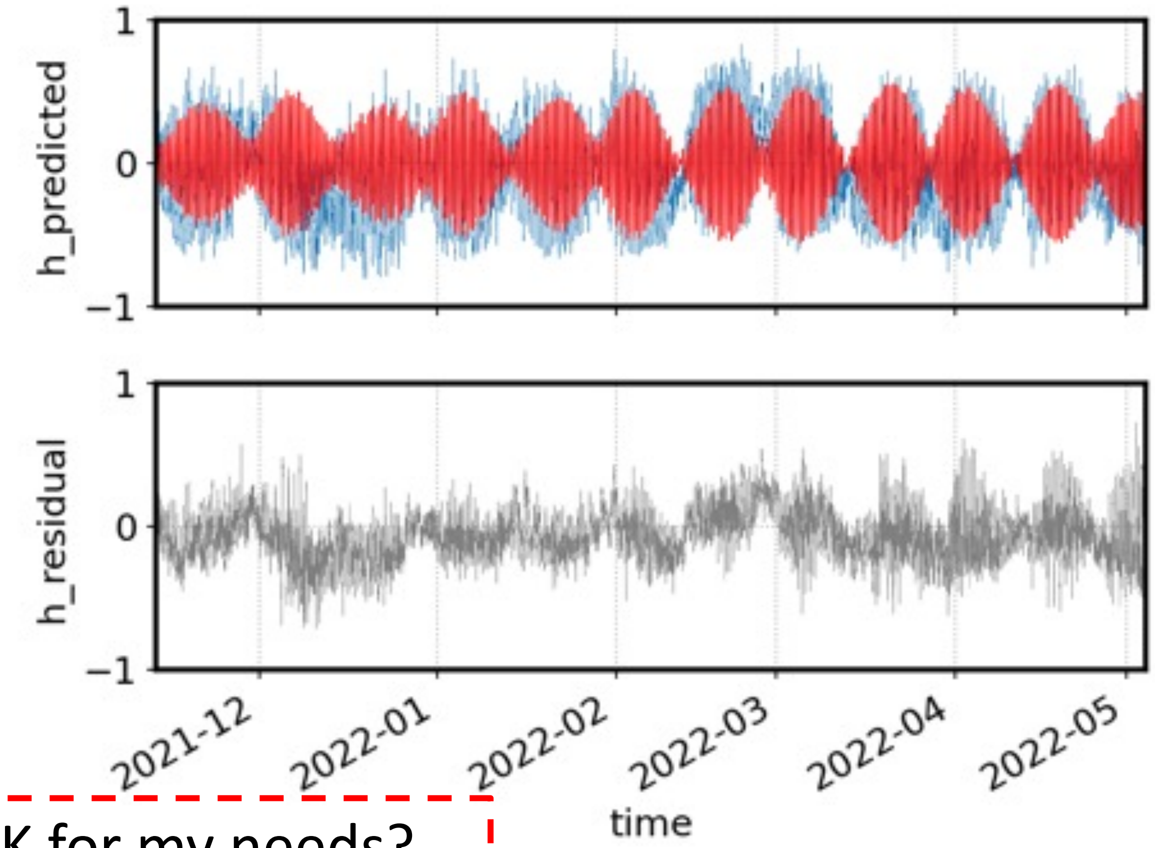
Data source: Australian Baseline Sea Level Monitoring Project (BoM)

Example 3: NWS ocean currents

$$y = \sum_j A_j \cos(\phi_j) + B_j \sin(\phi_j) + \varepsilon$$



Data source: IMOS National Mooring Network (NWSBRW)



Question: Is the residual OK for my needs?

Question 2: If no, can I retain the residual for decision-making?

A solution to keeping the residual

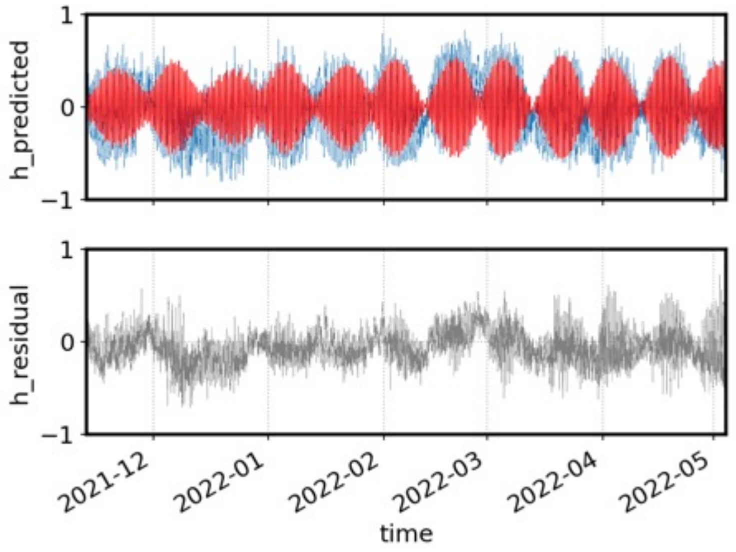
Model the tides deterministically (i.e. harmonics) and the residual as a *stochastic process* by retaining the same *statistical properties*

- *Stochastic process:* random draw of one possible outcome. This can be done many times e.g. Monte Carlo analysis.
- *Similar statistical properties*: signal variance partitioned into similar frequencies i.e. similar power spectral density

A solution is a machine learning technique called **Gaussian Process Regression**

Advantages of the method:

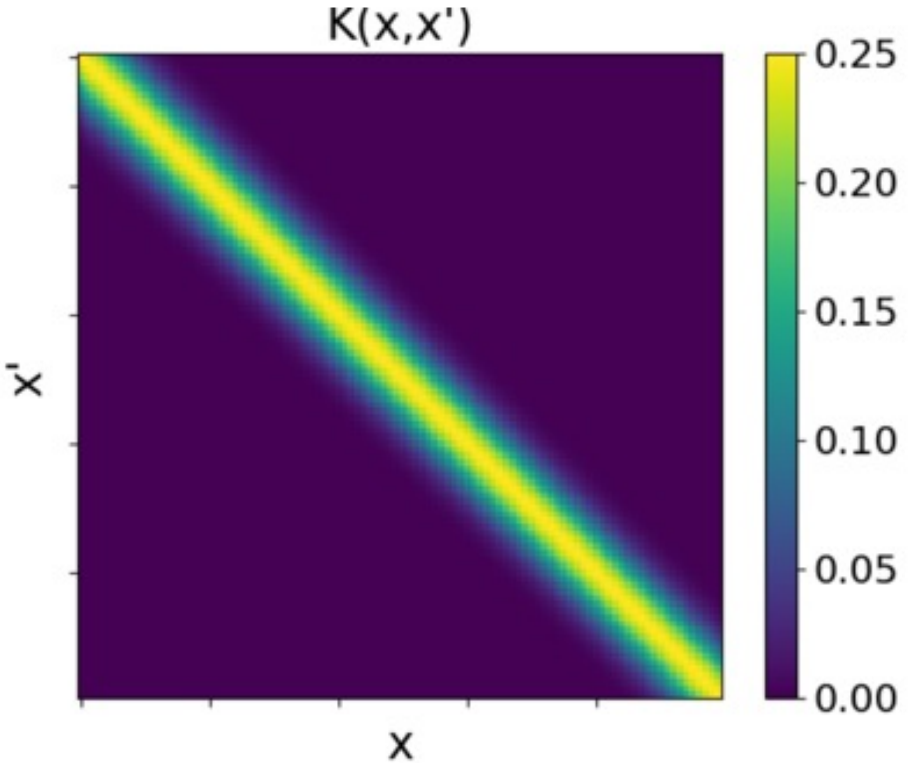
- Makes stochastic forecasts → **uncertainty quantification**
- It can be fast to train (compared to deep learning)
- It is much cheaper to run than traditional ocean models
- It is **interpretable** (parameters may be set by an expert without data)
- Predictions look realistic (not too smooth, not too rough)

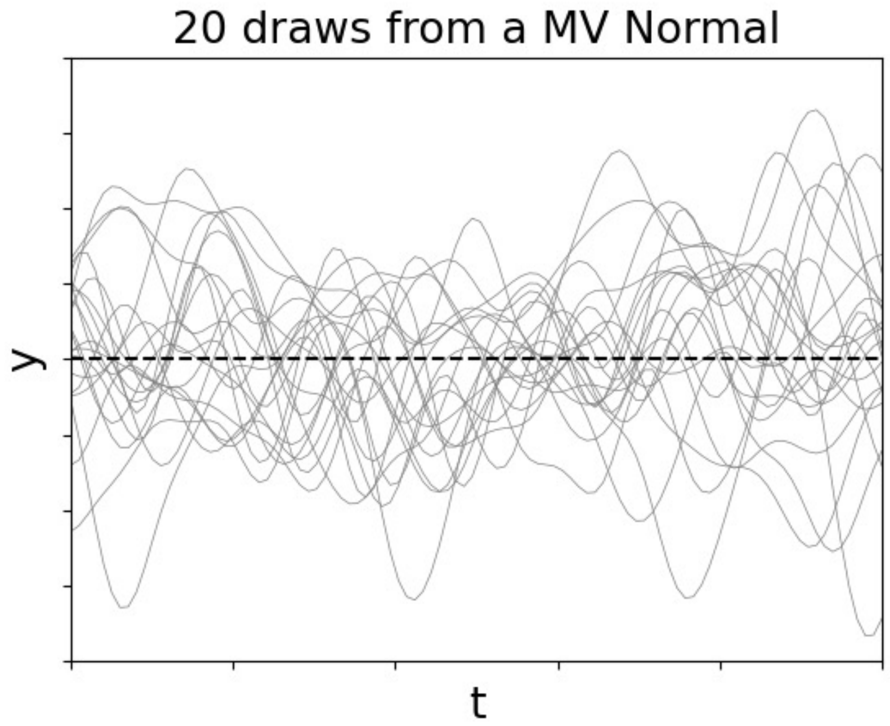


Multivariate Normal Distribution

$$y \sim MVN(\boldsymbol{\mu}, \Sigma)$$

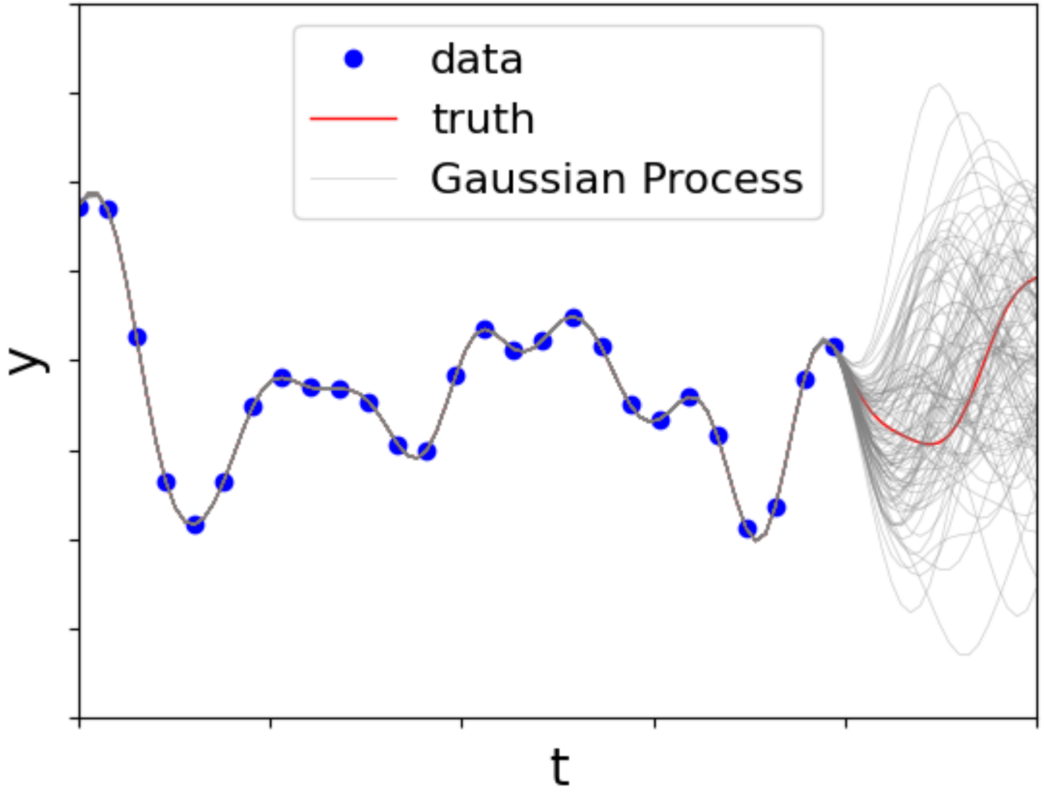
- $\boldsymbol{\mu}$ = mean function (e.g. tidal harmonics)
- Σ = covariance kernel, $\Sigma \approx \mathrm{K}(\mathrm{x}, \mathrm{x}'; \theta)$ (the statistical relationship between time points)





Gaussian Process Regression

- *Loose definition: Multivariate normal distribution conditioned on some data*

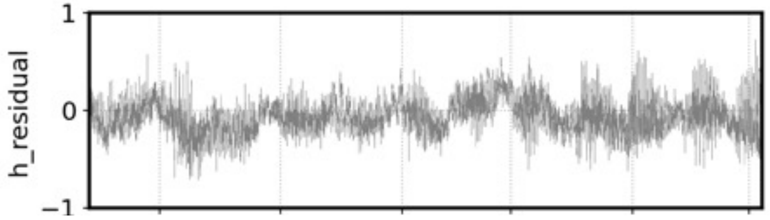


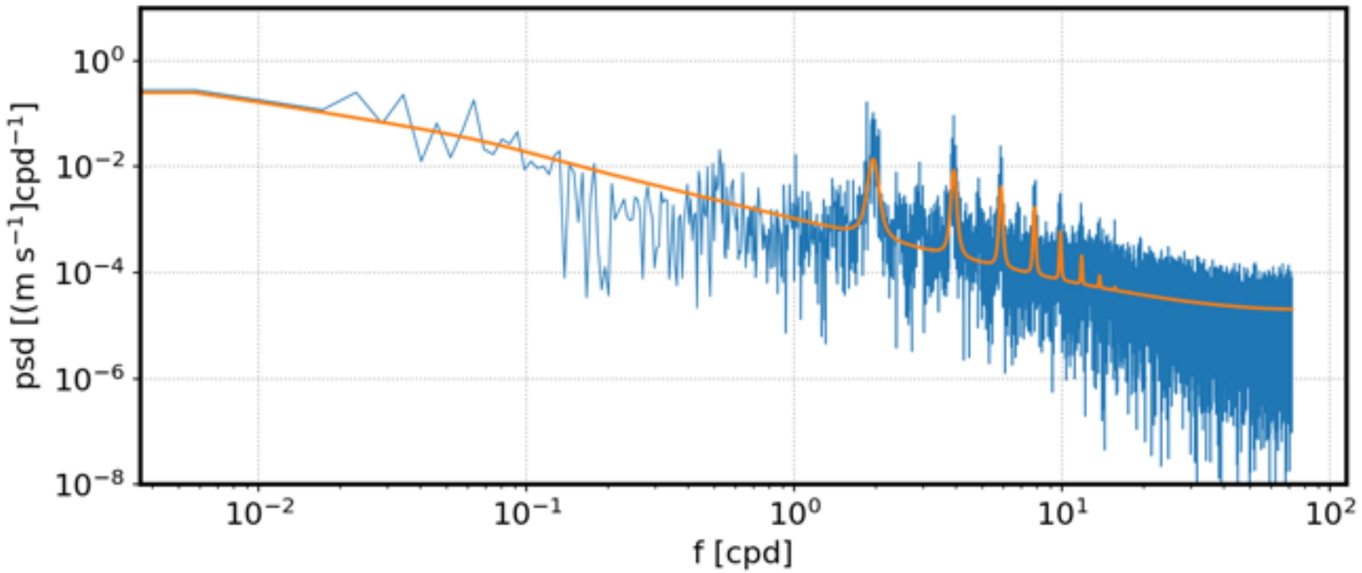
The key to the method producing useful forecasts is in the **choice of covariance kernel**, $\Sigma \approx \mathrm{K}(\mathrm{x}, \mathrm{x}'; \theta)$

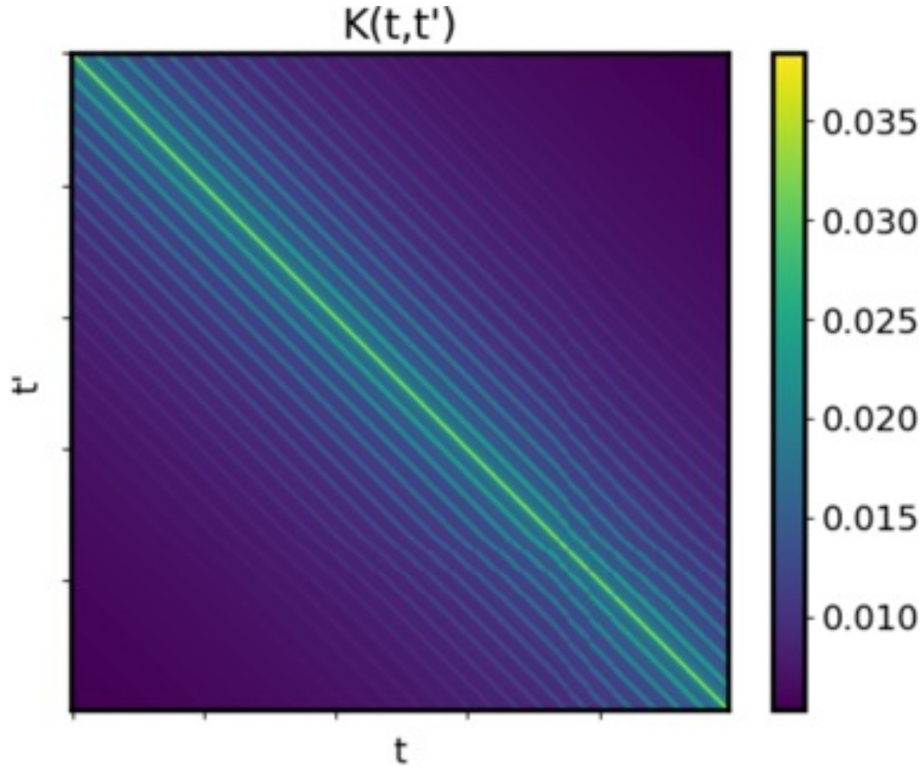
→ We do this based on the power spectrum of the tidal harmonic residual

Power Spectrum ←→ MV Normal

- *Similar statistical properties*: signal variance partitioned into similar frequencies i.e. similar power spectral density as the model residual
  - → "**realistic looking** predictions"

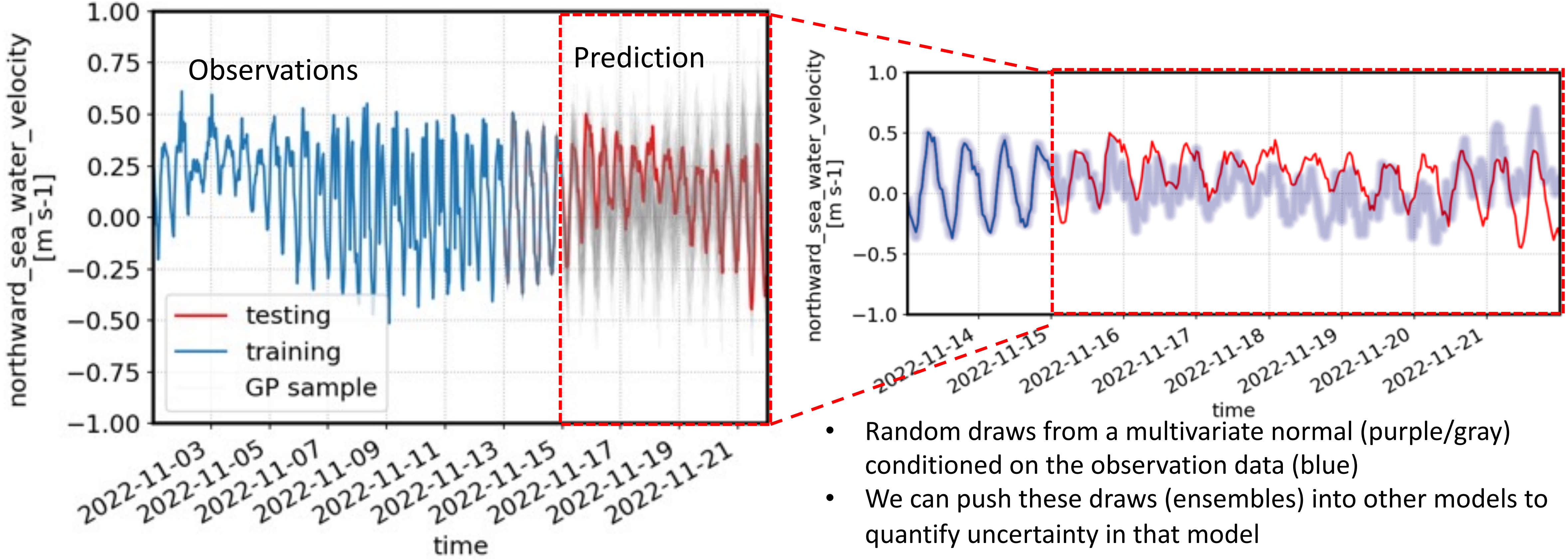






Stochastic predictions

Data source: IMOS National Mooring Network (NWSBRW)



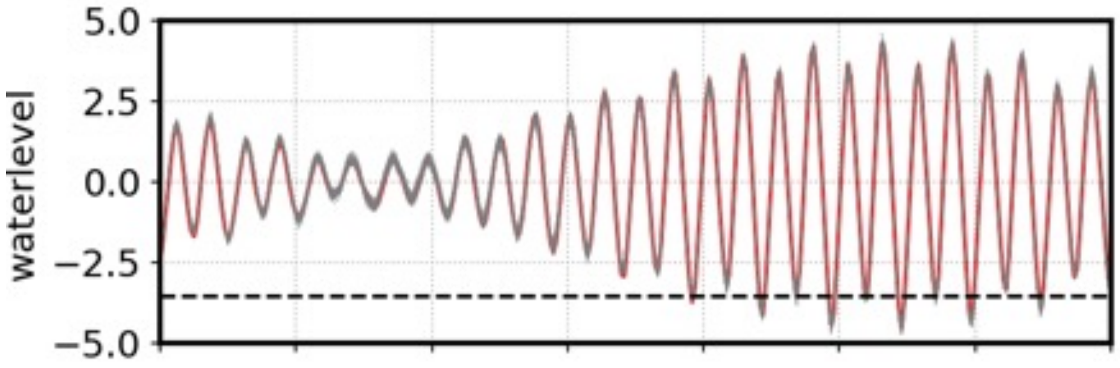
- Random draws from a multivariate normal (purple/gray) conditioned on the observation data (blue)
- We can push these draws (ensembles) into other models to quantify uncertainty in that model

Application Example

Uncertainty quantification of tidal forecast

- 14-d forecast at Broome tide gauge
- Gray lines are the stochastic predictions, red is truth

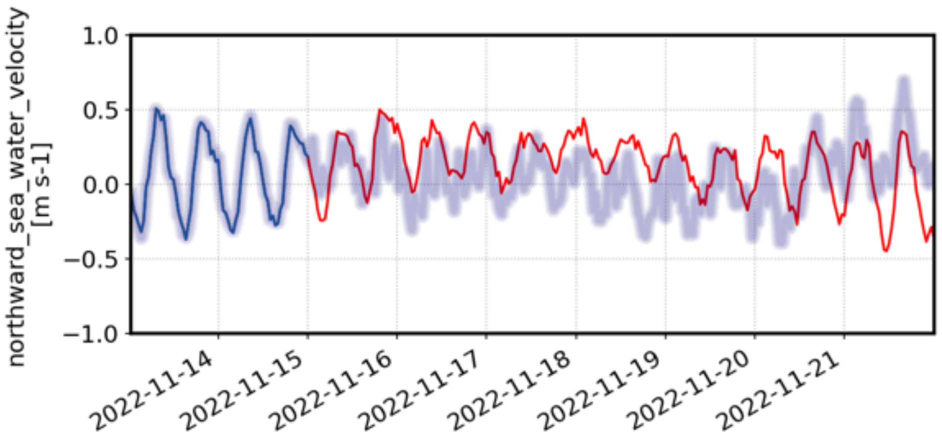
Broome Sea Level



<u>Example question:</u> *what is the probability of water level dropping below value -3.5 m in the next 14 days?*

Conclusions

- Machine learning method to make stochastic predictions with similar statistical (spectral) properties as observations of e.g. **sea level, currents, water temperature**.
  - → **Realistic looking** predictions
- **Uncertainty quantification** is a key by-product
- Extends the *useability* of tidal harmonic predictions to regions with mixture of tides and other ocean processes e.g. eddies, internal waves
- This method *has* been used operationally by offshore operators for ocean current prediction
- **Pushing model uncertainty into decision-making frameworks remains a hurdle**
  - requires forward propagation of many outcomes into response/decision models using Monte Carlo methods
  - This is time consuming and very specific to each use case
  - Ensemble forecasts suffer similar issues



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