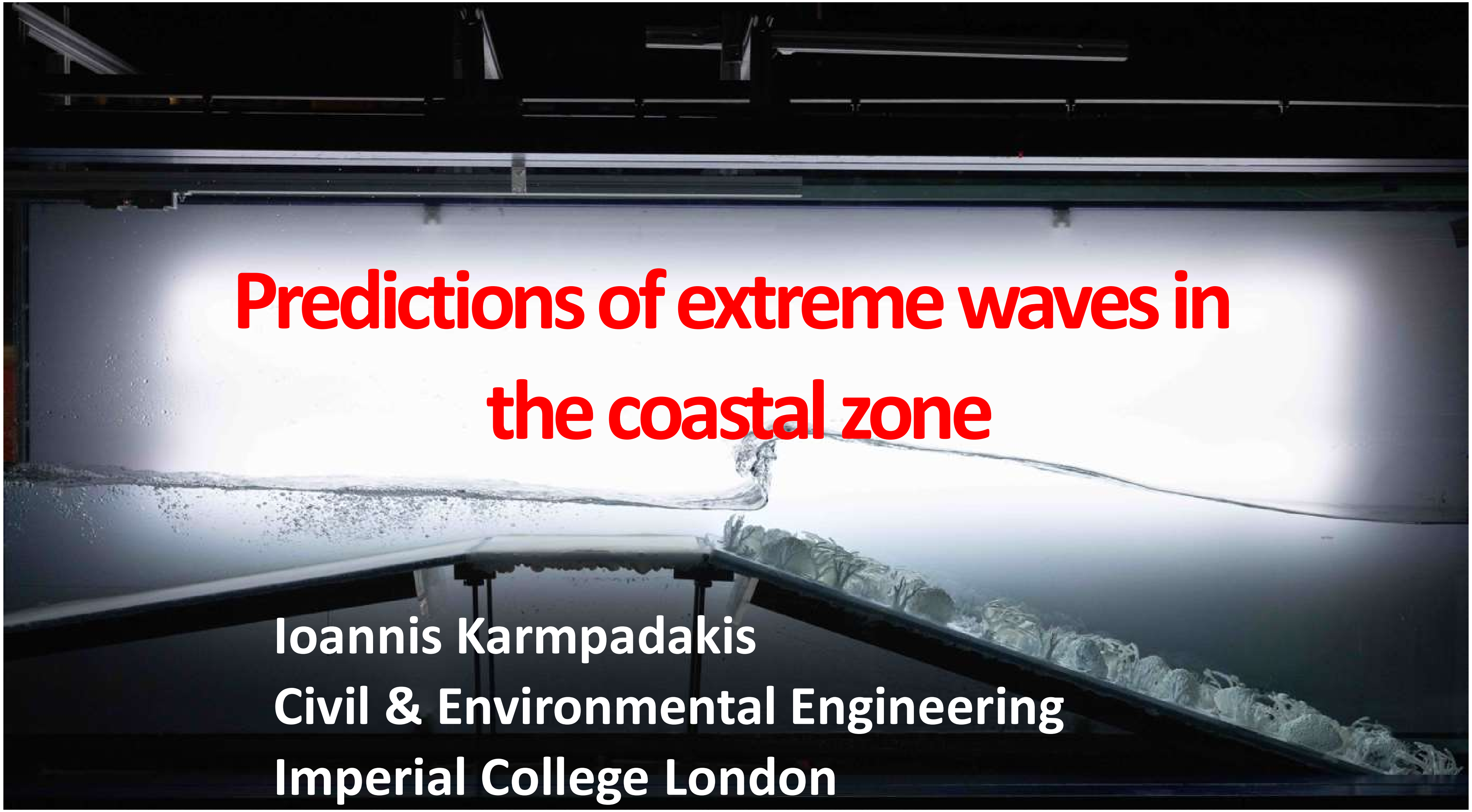
IMPERIAL

Challenger Society Ocean Wind Waves SIG
Liverpool, 30th June 2025



Predictions of extreme waves in the coastal zone

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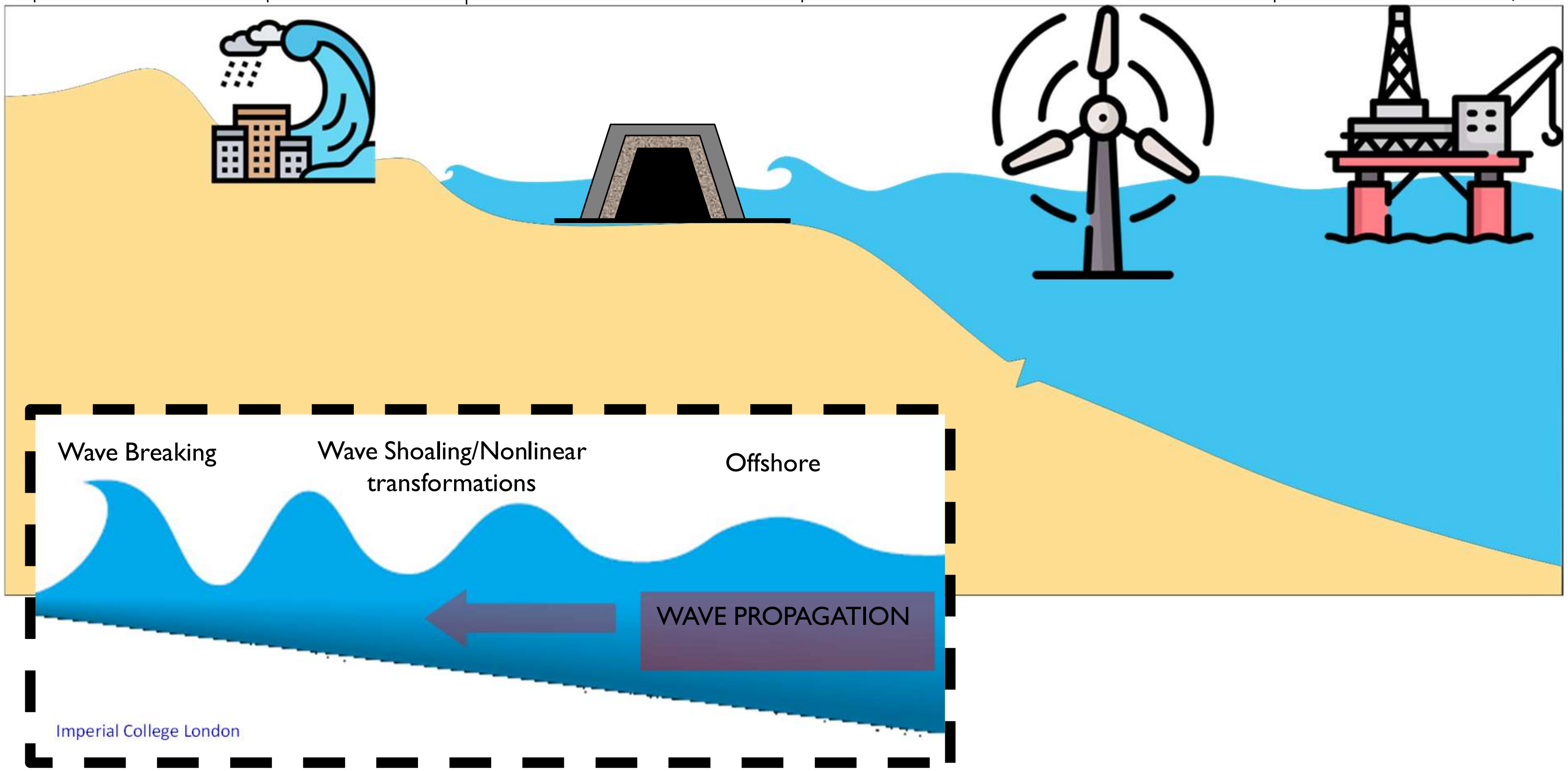
Motivation

Reliability of structures/vessels in intermediate and shallow water depths.

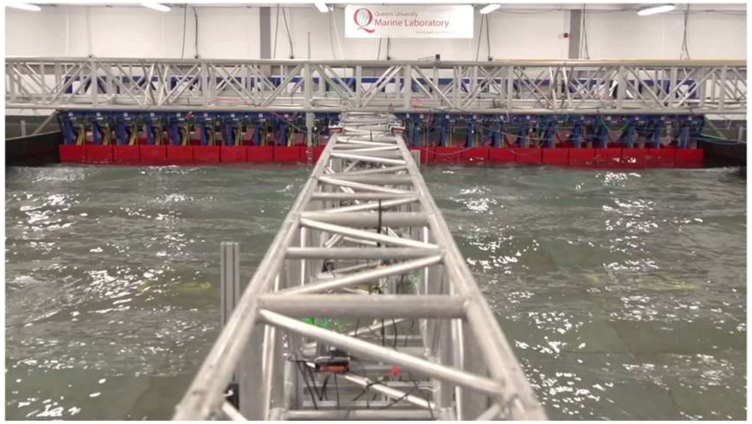
ZONE	BEACH	SURF ZONE	SHOALING ZONE	OFFSHORE
Structure	Flood/Harbour	Coastal protection	Wind Energy	Oil & Gas



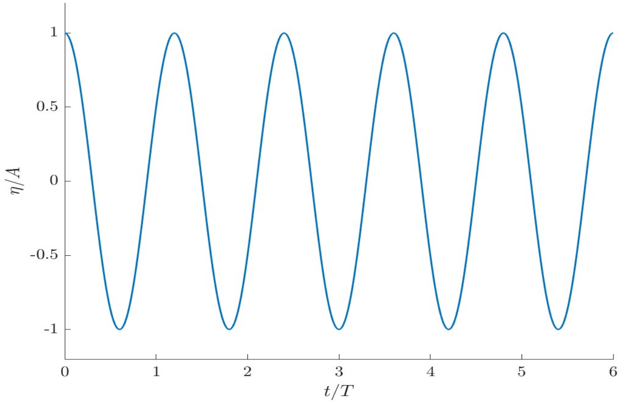
Theory

Why statistics?

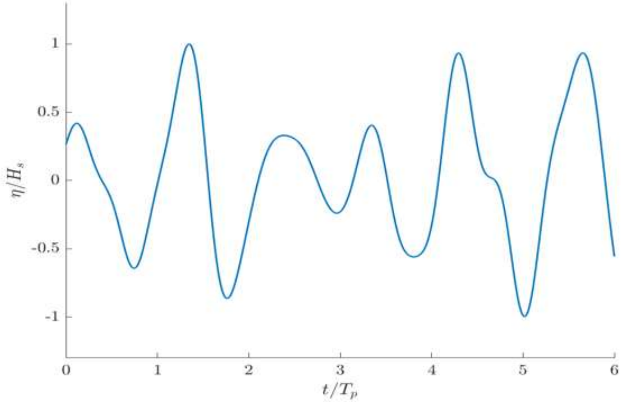
Nature of waves: random, multiple frequencies, amplitudes, directions.



Regular waves



Random waves

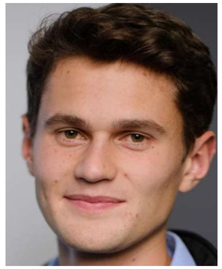


Outline

Predictions of extreme waves in the coastal zone

1. Context
2. Experimental results
3. Numerical modelling
4. Real-time prediction using CNN
5. Conclusions

Acknowledgements:

	
Vasilis Bellos	Umniya Al Khalili
	
William Wright	Oli Millar

Test cases

Rationale of parametric investigation

Wave generation: Karmpadakis & Swan (2020).
Each sea-state has >=20,000 waves.

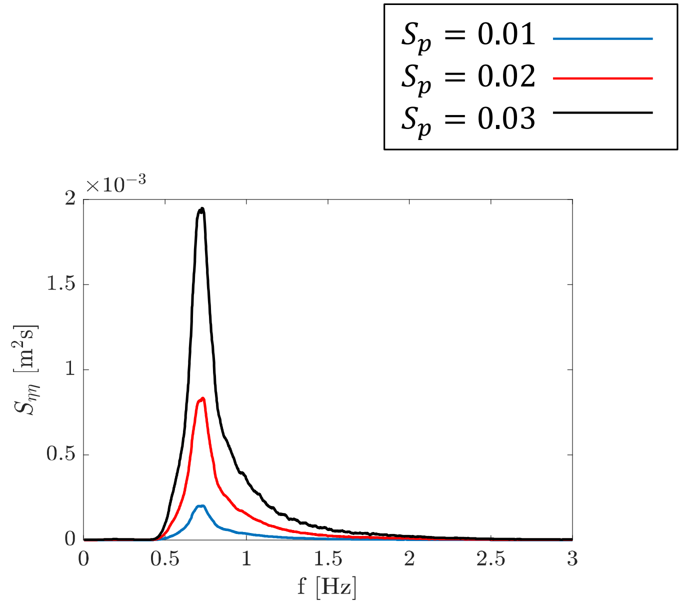
List of experimental cases

Sea-State	T_p [s]	$H_{s,0}$ [m]	$\frac{1}{2}H_s k_p$ [–]	s [–]	$k_p d$ [–]
Tp12SS1		0.023	0.035		
Tp12SS2		0.046	0.070		1.53
Tp12SS3	1.2	0.068	0.105	1/50	⋮
Tp12SS4		0.091	0.140	1/30	0.15
Tp12SS5		0.111	0.170		
Tp12SS6		0.124	0.190		
Tp14SS1		0.029	0.035		
Tp14SS2		0.057	0.070	0	1.22
Tp14SS3		0.086	0.105	1/50	⋮
Tp14SS4	1.4	0.115	0.140	1/30	0.13
Tp14SS5		0.139	0.170	1/15	
Tp14SS6		0.156	0.190		
Tp16SS1		0.034	0.035		
Tp16SS2		0.069	0.070	1/50	1.02
Tp16SS3	1.6	0.103	0.105	1/30	⋮
Tp16SS4		0.137	0.140		0.11
Tp16SS5		0.167	0.170		
Tp18SS1		0.040	0.035		0.88
Tp18SS2	1.8	0.080	0.070	1/50	⋮
Tp18SS3		0.119	0.105	1/30	0.10
Tp18SS4		0.159	0.140		

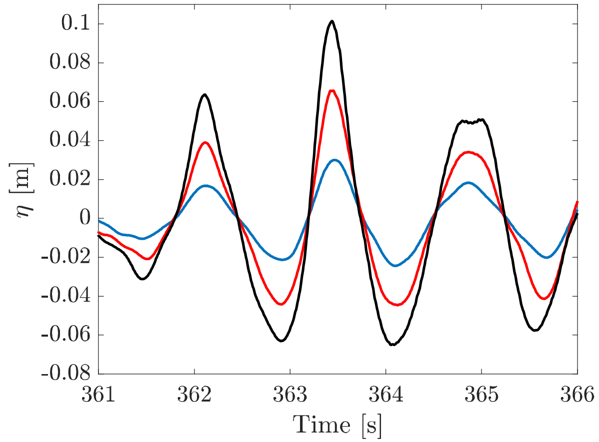
Effect of offshore steepness

Effect of bathymetry

Effect of bed slope



Variance spectrum



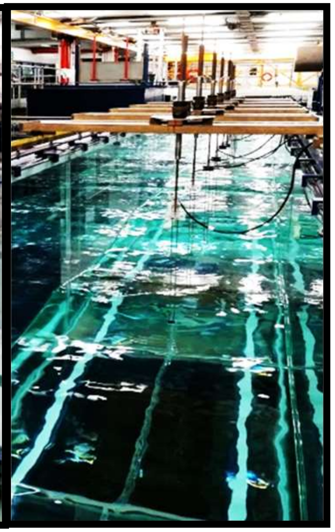
Timeseries segment

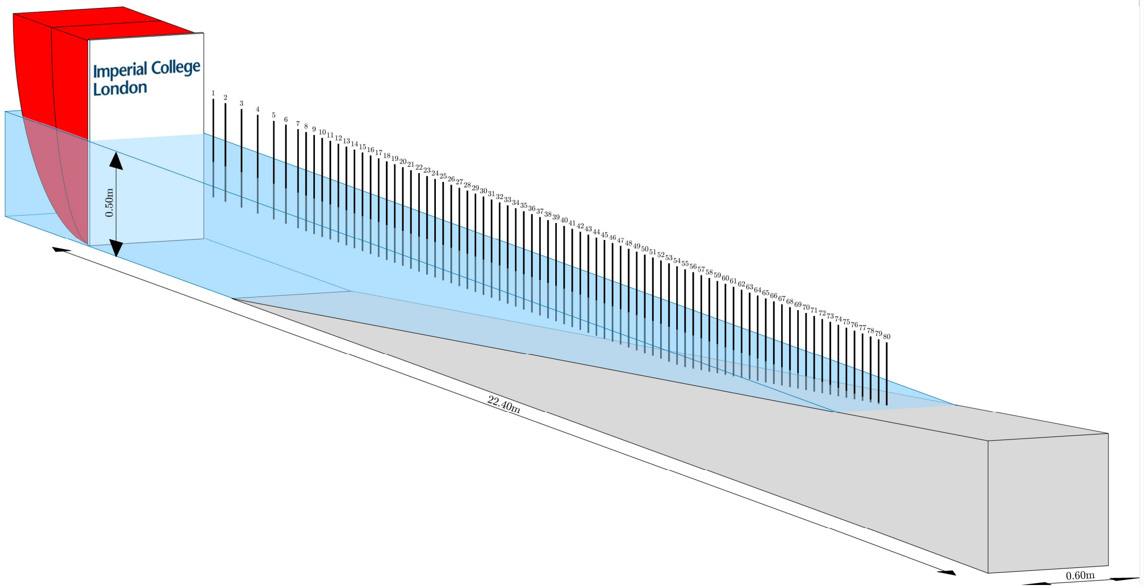
Karmpadakis and Swan, JPO (2020)

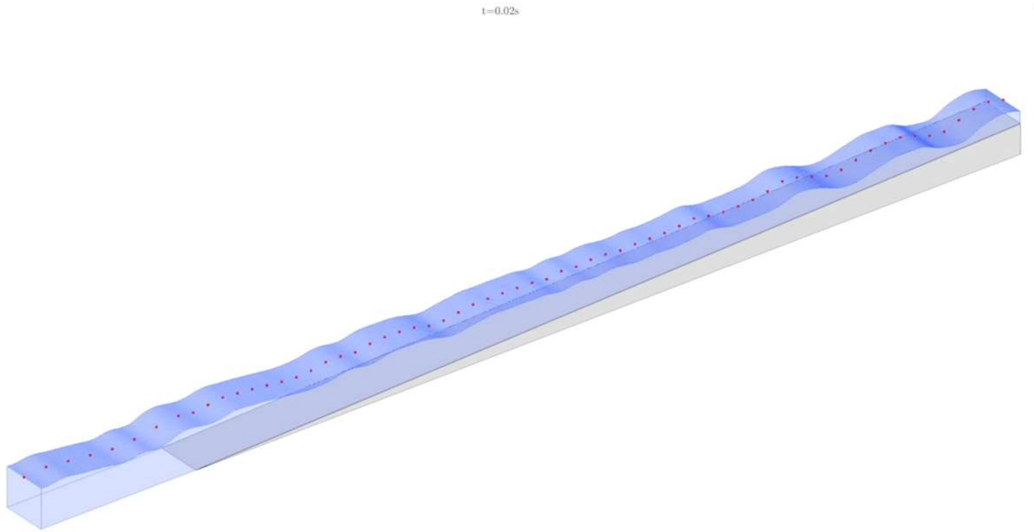
Experimental Setup

<u>Coastal Flume</u>

- L=22m, W=0.6m, d=0.4-0.8m
- Active & passive absorption
- Piston-type wave paddle
- Froude scaling ($L_s = 1{:}100$)
- Optimised active and passive absorption







Experimental Setup

4 different bed slopes

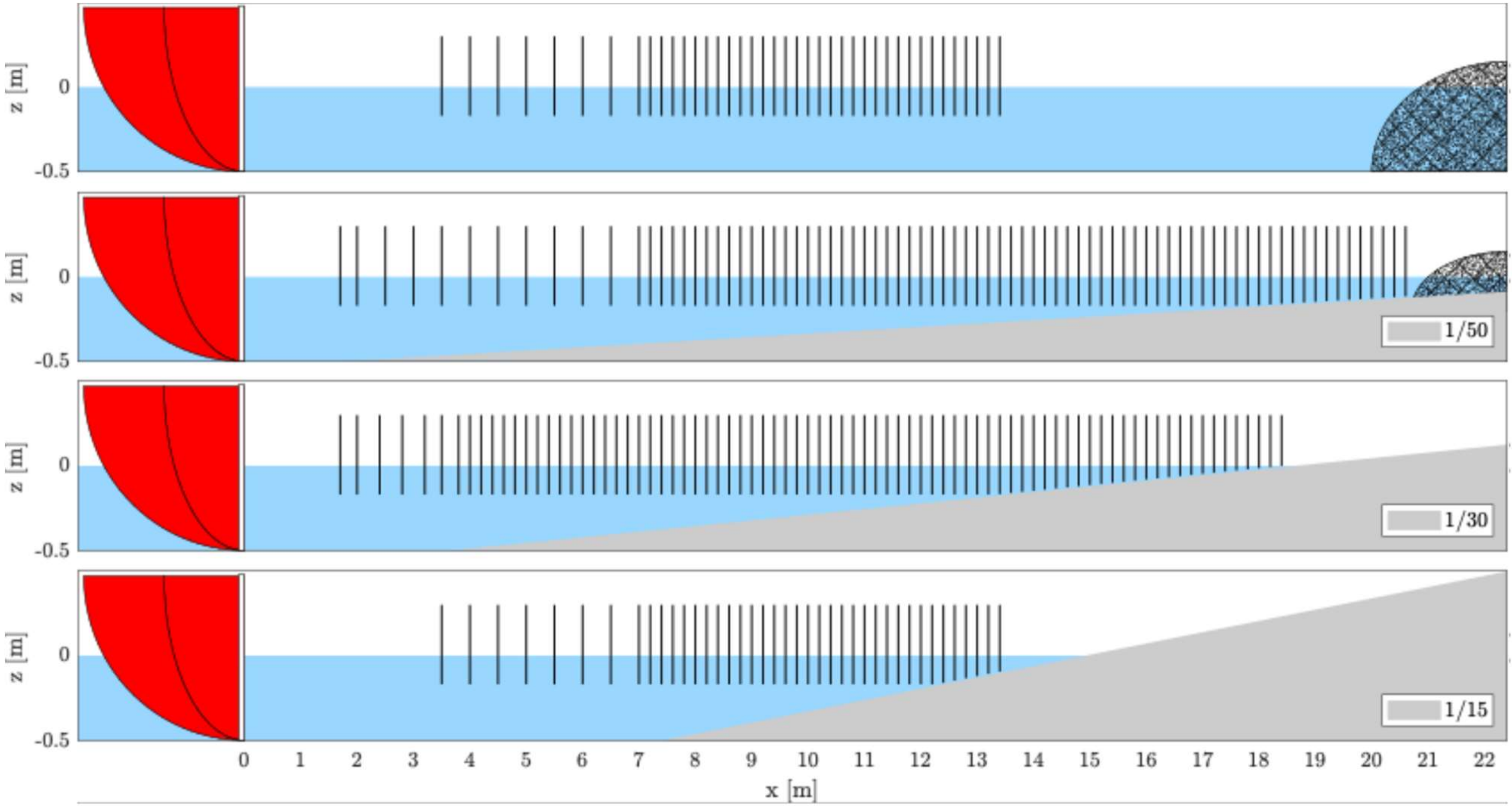
- Flat
- 1/50
- 1/30
- 1/15

40-80 wave gauges in each experiment

- 2m resolution in field scale

Total of

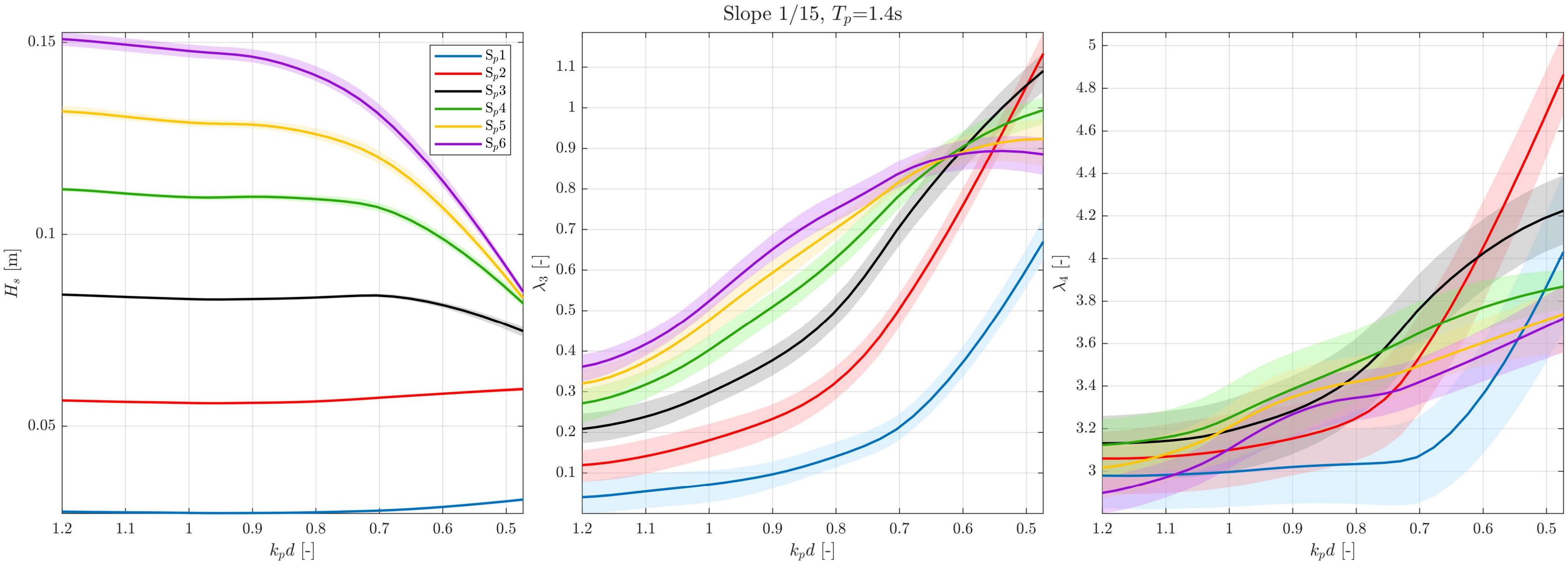
- 115 sea-states
- approx. 2m waves per location



Bellos & Karmpadakis, DMPCO (2023)
Bellos, Karmpadakis & Swan, ICCE Proceedings (2024)
Bellos, Karmpadakis & Swan, JFM(2025-under review)

Wave evolution
Challenges in modelling

Evolution of integral statistics with 90% CIs



H_s Skewness Kurtosis

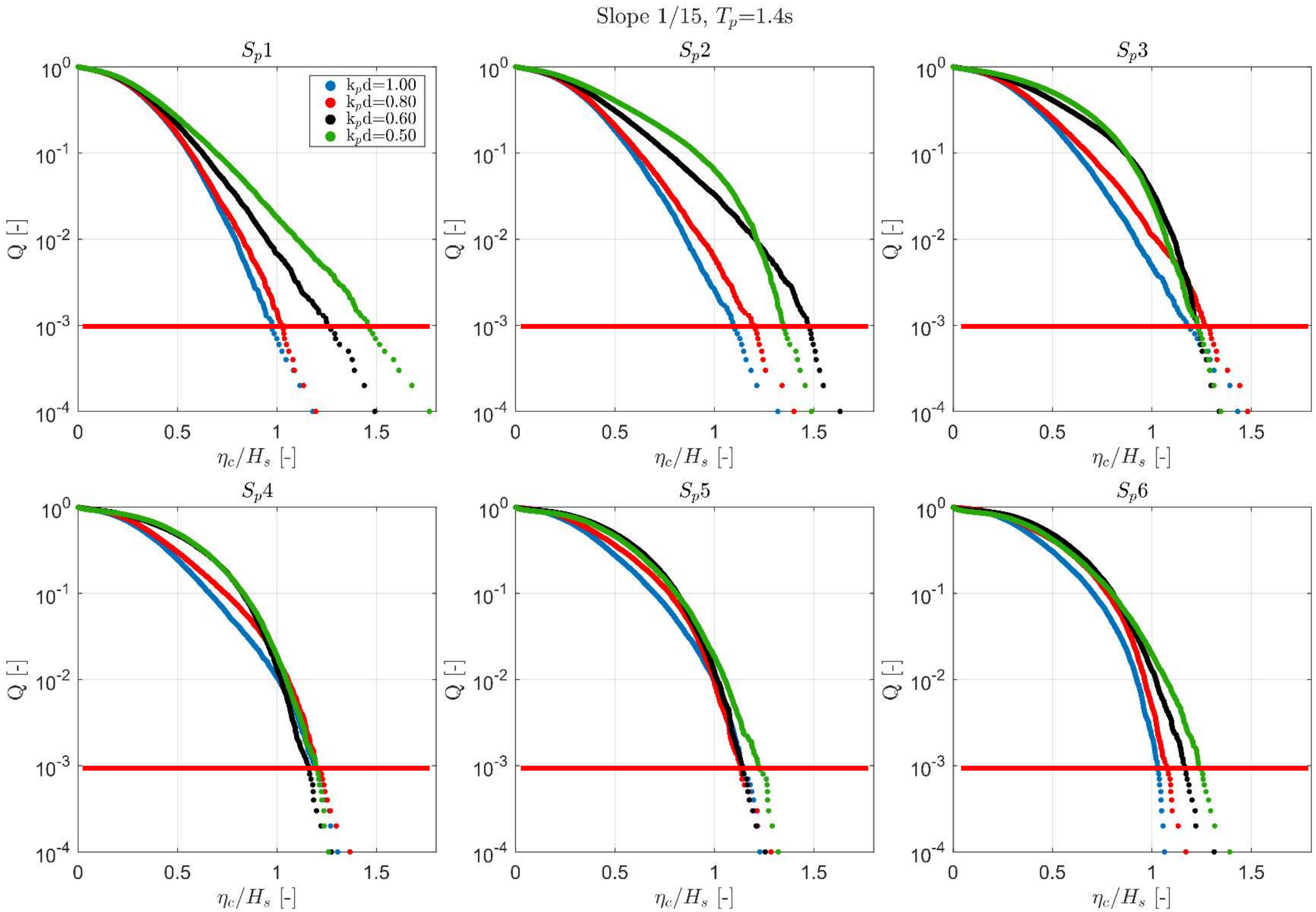
Wave statistics
Effect of Bathymetry

- $k_p d$ reduces:
  - η_c/Hs increases

- Wave breaking:
  - η_c/Hs reduces in the tail of the distributions

- Tail changes:
  - Changes progressively earlier as S_p increases

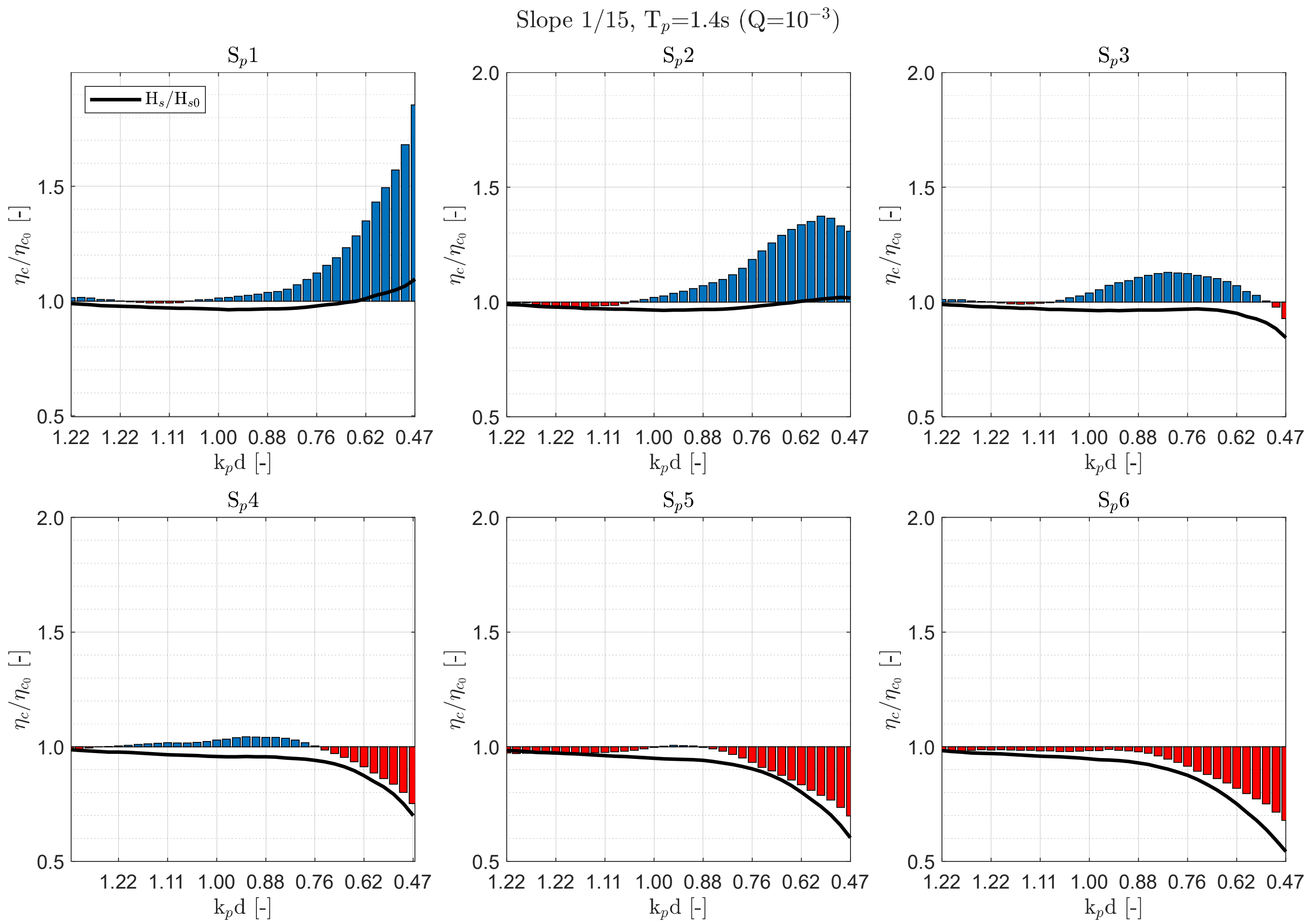
The distributions eventually converge and then once again start to increase



Wave statistics
Effect of Bathymetry

- Spatial evolution for Q=10^{-3}
- η_c/η_{c0} and H_s/Hs_0 separately
- Increase:
  - Nonlinear amplifications & wave shoaling
- Decrease:
  - Breaking dissipation

The evolution ratio has important implications for the definition of design waves.



Numerical results

Can SWASH recover these statistics?

- Numerical reproduction of experimental results using SWASH (Zijlema, 2011).
- Reduced equations relevant to 2D problem.
- Phase –resolving, non-hydrostatic.

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu}{\partial x} = 0 \quad (1)$$

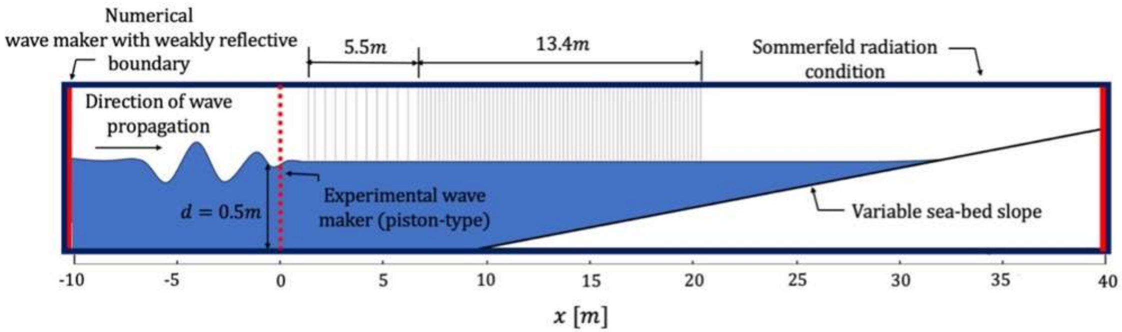
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} + \frac{1}{2}\frac{\partial q}{\partial x} + \frac{1}{2}\frac{q}{h}\frac{\partial(\eta - d)}{\partial x} + c_f\frac{u|u|}{h} = \frac{1}{h}\frac{\partial}{\partial x}\left(h\nu_T\frac{\partial u}{\partial x}\right) \quad (2)$$

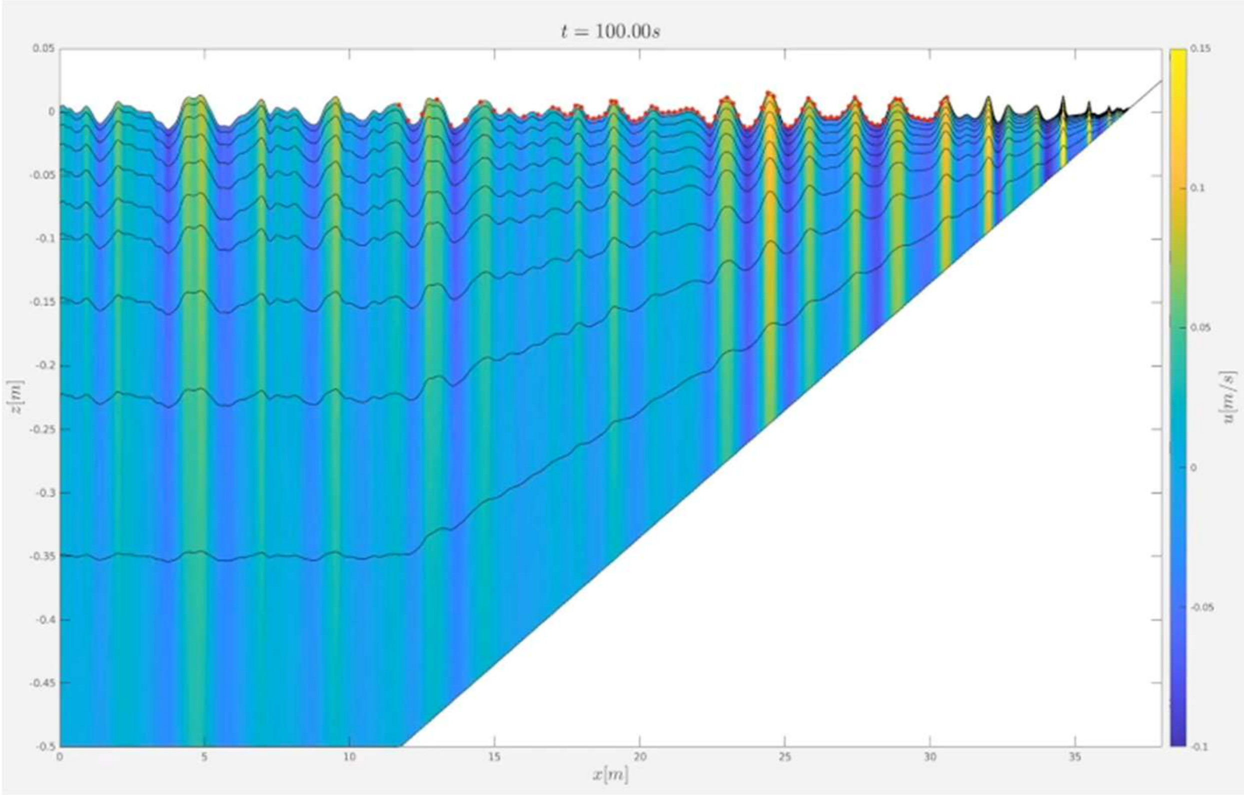
$$\frac{\partial w_s}{\partial t} = \frac{2q}{h} - \frac{\partial w_b}{\partial t} \quad (3)$$

$$w_b = -u\frac{\partial d}{\partial x} \quad (4)$$

$$\frac{\partial u}{\partial x} + \frac{w_s - w_b}{h} = 0 \quad (5)$$

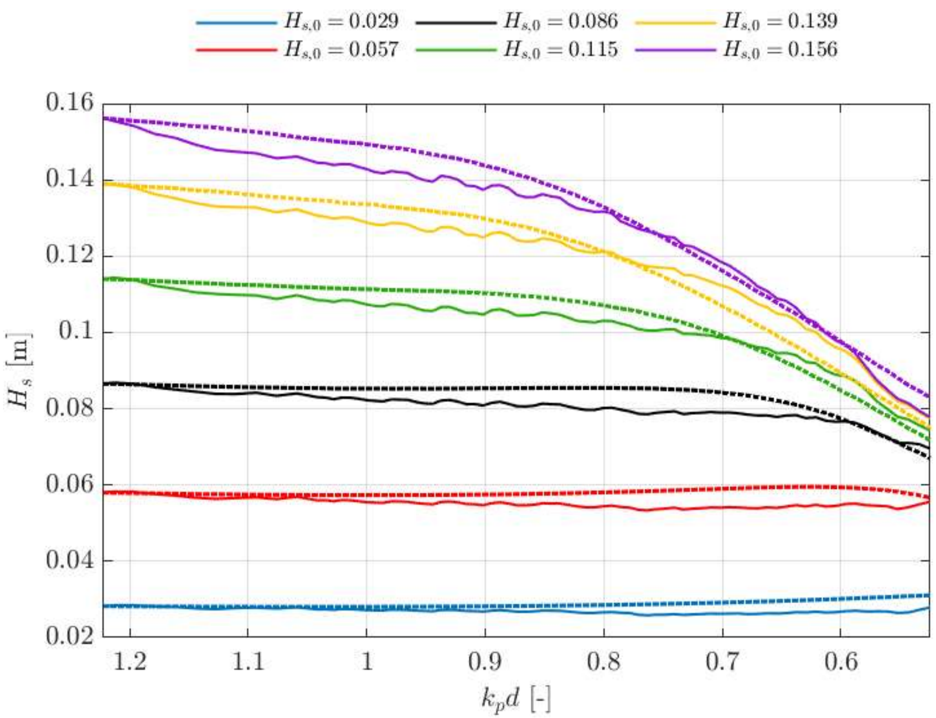
Al Khalili, Karmpadakis, Christou & Bellos, Coastal Eng (2025)

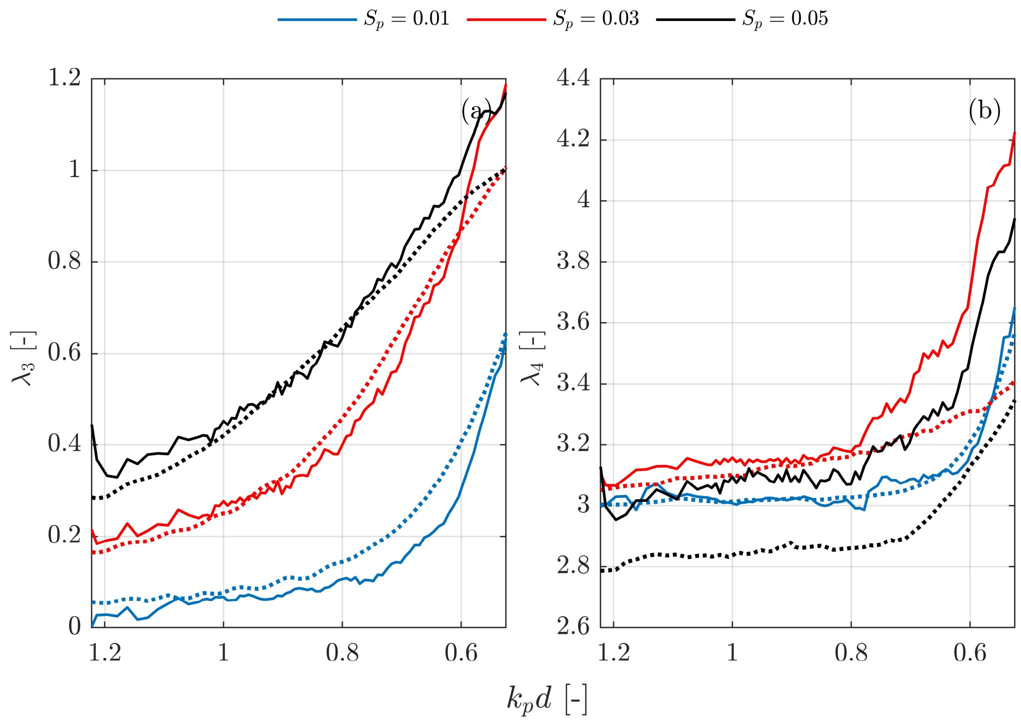




Numerical results
Comparison to experiments

Slope 1/50

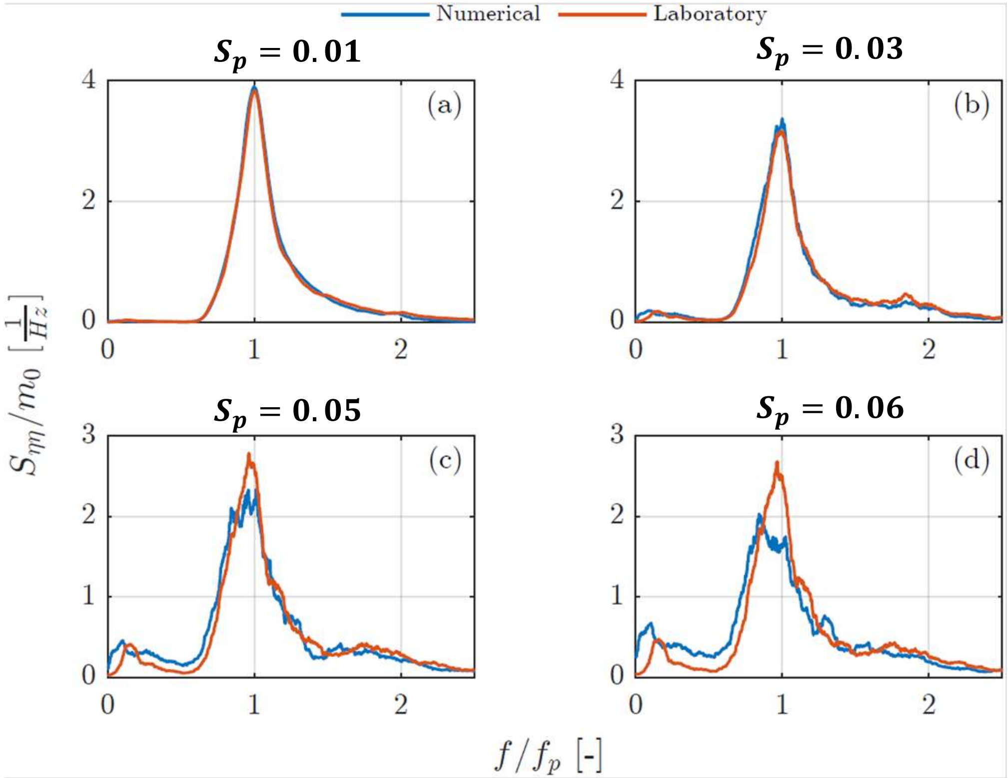


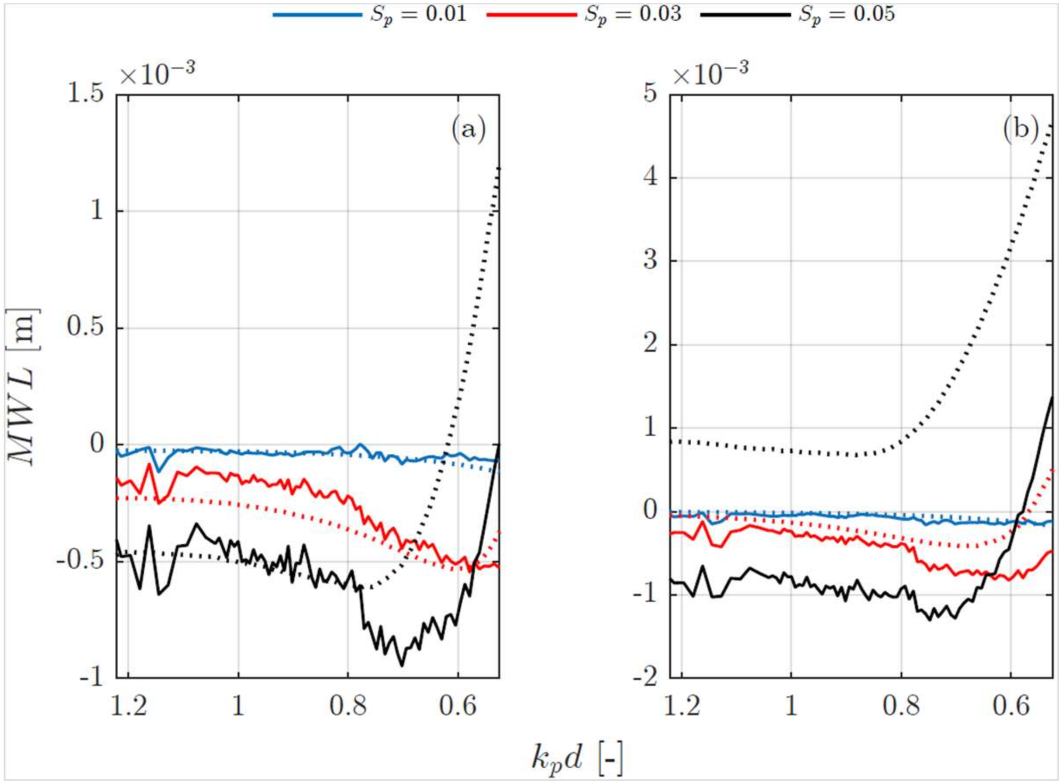


Experimental data
Numerical data

Numerical results
Comparison to experiments

Slope 1/50





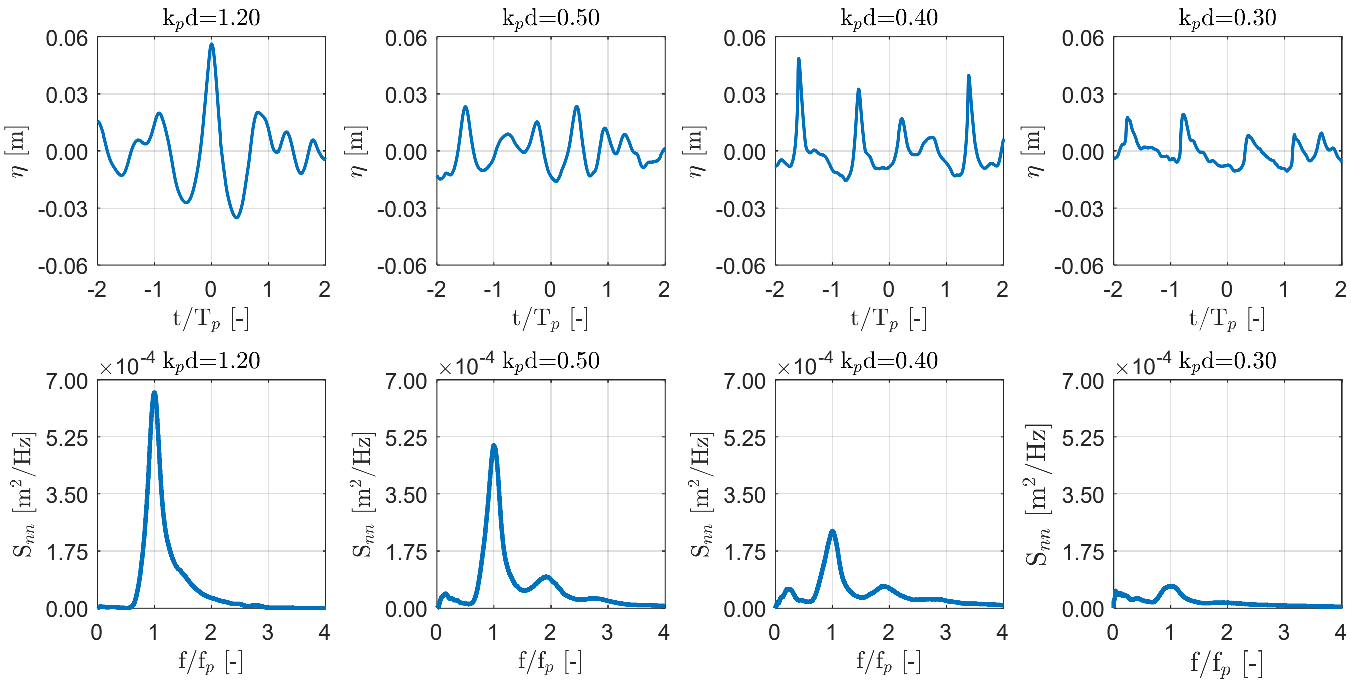
$k_p d = 0.69$

Al Khalili, Karmpadakis, Christou & Bellos, Coastal Eng (2025)

———	Experimental data
- - - ·	Numerical data

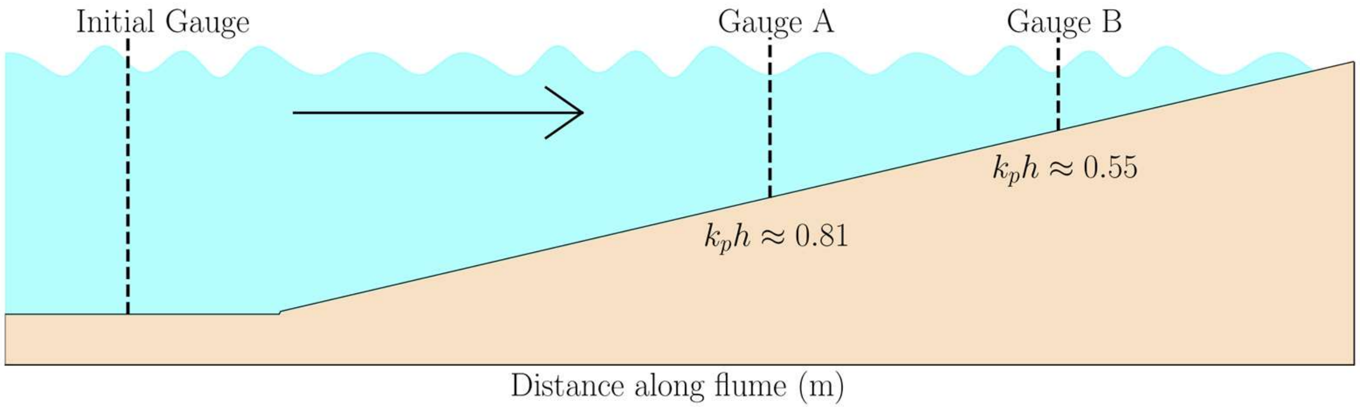
Wave evolution
Challenges in modelling

$k_p d$ reduces → nonlinearity increases:
- Crest-trough asymmetry
- Higher and sharper crests
- Shallower and broader troughs
- Transfer of energy to super/sub harmonics
- Wave breaking:
  - ➢ Energy dissipation

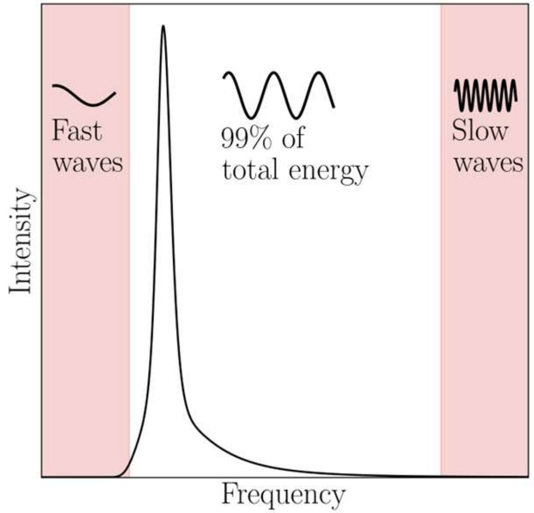


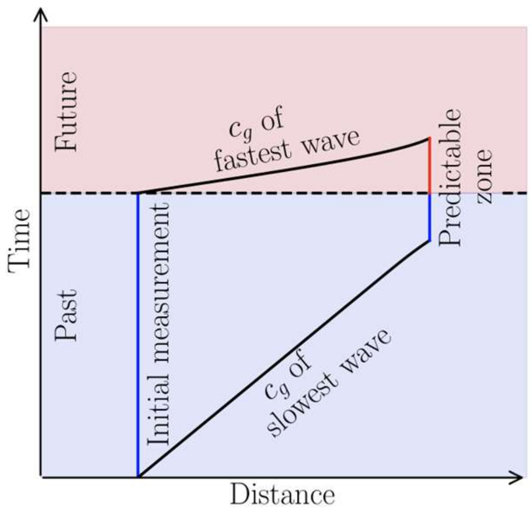
Interplay:
- Nonlinear wave-wave interactions
- Dispersion
- Wave breaking

Wave evolution
Problem statement



- Take a short measurement of $\eta(t)$ offshore
- Predict $\eta(t)$ onshore
- Examine and compare the accuracy of different methods.





- Incorporate limitations by the prediction zone

Wave evolution
Physics-based modelling and NN

Linear Wave Theory (LWT):

$$\eta(x,t) = \mathrm{Re}\left\{ \sum_n a_n e^{-i\omega_n t} \right\}$$

$$\mathrm{d}_x a_n = \left(ik_n - \mathrm{d}_x \sqrt{c_{g,n}} \right) a_n$$

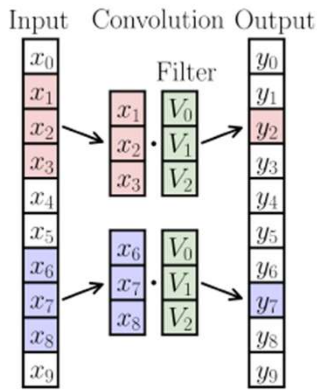
Second order correction (SOWT):

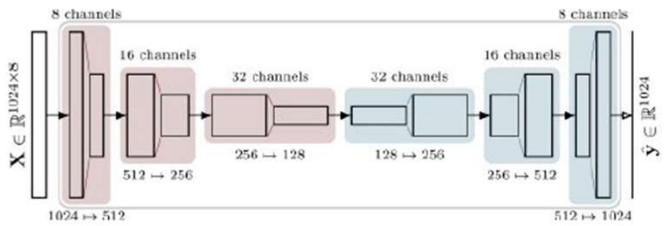
$$\mathrm{d}_x a_n = \left(ik_n - \mathrm{d}_x \sqrt{c_{g,n}} \right) a_n - i \sum_r V_{r,n-r} a_r a_{n-r}$$

The interaction kernels V are taken from Akrish et al. 2024 (QuadWave1D).

In this work we use a **convolutional neural network (CNN)**:

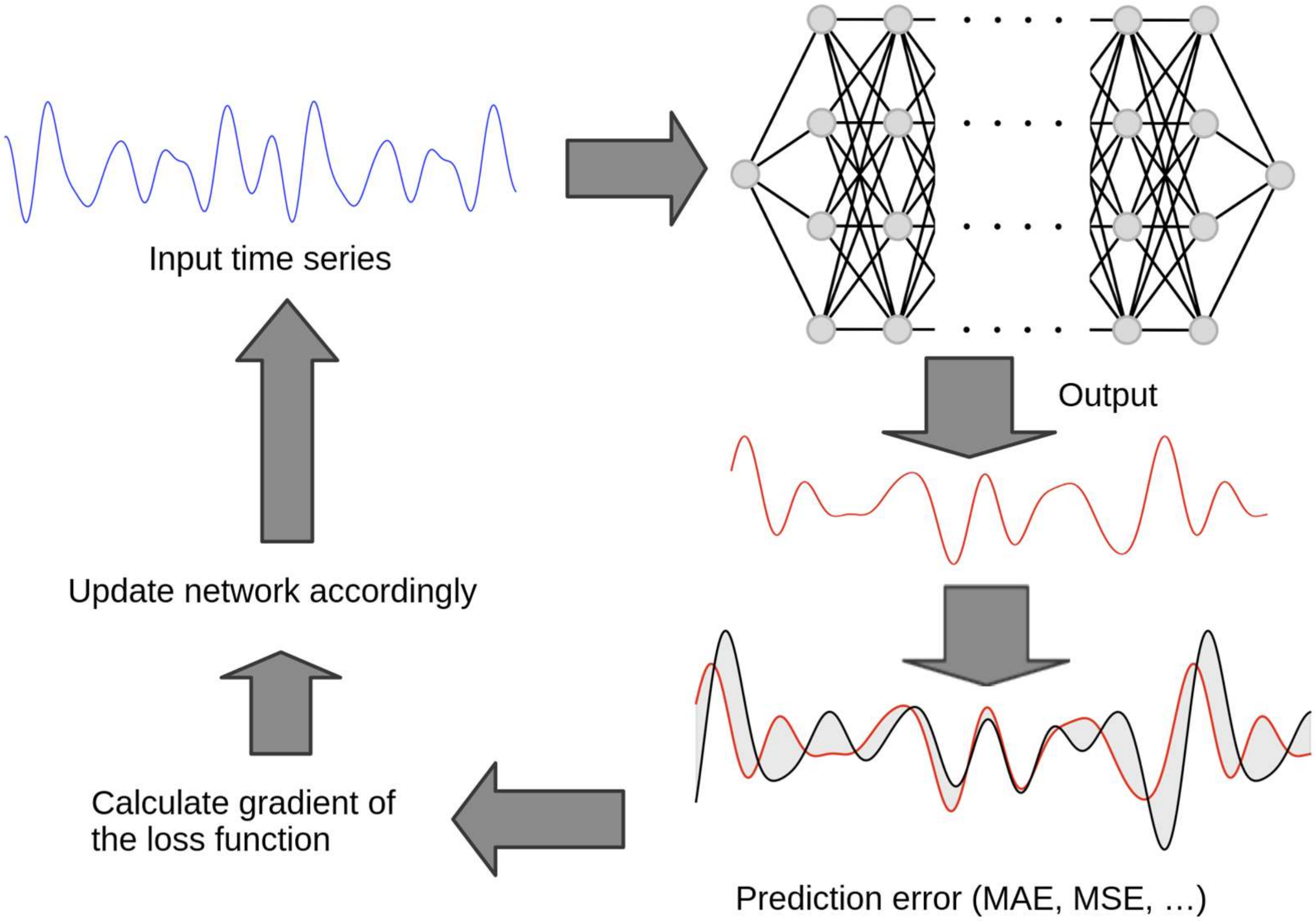
- Trainable parameters take the form of **filters**
- These are fixed arrays which sweep along the input arrays, as shown in the figure
- Multiple filters expand the input dimension into multiple **channels**



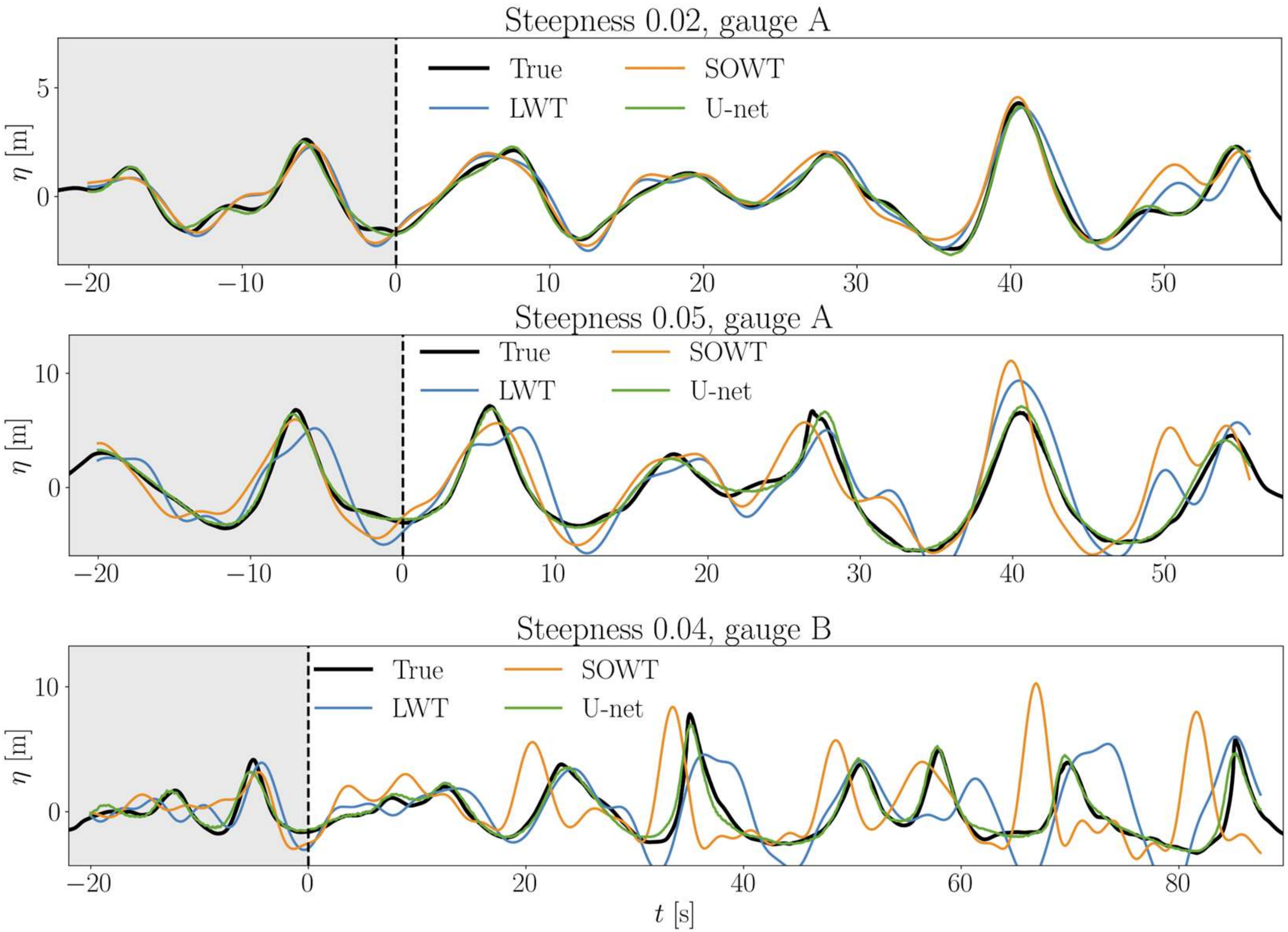


We use a **U-net** architecture.
Picture taken from Wedler et al. (2022).

Wave evolution
Physics-based modelling and NN

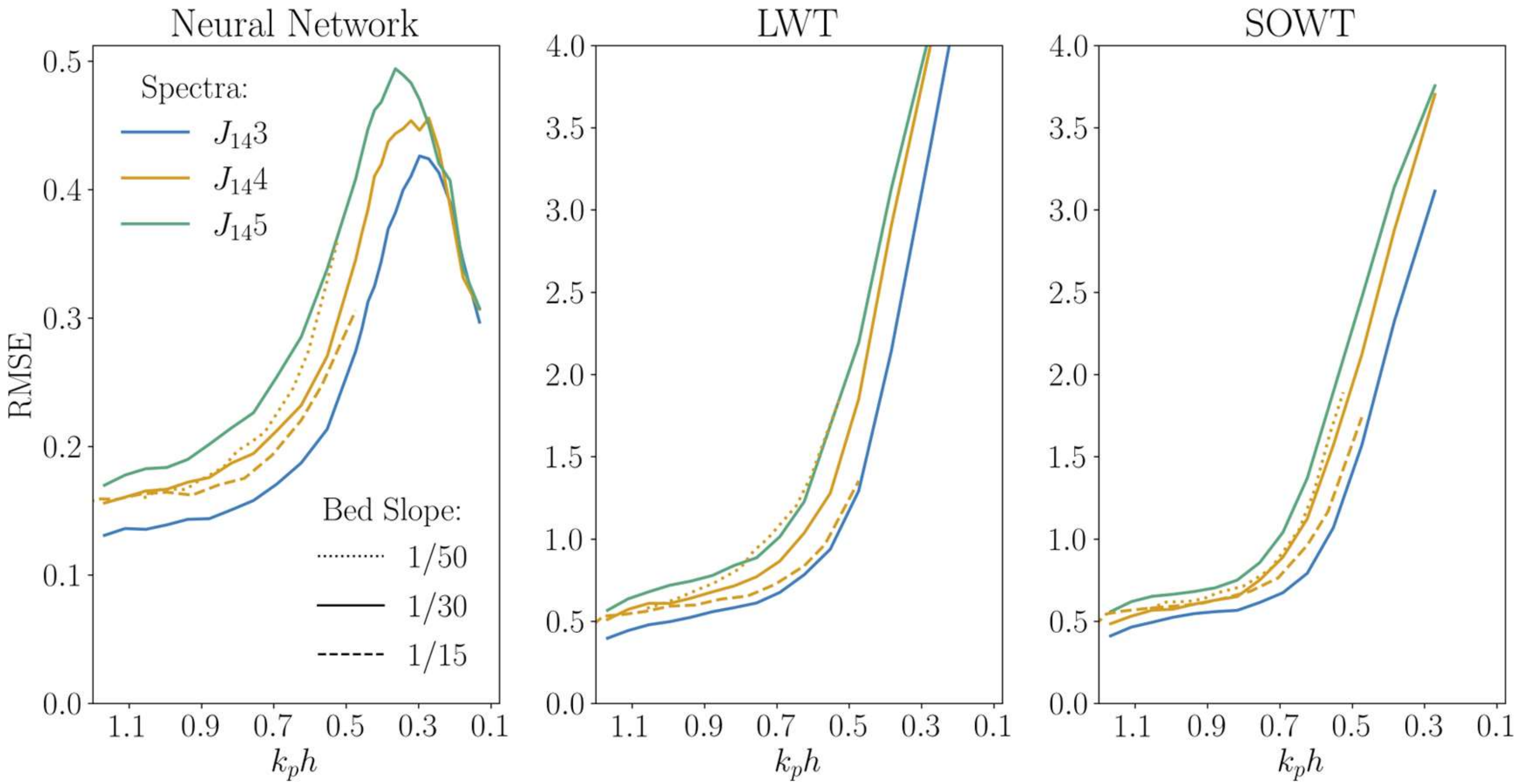


Wave evolution
UNET predictions



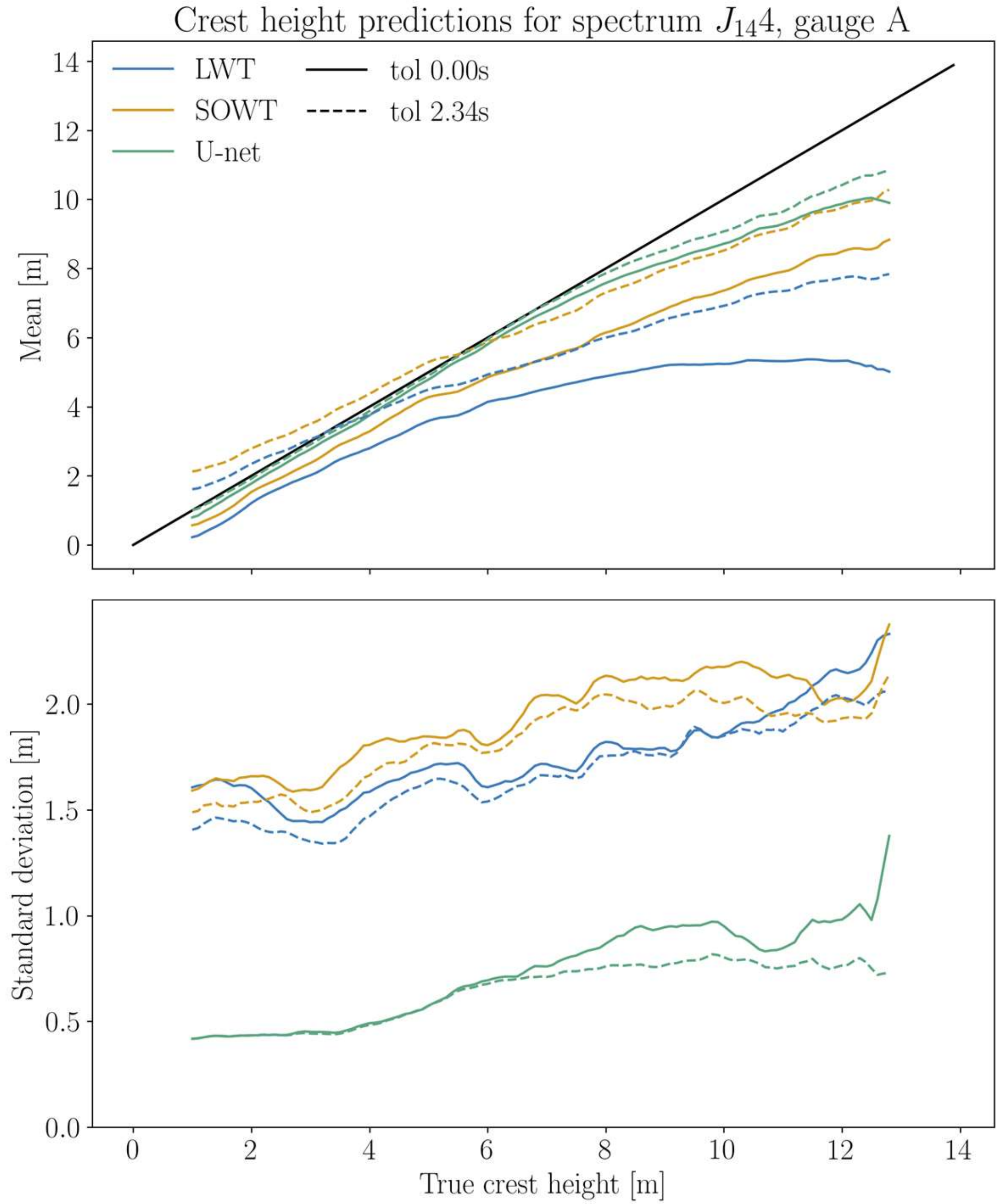
Wave evolution

Effect of depth on predictions



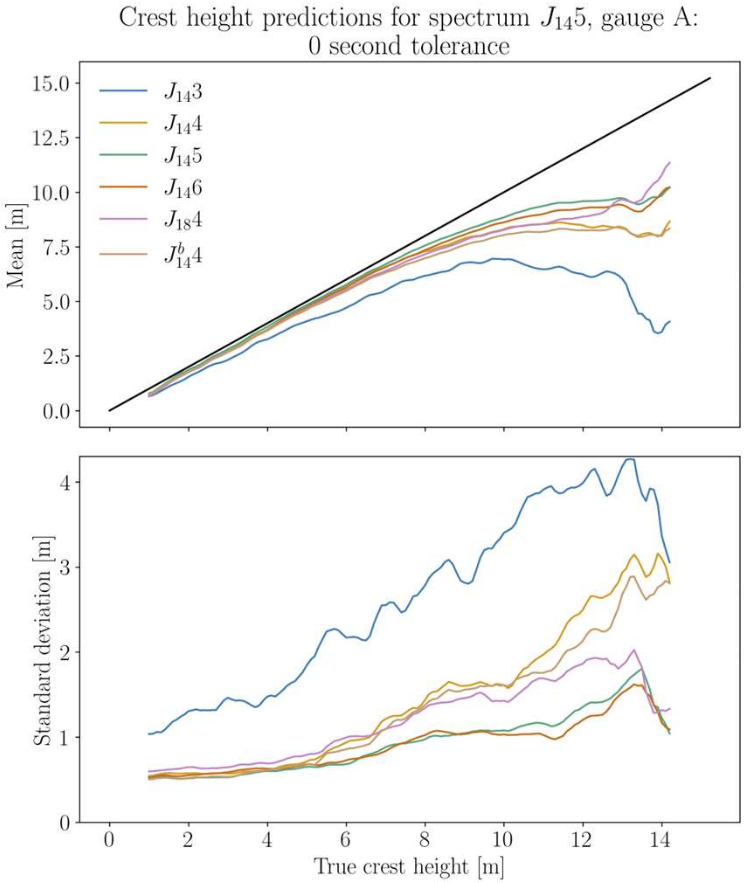
Wave evolution
Crest predictions

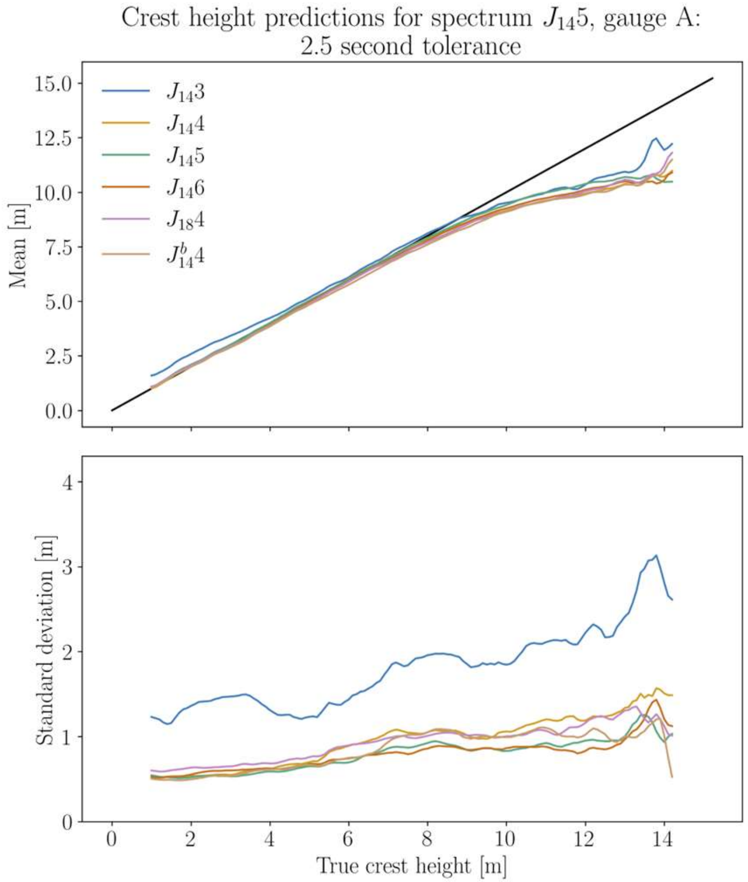
- Predict 2,000 η_c for 35 T_p in advance
- Overall, very good predictive capacity
- Some challenges in the largest crests
- Significantly reduced std compared to other methods



Wave evolution
Overall performance

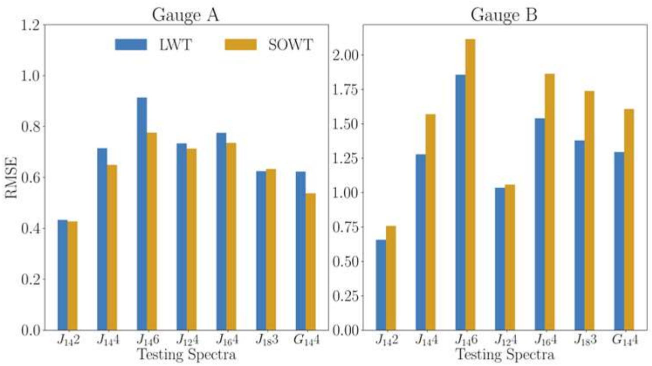
- Networks trained on different spectra provide similar accuracy
- Considerations for dispersion

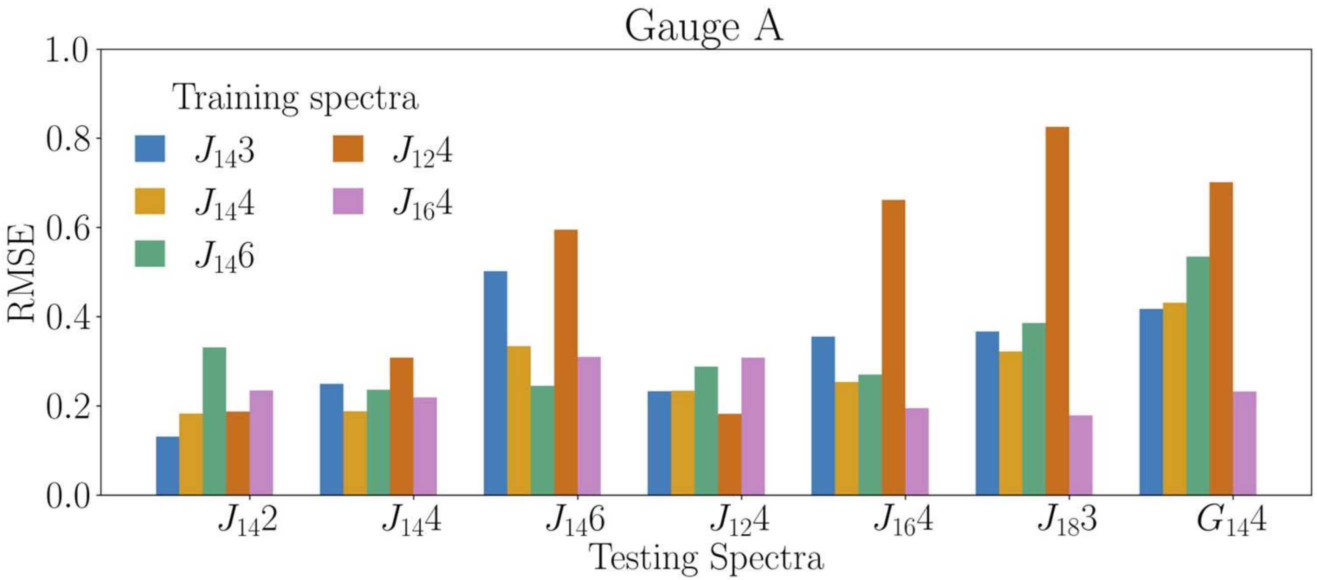


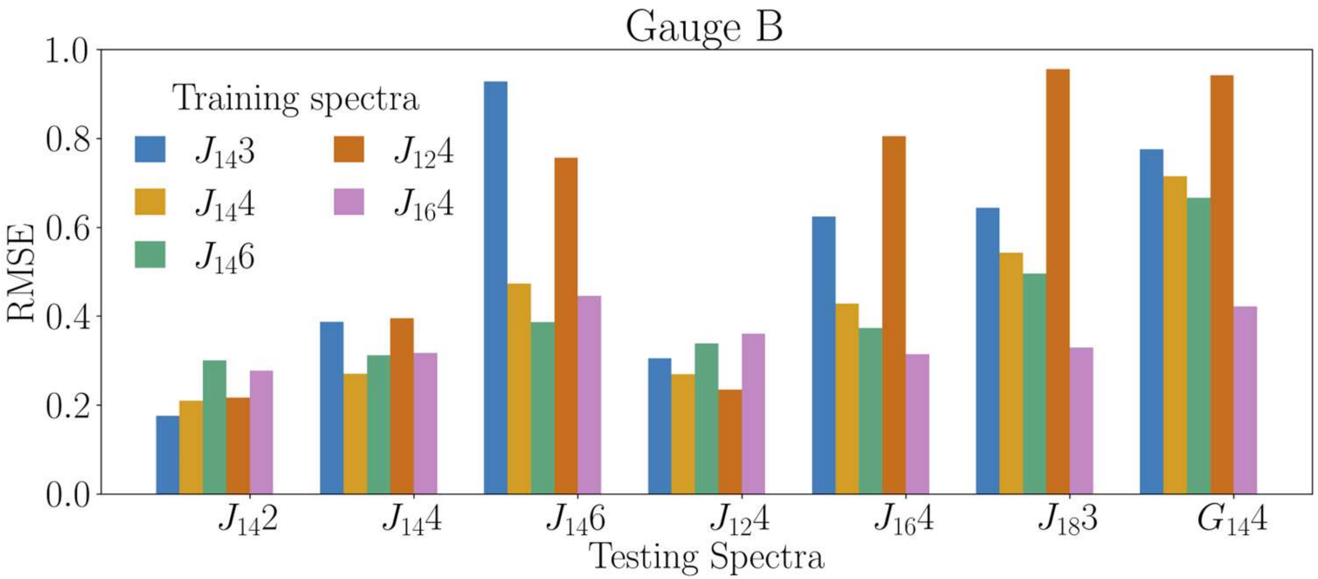


Wave evolution
Overall performance

- Generalisation to different spectral shapes
- Errors at least 5 times smaller than other methods







Conclusions

Real-time prediction of waves in the coastal zone.

➢Use of new extensive experimental/numerical dataset

➢NNs learn to a high degree of accuracy the propagation between 2 points

➢UNETs generalise well to unseen spectra

➢Challenges remain for extreme events

Wave evolution

Overall performance

Higher Loss & overfitting:

- Higher steepness
- Shallower depths