Simulation Methodologies and Statistical Analysis for Realistic Wave Representation in Wave Energy Converter Design

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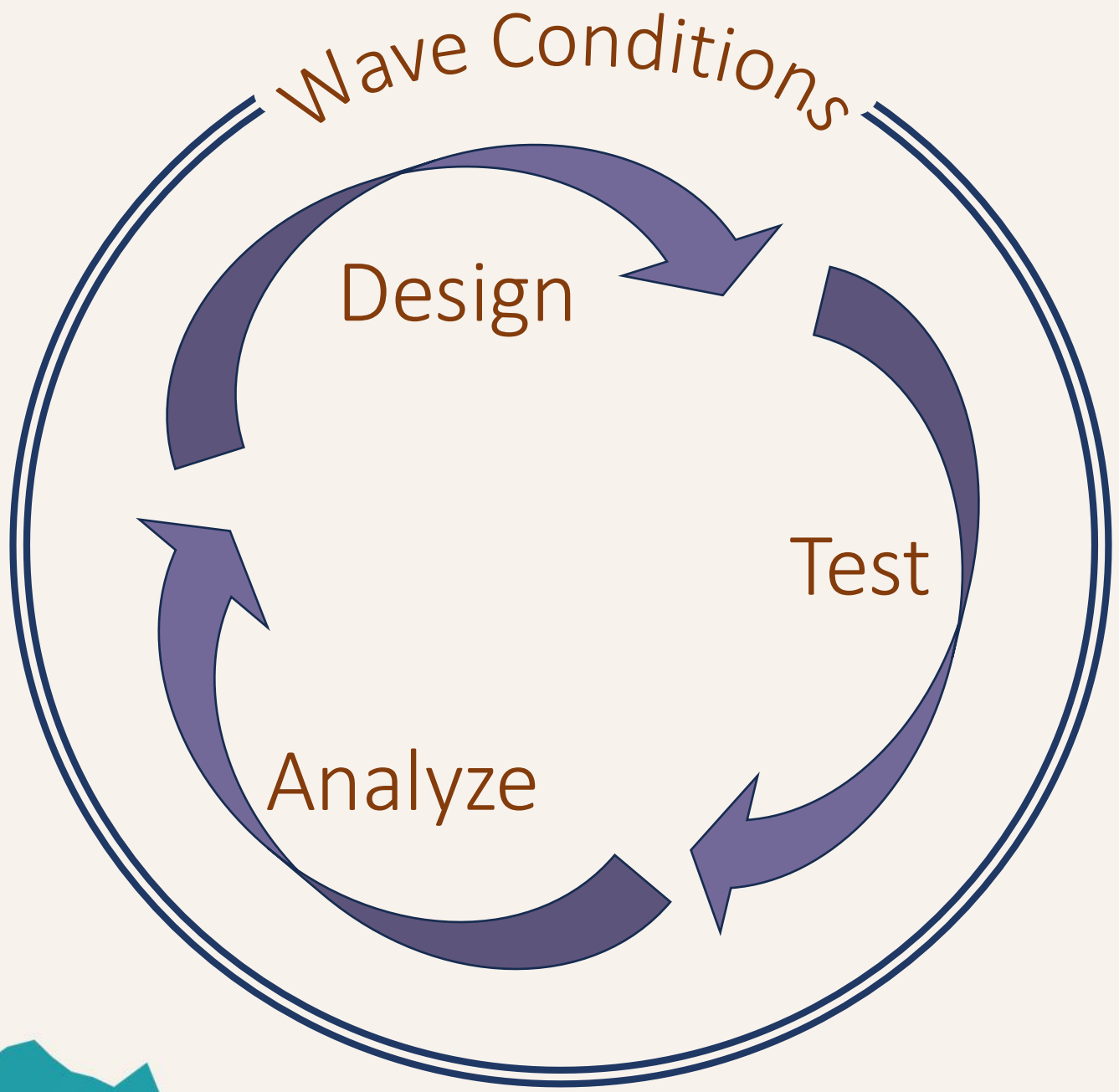
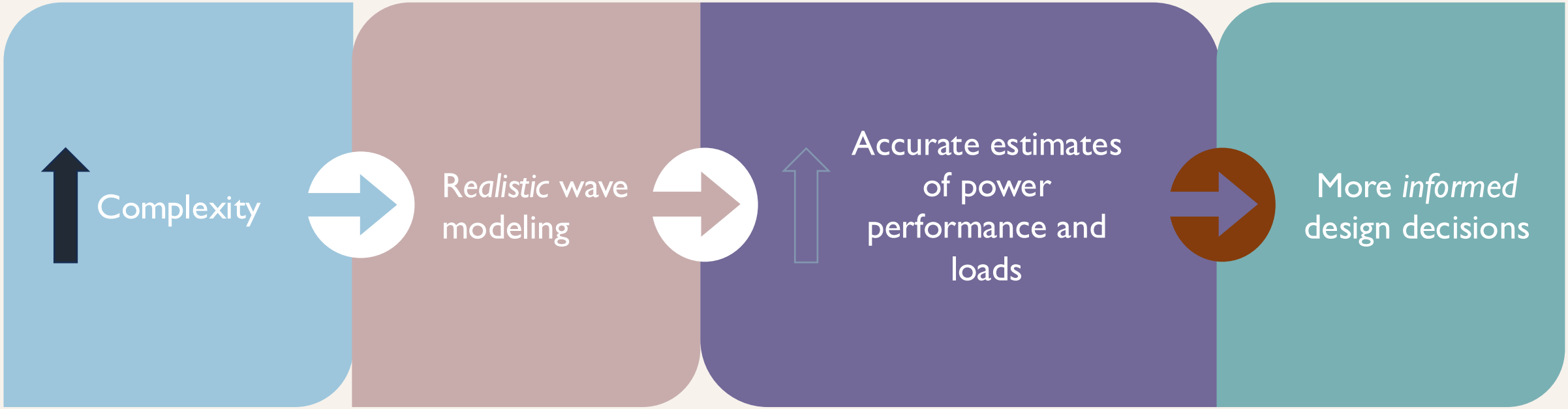
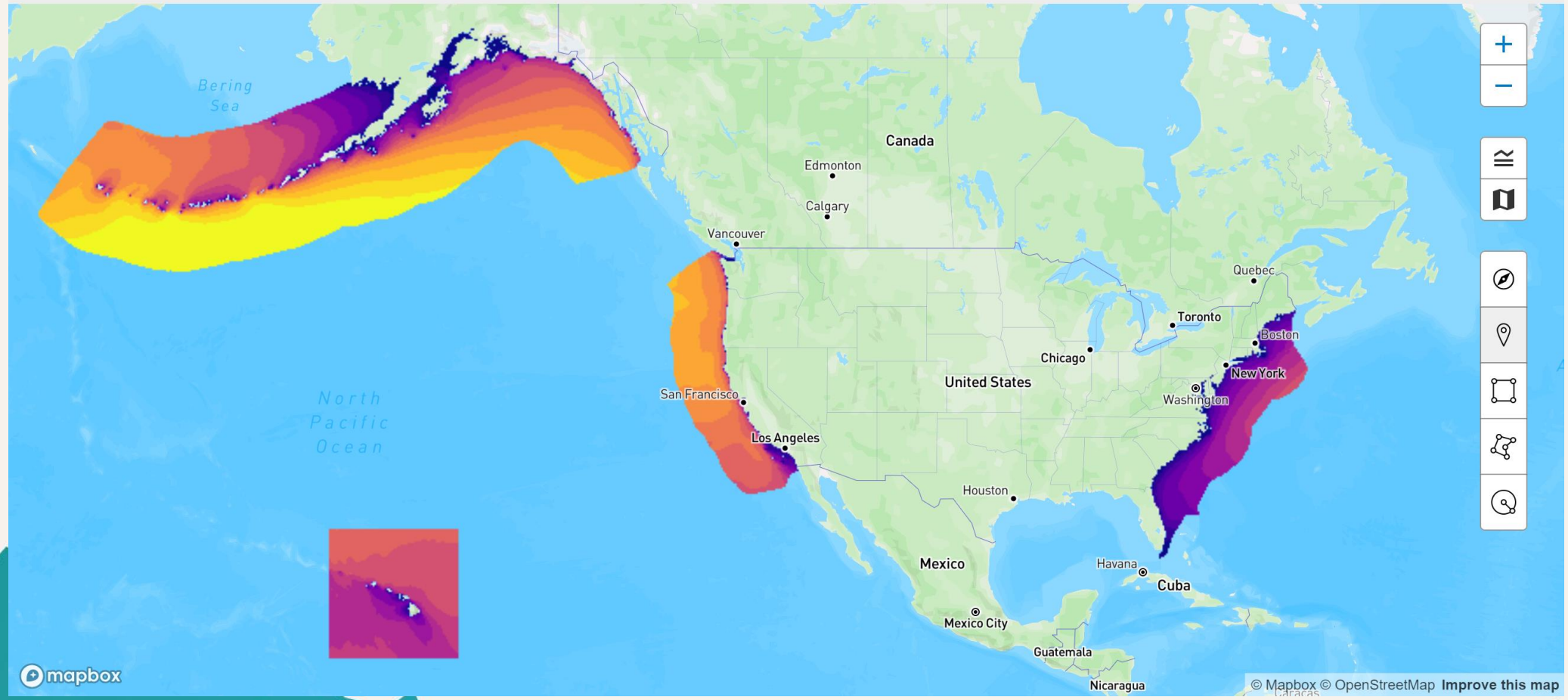

Wave Conditions
Design
Test
Analyze

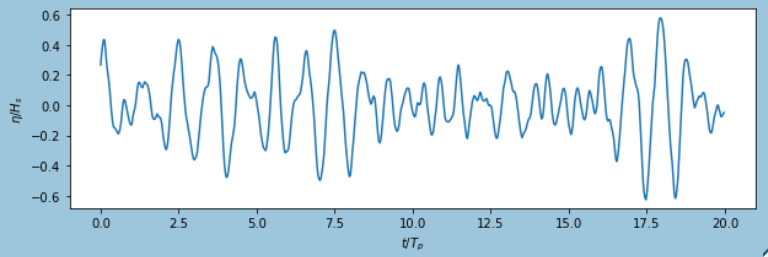

Complexity
Realistic wave modeling
Accurate estimates of power performance and loads
More informed design decisions

Marine Energy Atlas

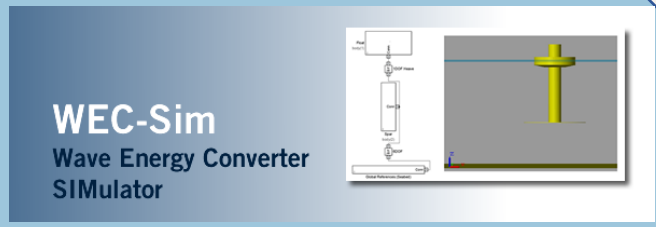


Low resolution data (i.e., buoy data, hindcast data)

High temporal free-surface time series



Numerical Modeling



WecOptTool

How can wave resource modeling be improved to provide ***realistic, representative*** wave time series?

Time Series Generation Methods

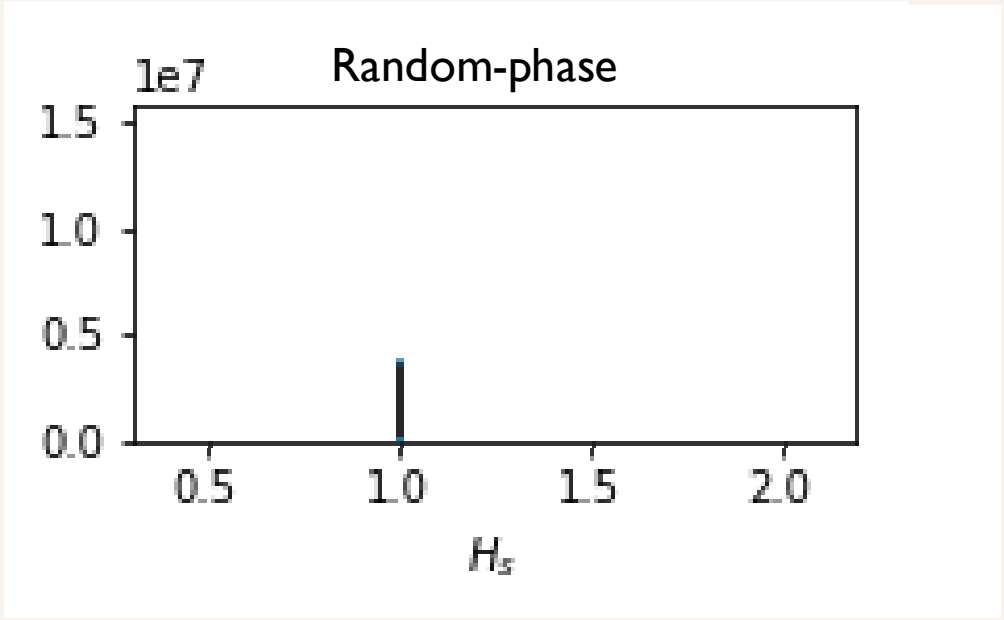
Random-phase Method

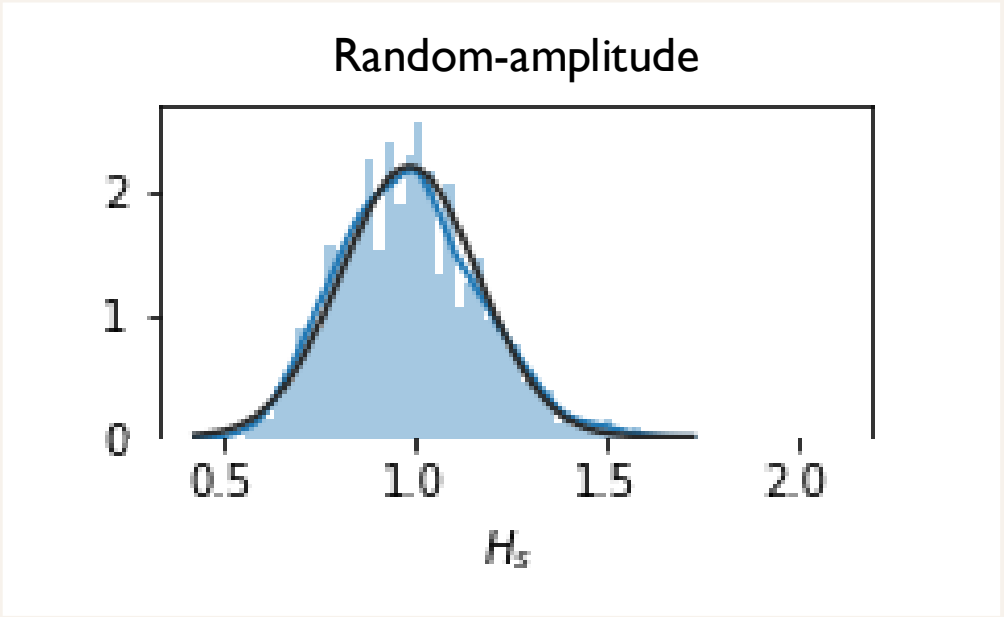
$$\eta_{t_i} = \sum_{k=1}^{M/2} A_k \cos(2\pi f_k t_i + \phi_k)$$

$$A_k = \sqrt{2S(f_k)\Delta f}$$

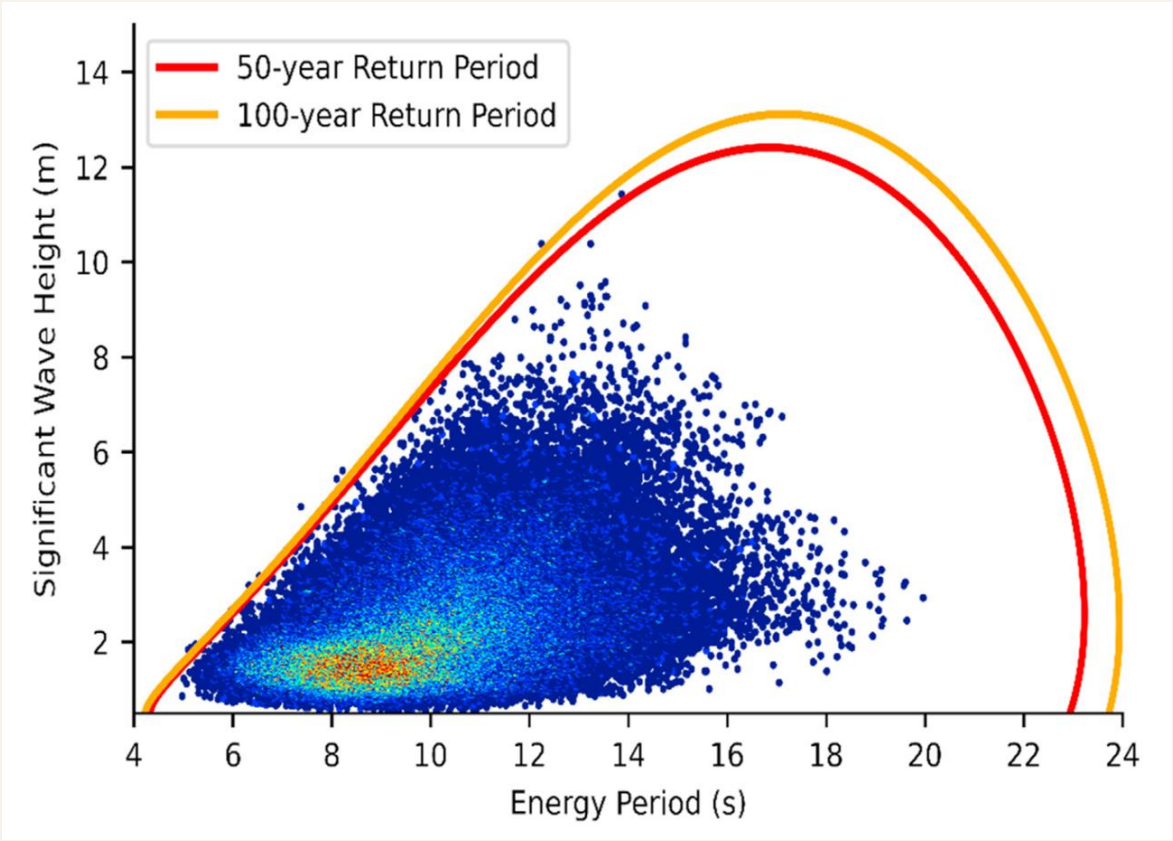
Random-amplitude Method

$$\eta_{t_i} = \sum_{k=1}^{M/2} A_k \cos(2\pi f_k t_i + \phi_k)$$


Random-phase
1e7
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
H_s


Random-amplitude
2
1
0
0.5
1.0
1.5
2.0
H_s

How many time series are needed to sufficiently represent key wave height percentiles?



Current International Electrotechnical Commission Guidelines

Normal operating wave conditions

- Three-hour time series
- 6 instances for each wave condition considered

Wave conditions prompting stopping conditions

- Ten-minute time series
- 6 instances for each wave condition considered

Previous Literature

Wave variation

Assessing wave variation in finite durations and effects on WEC power variation

- Tucker et al. (1984)
- Saulnier et al. (2011)
- Mérigaud & Ringwood (2018)
- Mankle et al. (2023)

Wave representation

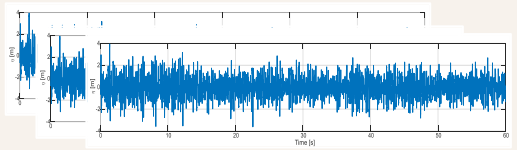
Investigating number of time series required for adequate extreme wave representation

- Tabeshpour & Belvasi (2023) found 50 time series required for extreme wave representation
  - Study limitation:
    - maximum wave height metric
    - Random-phase method

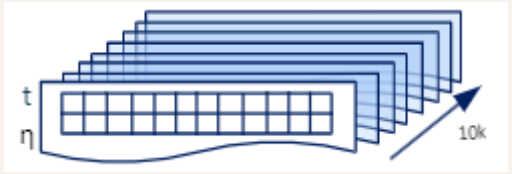
Methodology

Generate time series

$$\eta_{t_i} = \sum_{k=1}^{M/2} A_k \cos(2\pi f_k t_i + \phi_k)$$



Create ensemble of time series



Calculate wave height percentiles of ensemble

Record number of waves

Yes

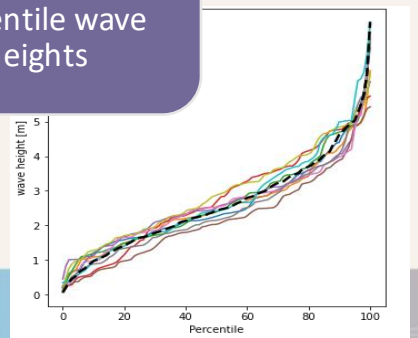
Stopping criteria met?

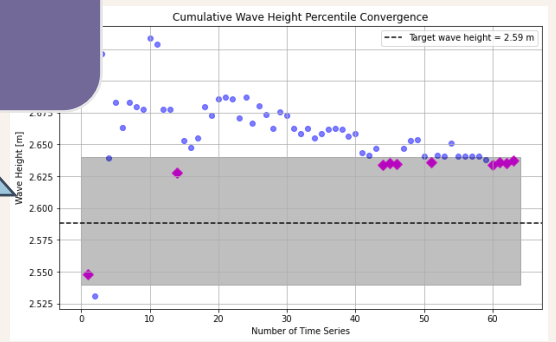
Target wave height values

Determine number of waves to represent target wave height values

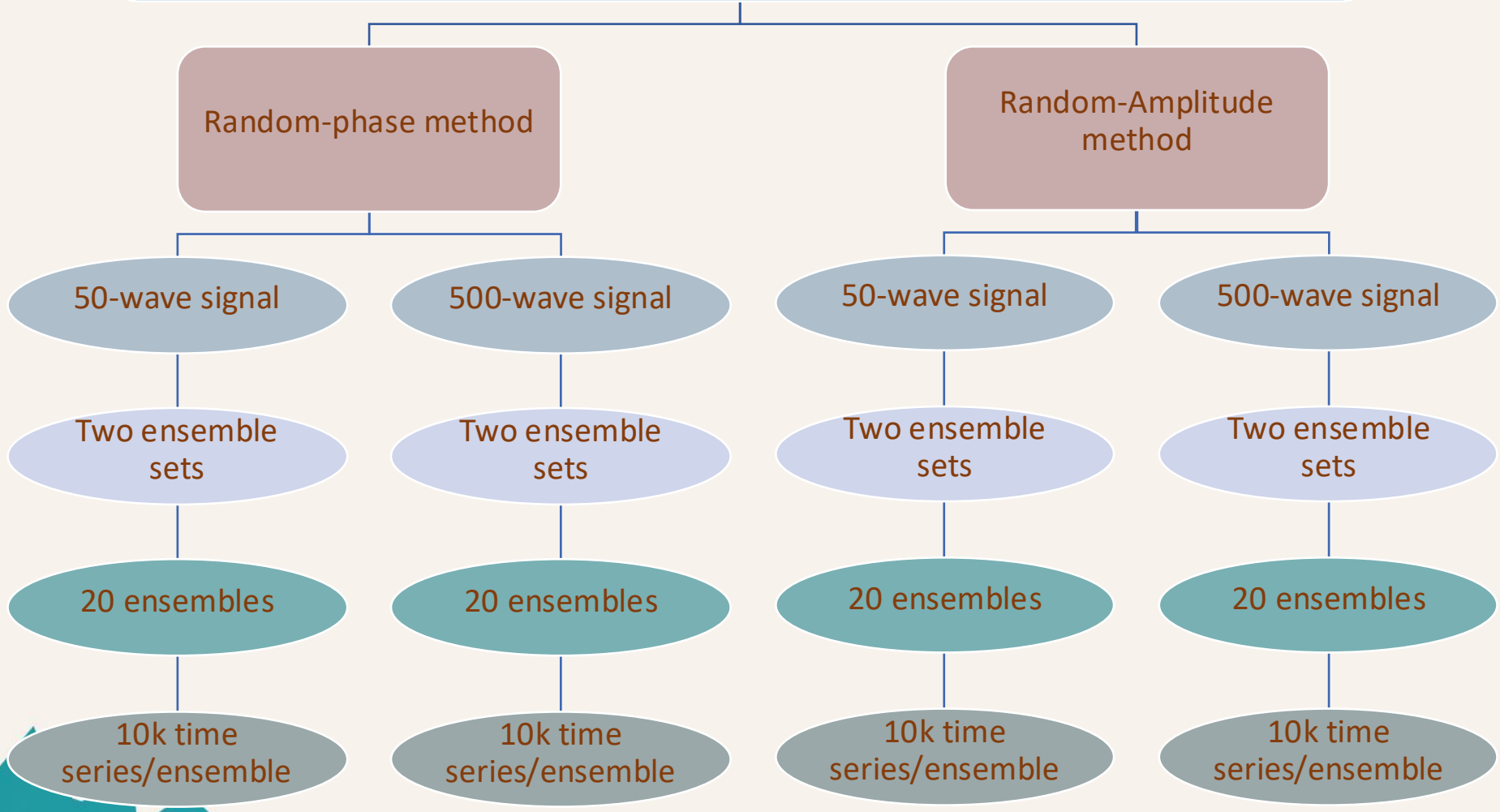
No, add time series

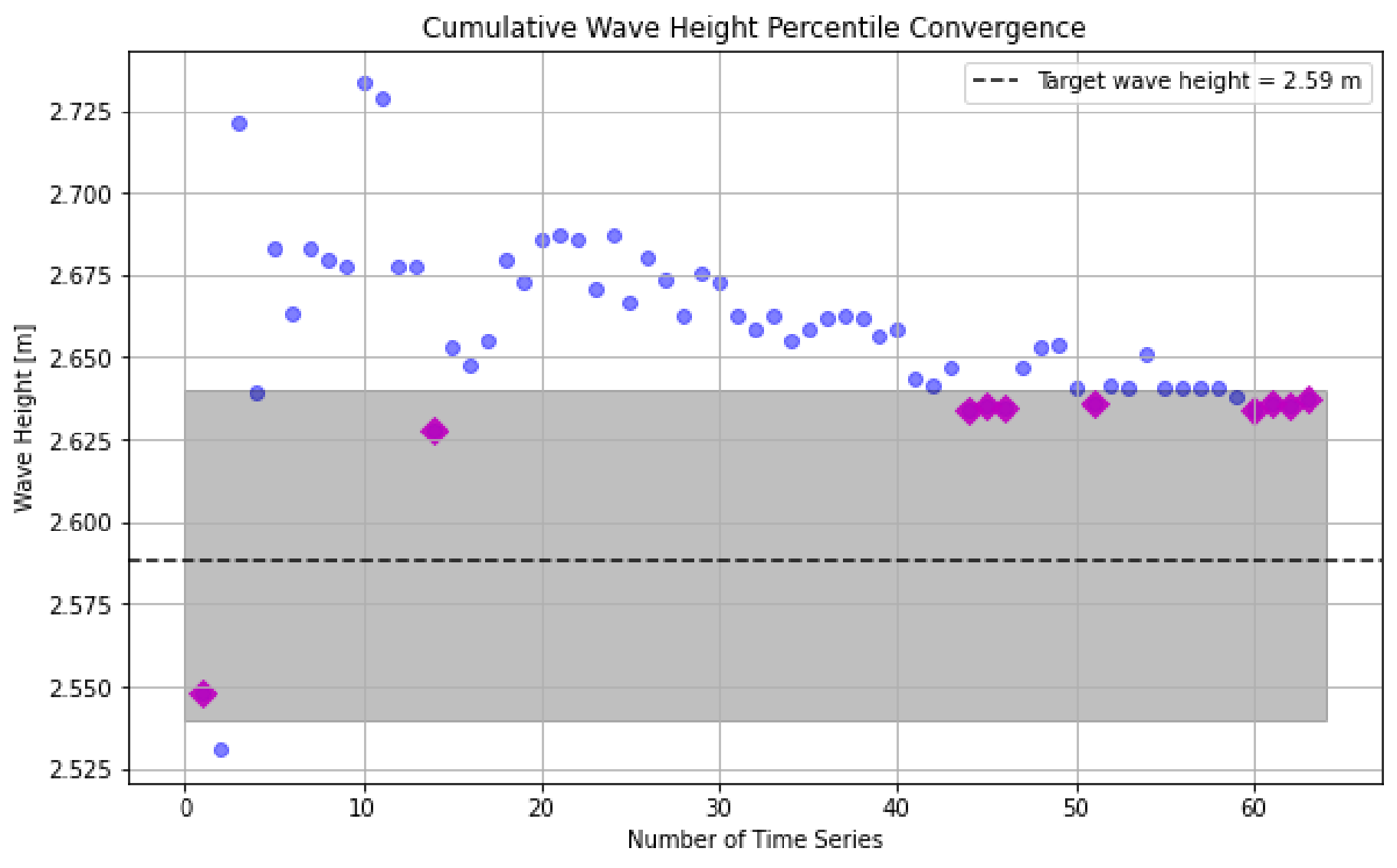
Calculate cumulative percentile wave heights



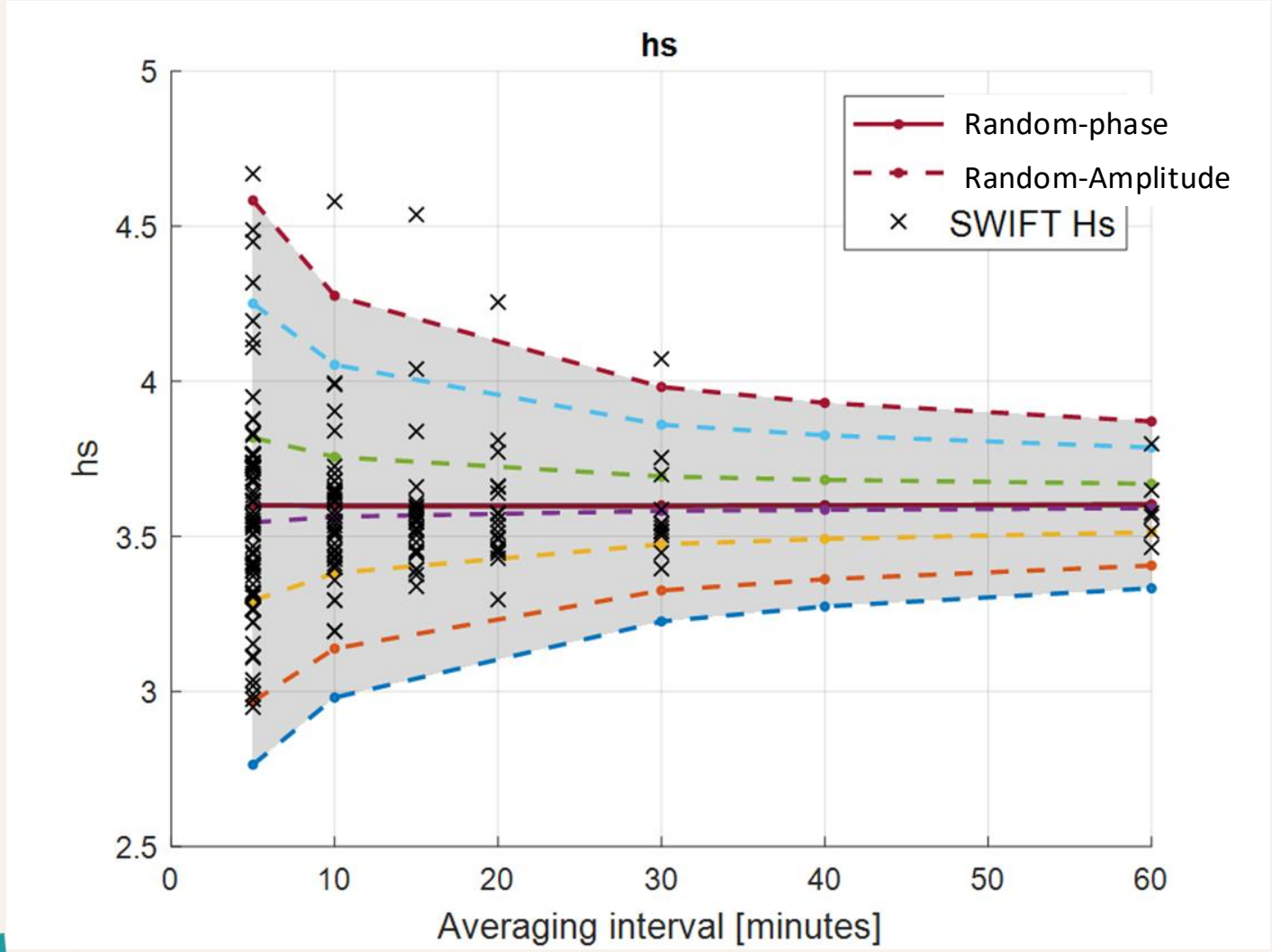


Statistical Analysis




Cumulative Wave Height Percentile Convergence
Target wave height = 2.59 m
Wave Height [m]
2.725
2.700
2.675
2.650
2.625
2.600
2.575
2.550
2.525
0
10
20
30
40
50
60
Number of Time Series

SIGNIFICANT WAVE HEIGHT DISTRIBUTION



Input Wave Conditions:
Hs = 4.5 m
Tp = 10 s

50-wave signal = 8.3-minute duration time series
500-wave signal = 83-minute duration time series

Random Amplitude Method

Mean number of time series for each wave height percentile

Wave height percentile	Time series duration				Total simulated time required			
	8.3 minutes		83 minutes		8.3-min time series		83-min time series	
50	32	31	9	9	4.5	4.3	12.5	12.5
75	30	36	14	12	4.2	5	19.4	16.7
90	43	34	20	16	6	4.7	27.7	22.2
95	53	40	18	20	7.4	5.5	24.8	27.8
99	143	128	20	33	19.8	17.8	27.7	45.8

Input Wave Conditions:
Hs = 4.5 m
Tp = 10 s

50-wave signal = 8.3-minute duration time series
500-wave signal = 83-minute duration time series

Random Phase Method

Mean number of time series for each wave height percentile

Wave height percentile	Number of time series				Total simulated time required			
	8.3 min duration		83 min dure		8.3-min time series		83-min time series	
50	26	12	8	8	3.5	1.6	10.6	10.6
75	15	13	8	8	2	1.8	10.6	10.6
90	25	22	12	16	3.3	3.1	16	22.2
95	28	27	15	16	3.9	3.7	20	22.2
99	49	71	23	36	6.9	9.9	30.6	50

Random Amplitude Method

Wave height percentile	Total simulated time required			
	8.3-min time series		83-min time series	
50	4.5	4.3	12.5	12.5
75	4.2	5	19.4	16.7
90	6	4.7	27.7	22.2
95	7.4	5.5	24.84	27.8
99	19.8	17.8	27.7	45.8

Random Phase Method

Wave height percentile	Total simulated time required			
	8.3-min time series		83-min time series	
50	3.5	1.6	10.6	10.6
75	2	1.8	10.6	10.6
90	3.3	3.1	16	22.2
95	3.9	3.7	20	22.2
99	6.9	9.9	30.6	50

Contributions

- Shorter duration time series show an increase in wave variability using the random amplitude method
- Wave height percentile representation using shorter-duration time series will decrease computational time

Thank you!

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Acknowledgements:

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[1] A. Mérigaud, J.V. Ringwood, Free-Surface Time-Series Generation for Wave Energy Applications, IEEE Journal of Oceanic Engineering 43 (2018) 19–35. https://doi.org/10.1109/JOE.2017.2691199.

[2] M.J. Tucker, P.G. Challenor, D.J.T. Carter, Numerical simulation of a random sea: a common error and its effect upon wave group statistics, Applied Ocean Research 6 (1984) 118–122.

[3] J. Saulnier -B., P. Ricci, A.H. Clément, A.F. de O. Falcaõ, Mean Power Output Estimation of WECs in Simulated Sea, in: Proceedings of The 8th European Wave and Tidal Energy Conference (EWTEC 2009, Uppsala, Sweden, 2009.

[4] H. Mankle, P. Branson, B. DuPont, B. Robertson, Temporal Upsampling of Wave Parameters and Impact on Time-Domain Floating Body Response and Wave Power, Journal of Ocean Engineering and Marine Energy[Manuscript Submitted for Publication] (2023).

[5] M.R. Tabeshpour, N. Belvasi, Ocean waves time-series generation: minimum required artificial wave time-series for wave energy converter analysis, Journal of Marine Engineering & Technology 22 (2023) 273–283. https://doi.org/10.1080/20464177.2023.2197280.

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