SAND2024-09889C

Sandia National Laboratories

Exceptional service in the national interest

CHARACTERIZATION OF WAVE ENERGY RESOURCE AND WAVE LOAD CONDITIONS AT ATLANTIC MARINE ENERGY CENTER WAVE ENERGY CONVERTER TEST SITES

Brek J. Meuris & Vincent S. Neary

UMERC+METS Conference 2024, Duluth, MN, Aug. 7–9

August 9th, 2024

umerc + METS

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

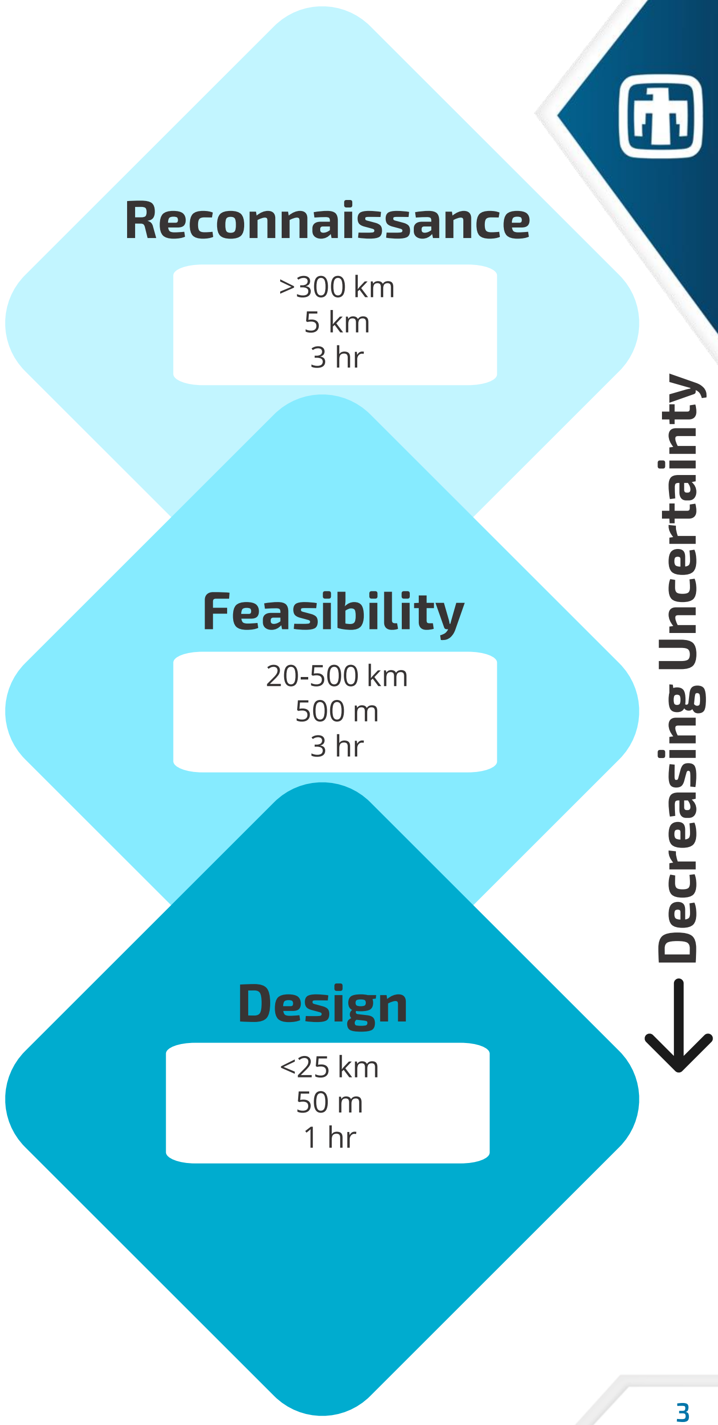
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

MOTIVATION

- Open-ocean test sites enable the testing and demonstration of wave energy converters (WECs) and aid in advancement to commercialization
- Met-ocean data, complete with key IEC resource parameters, is needed for open-ocean WEC test sites
- Wave energy resource characterization provides essential data for WEC design, test planning, installation, operation, maintenance, and decommissioning
- Consistent modeling, data analysis, and presentation procedures are necessary for commensurable comparison between test sites

INTRODUCTION

- International Electrotechnical Commission (IEC) provides standards for marine energy systems
  - IEC 62600-101: Marine Energy – Wave, Tidal and Other Water Current Converters – Part 101: Wave Energy Resource Assessment and Characterization
    - Methodology for consistent and accurate resource characterization and commensurable comparison among various sites
    - Three resource assessment stages
    - Suitable numerical models + model validation procedures
    - Data analysis and presentation procedures
  - IEC 62600-2: Marine Energy – Wave, Tidal and Other Water Current Converters – Part 2: Design Requirements for Marine Energy Systems
    - Requires estimation of 1-, 5-, and 50-year extreme wave heights and associated wave periods



STUDY OBJECTIVE

- Estimate and catalogue the wave climate at open-ocean WEC test sites following international standards for analysis, characterization, and classification to enable commensurable comparison between test sites
  - Facilitates the selection of test sites that are most suitable for a developer's needs and objectives

METHODS & DATA

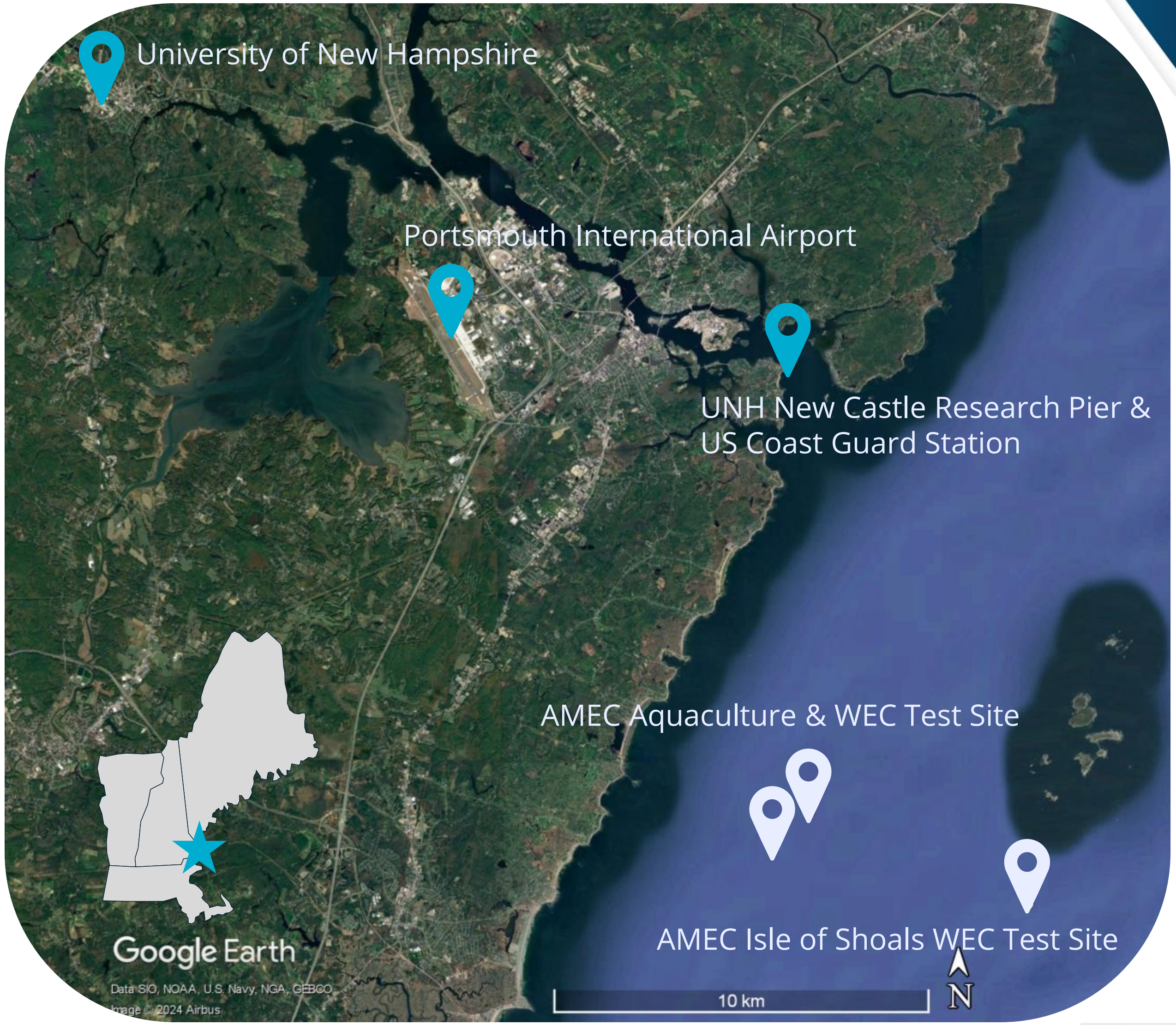
- Utilized validated, high-resolution 42-year hindcast data produced from a third-generation spectral wave model [Allahdadi et al. 2019, Yang et al. 2023]
  - Feasibility-level wave energy resource characterization
- IEC 62600-101 specifies six key parameters for characterizing the wave energy resource
  - J: Omnidirectional wave power
  - H_{m0}: Significant wave height
  - T_e: Energy period
  - ϵ_0: Spectral width
  - θ_J: Direction of maximum directionally resolved wave power
  - d_θ: Directionality coefficient
- IEC 62600-101 specifies how wave energy resource data should be presented
  - E.g., Joint probability distribution plot showing frequency of occurrence of sea states

Allahdadi et al. (2019). Development and validation of a regional-scale high-resolution unstructured model for wave energy resource characterization along the US East Coast. *Renewable Energy*, *136*, 500-511.
Yang et al. (2023). Multi-decade high-resolution regional hindcasts for wave energy resource characterization in US coastal waters. *Renewable Energy*, *212*, 803-817.

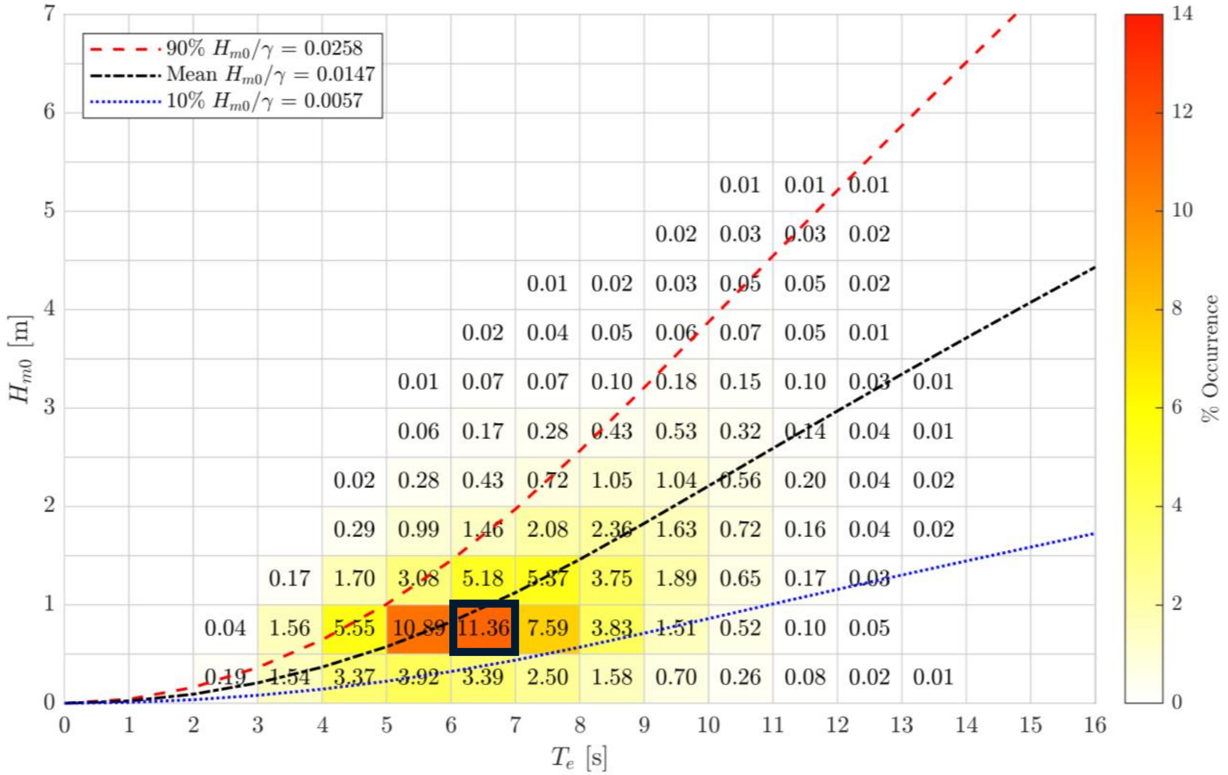
ATLANTIC MARINE ENERGY CENTER WEC TEST SITES

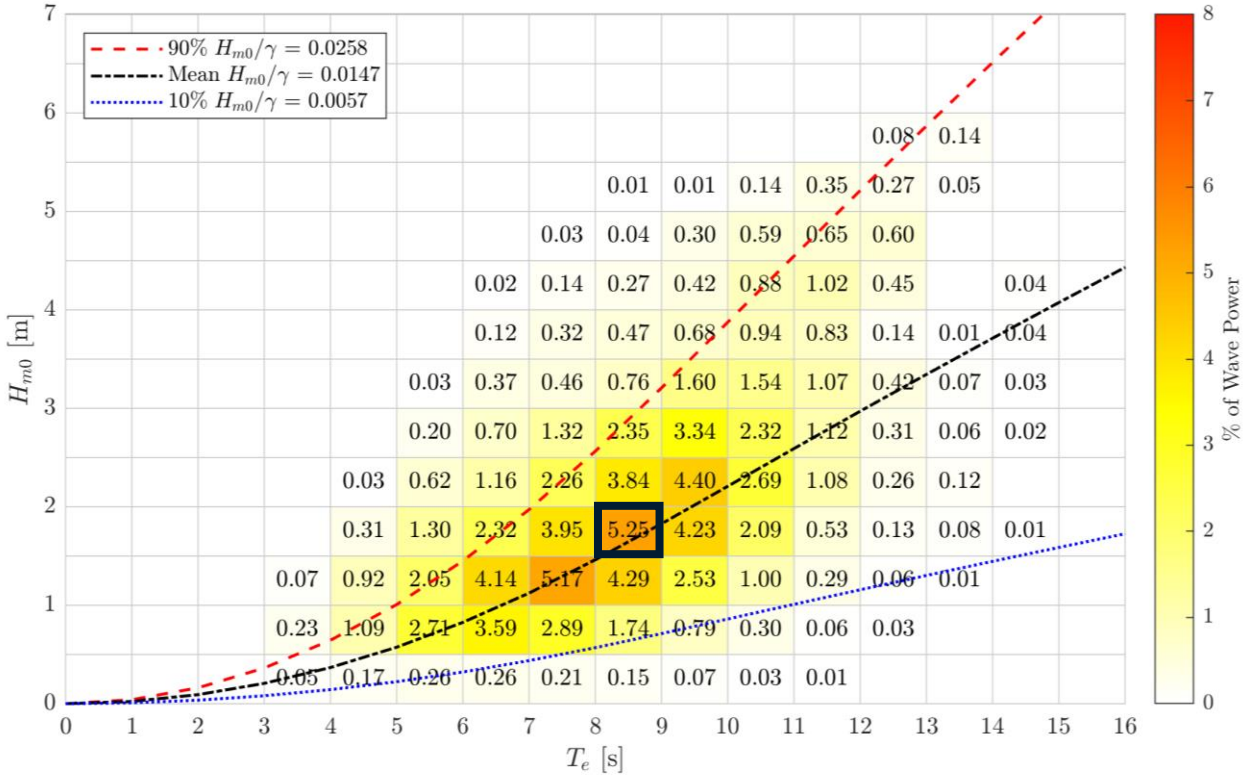
- AMEC Isle of Shoals WEC Test Site
  - Approximately 36 acres in size
  - Previously facilitated open-ocean WEC testing for 10+ years
- AMEC Aquaculture & WEC Test Site
  - Approximately 130 acres consisting of two connected parcels

	Latitude	Longitude	Depth [m]
AMEC Isle of Shoals WEC Test Site	**42.9422**	**-70.632**	**47.1**
AMEC Aquaculture & WEC Test Site NE Marker	42.9643	-70.703	33.1
AMEC Aquaculture & WEC Test Site SW Marker	42.9547	-70.715	33.2

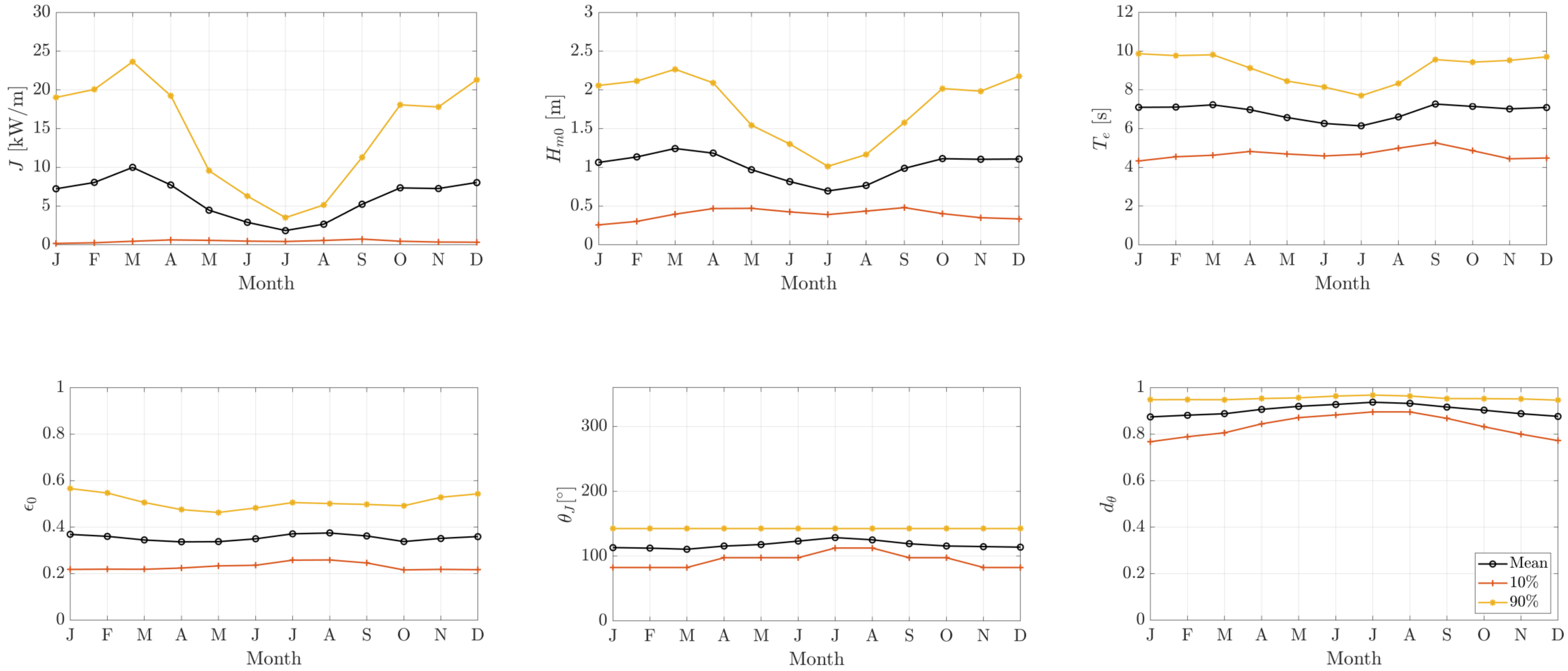


RESULTS | JOINT PROBABILITY DISTRIBUTIONS

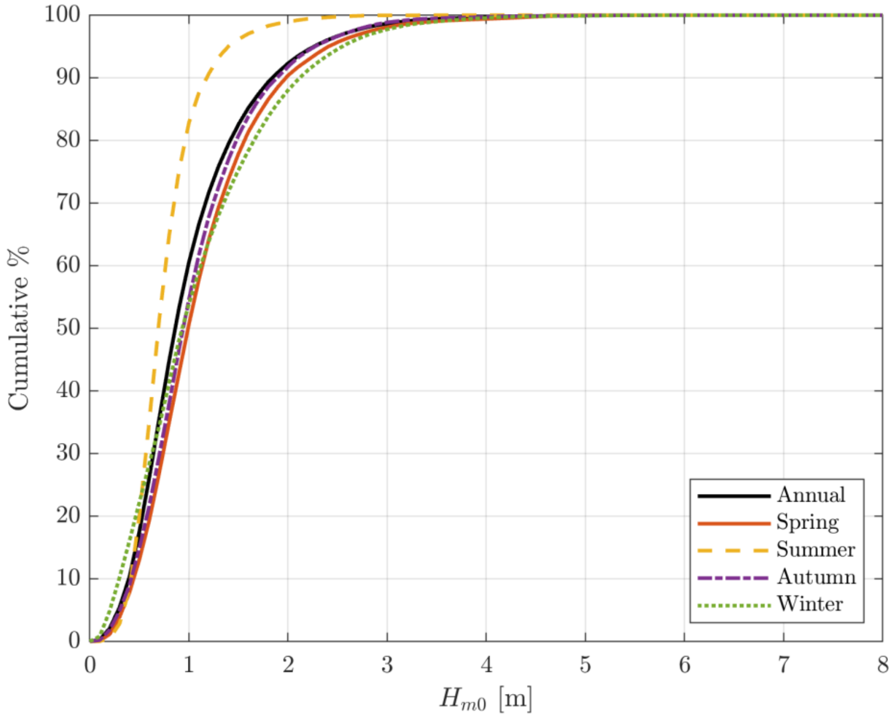


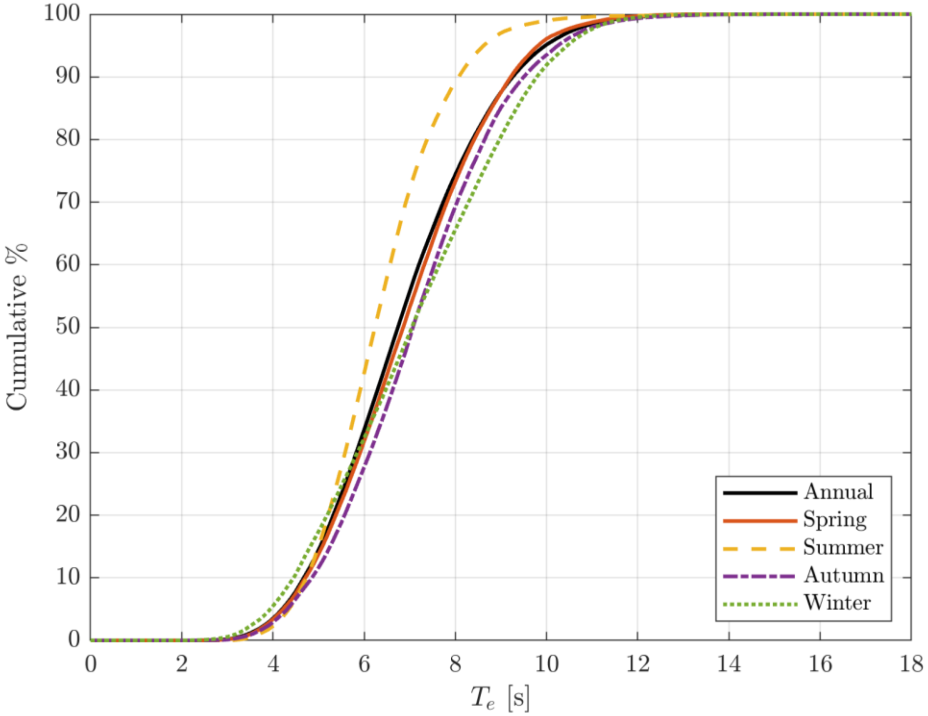


RESULTS | MONTHLY VARIATION OF IEC PARAMETERS



RESULTS | SEASONAL CUMULATIVE DISTRIBUTIONS





	Spring	Summer	Autumn	Winter
$H_{m0} = 1.5$	78 %	96 %	81 %	75 %
$H_{m0} = 2.0$	90 %	99 %	92 %	88 %

	Spring	Summer	Autumn	Winter
$T_e = 8$	73 %	89 %	69 %	66 %
$T_e = 9$	88 %	97 %	85 %	80 %

Spring: March – May | Summer: June – August | Autumn: September – November | Winter: December - February

RESULTS | WEATHER WINDOWS

Winter

H_{m0} [m] \ Consecutive Hours Below Threshold	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
	339	169	111	83	66	55	47	40	36	32	29	26	24	22	21	19
	314	155	102	76	60	49	42	36	32	28	25	23	21	19	18	16
	266	130	85	62	48	40	34	28	25	22	19	18	16	14	13	12
	188	90	58	41	32	26	21	17	15	13	11	10	9	8	7	6
	75	35	21	15	10	8	6	5	4	3	3	2	2	2	1	1

H_{m0} [m] axis: 2.5, 2, 1.5, 1, 0.5, 0

Spring

H_{m0} [m] \ Consecutive Hours Below Threshold	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
	351	175	116	87	69	57	49	43	37	34	30	28	26	24	22	21
	330	164	108	80	64	53	45	39	34	30	28	25	23	21	20	18
	282	139	91	67	52	43	36	31	27	24	22	20	18	16	15	14
	180	86	55	40	30	24	20	17	14	12	11	10	8	8	7	6
	45	20	12	8	6	4	4	3	2	2	1	1	1	1	1	1

H_{m0} [m] axis: 2.5, 2, 1.5, 1, 0.5, 0

Summer

H_{m0} [m] \ Consecutive Hours Below Threshold	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
	367	183	122	92	73	61	52	46	40	36	33	30	28	26	24	23
	364	182	121	90	72	60	51	45	39	35	32	29	27	25	23	22
	353	175	116	87	69	57	49	43	38	34	31	28	26	24	22	21
	301	148	97	72	57	46	39	34	30	26	24	21	20	18	16	15
	69	31	19	13	10	7	6	5	4	3	2	2	2	1	1	1

H_{m0} [m] axis: 2.5, 2, 1.5, 1, 0.5, 0

Autumn

H_{m0} [m] \ Consecutive Hours Below Threshold	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
	350	175	116	87	69	57	49	43	37	34	30	28	26	24	22	20
	332	164	109	81	64	53	45	39	35	31	28	25	23	21	20	18
	290	143	94	69	54	44	38	32	28	25	22	20	18	17	15	14
	193	93	60	43	33	27	22	19	16	14	12	11	10	9	8	7
	51	23	14	10	7	5	4	3	3	2	2	2	1	1	1	1

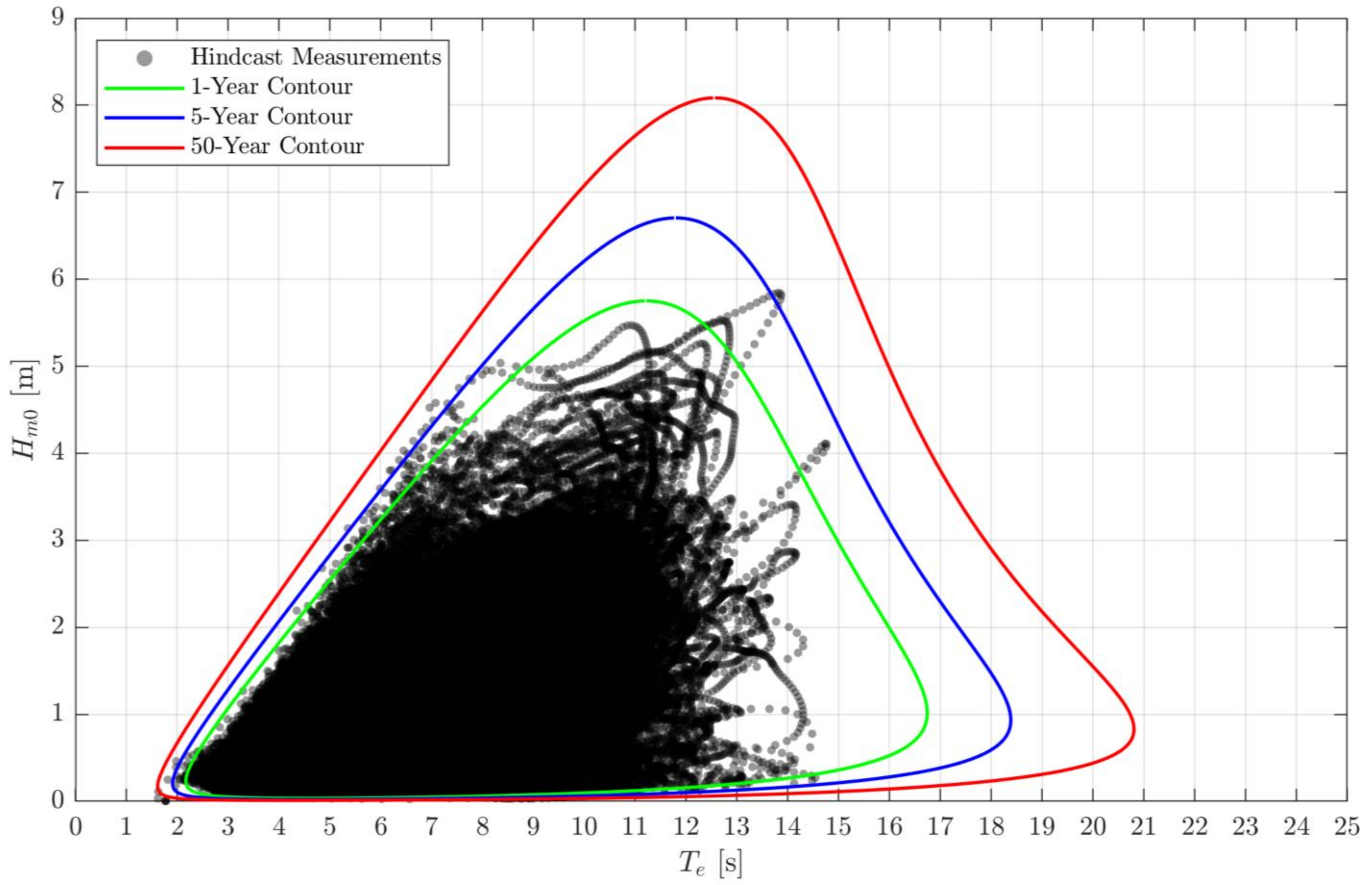
H_{m0} [m] axis: 2.5, 2, 1.5, 1, 0.5, 0

RESULTS | ENVIRONMENTAL CONTOURS

- Extreme conditions for 1-, 5-, and 50-year return periods
- Utilized OMAE 2020 method [Haselsteiner et al. 2020, Neary et al. 2021]

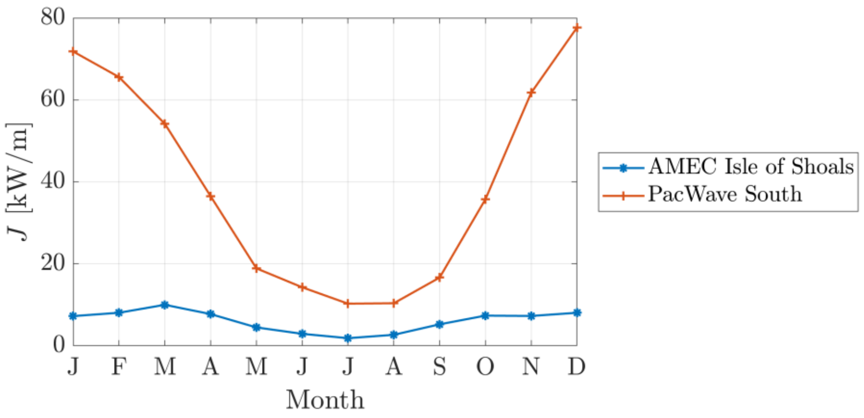
H_{m0} [m]	T_e [s]
4.0	6.0
6.0	8.5
8.1	12.6
6.0	15.3
4.0	16.8

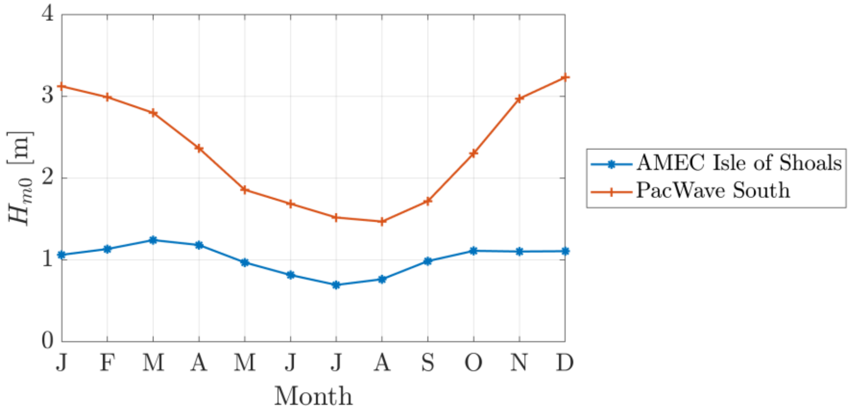
*50-year contour values

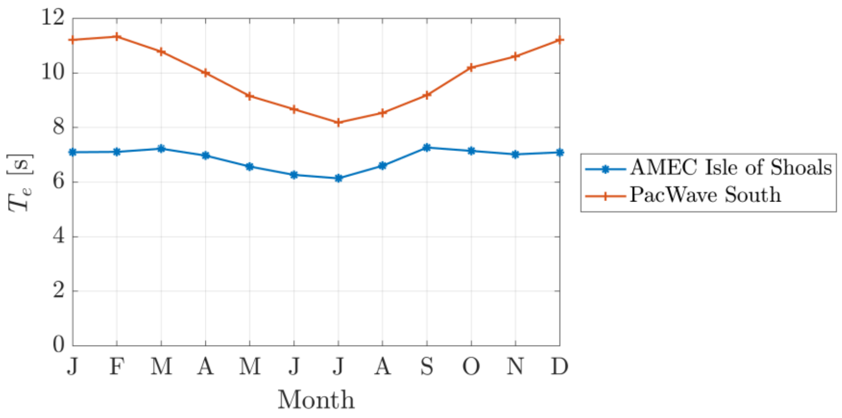


Haselsteiner et al. (2020). Global hierarchical models for wind and wave contours: Physical interpretations of the dependence functions. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 84324, p. 1-10). American Society of Mechanical Engineers.
Neary et al. (2021) Design Load Case Generator: Web-based Tool to Support IEC 62600-2 Standard Design Load Case Analyses. *Proceedings of 13th European Wave and Tidal Energy Conference Series (EWTEC 2021), 2095, 1-10.*

RESULTS | COMPARISON TO PACWAVE SOUTH WEC TEST SITE







	H_{m0} [m]	T_e [s]	$\bar{J}$ [kW/m]
AMEC Isle of Shoals	1.5 – 2.0	8 - 9	13.5
PacWave South	3.0 – 3.5	10 - 11	59.5

*Sea state contributing greatest % of wave power

	1-Year		5-Year		50-Year	
	H_{m0} [m]	T_e [s]	H_{m0} [m]	T_e [s]	H_{m0} [m]	T_e [s]
AMEC Isle of Shoals	5.8	11.2	6.7	11.8	8.1	12.6
PacWave South	9.5	13.5	10.8	14.0	12.6	14.6

*Sea state corresponding to peak H_{m0} value for n-year return period

	TP	FP	FDP
AMEC Isle of Shoals	III	III(2)	III(2)120˚
PacWave South	I	II(4)	II(4)280˚

*Wave resource classification [Ahn et al. 2022]

Ahn et al. (2022). Global wave energy resource classification system for regional energy planning and project development. *Renewable and Sustainable Energy Reviews*, *162*, 112438.

CONCLUSIONS & FUTURE WORK

- Estimated and catalogued the wave climate at the AMEC open-ocean WEC test sites following international standards for analysis, characterization, and classification to enable commensurable comparison between test sites
- Presented preliminary commensurable comparison between AMEC and PacWave sites for several key IEC parameters
- Future work will expand this estimation and cataloging to additional US WEC test sites

THANK YOU

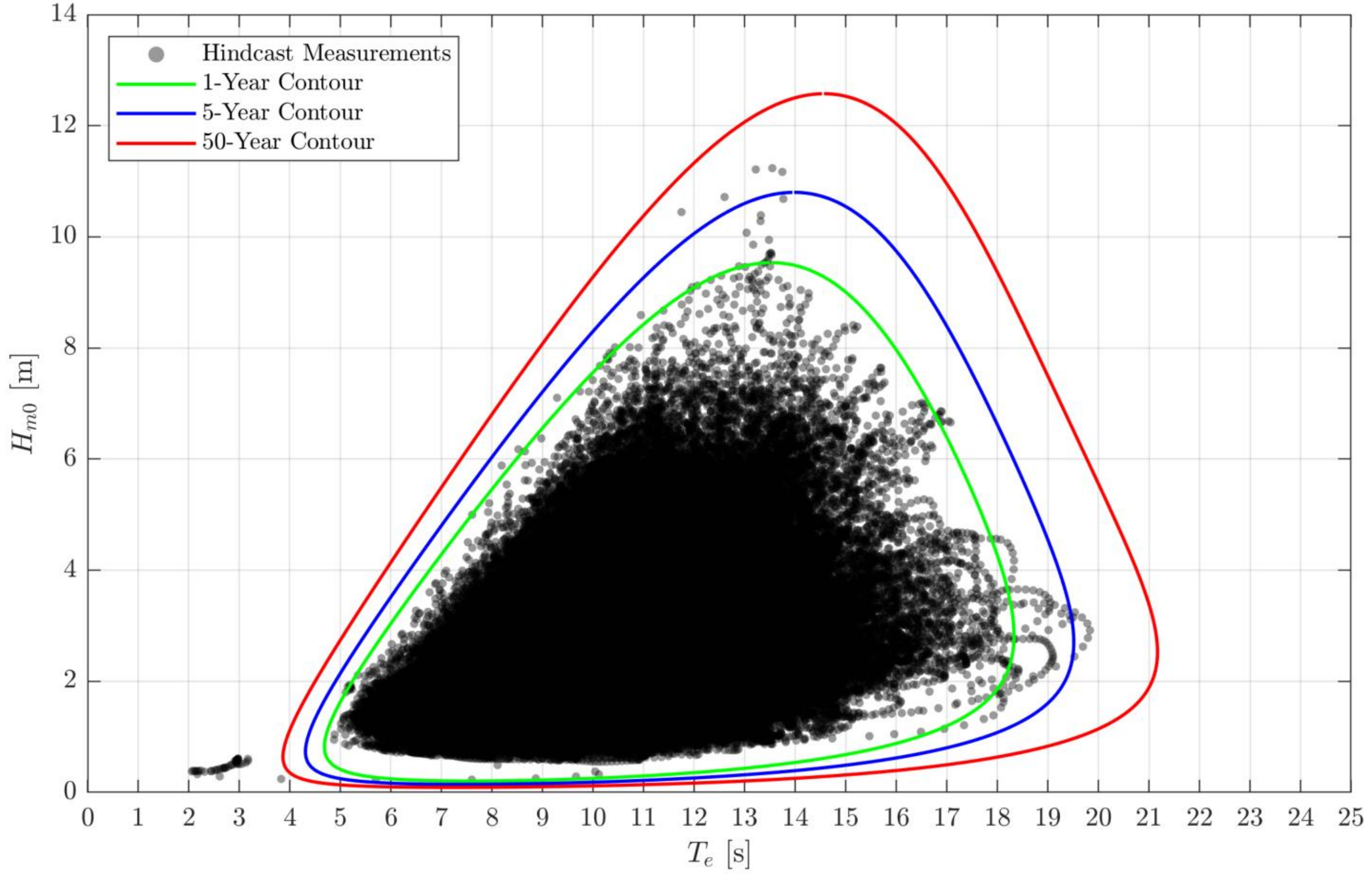
REFERENCES

- IEC, TS 62600 Marine Energy – Wave, Tidal and Other Water Current Converters – Part 101: Wave Energy Resource Assessment and Characterization, International Electrotechnical Commission, Geneva, Switzerland, 2012.
- IEC, TS 62600 Marine Energy – Wave, Tidal and Other Water Current Converters – Part 2: Design Requirements for Marine Energy Systems, International Electrotechnical Commission, Geneva, Switzerland, 2019.
- Allahdadi, M. N., Gunawan, B., Lai, J., He, R., & Neary, V. S. (2019). Development and validation of a regional-scale high-resolution unstructured model for wave energy resource characterization along the US East Coast. *Renewable Energy*, *136*, 500-511.
- Yang, Z., Medina, G. G., Neary, V. S., Ahn, S., Kilcher, L., & Bharath, A. (2023). Multi-decade high-resolution regional hindcasts for wave energy resource characterization in US coastal waters. *Renewable Energy*, *212*, 803-817.
- Haselsteiner, A. F., Sander, A., Ohlendorf, J. H., & Thoben, K. D. (2020). Global hierarchical models for wind and wave contours: Physical interpretations of the dependence functions. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 84324, p. 1-10). American Society of Mechanical Engineers.
- Neary, V.S., An, R.J., Coe, R.G., Haselsteiner, A., Stroer, L., Ahn, S., Windmeier, K. (2021) Design Load Case Generator: Web-based Tool to Support IEC 62600-2 Standard Design Load Case Analyses. *Proceedings of 13th European Wave and Tidal Energy Conference Series (EWTEC 2021), 2095, 1-10*.
- Ahn, S., Neary, V. S., & Haas, K. A. (2022). Global wave energy resource classification system for regional energy planning and project development. *Renewable and Sustainable Energy Reviews*, *162*, 112438.

APPENDIX | IEC PARAMETER EQUATIONS

- Omnidirectional wave power: $J = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j$
- Significant wave height: $H_{m0} = 4\sqrt{m_0}$
  - $m_n = \sum_i f_i^n \left(\sum_j S_{ij} \Delta\theta_j\right) \Delta f_i$
- Energy period: $T_e = \frac{m_{-1}}{m_0}$
- Spectral width: $\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}^2} - 1}$
- Direction of maximum directionally resolved wave power: θ_J, value corresponding to maximum value of J_θ, J_{θ_J}
  - $J_\theta = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \cos(\theta - \theta_j)\delta$
    - $\delta = 1, \cos(\theta - \theta_j) \geq 0$
    - $\delta = 0, \cos(\theta - \theta_j) < 0$
- Directionality coefficient: $d_\theta = \frac{J_{\theta_J}}{J}$

APPENDIX | PACWAVE SOUTH ENVIRONMENTAL CONTOURS



Latitude	Longitude	Depth [m]
44.5670	-124.229	67.7