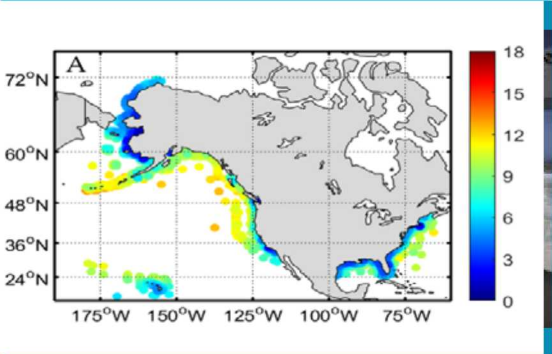
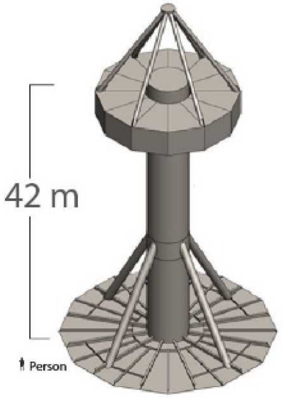
SAND2019-12768PE

Wave energy resource characterization for advancing a nascent marine renewable energy industry





PRESENTED BY

Vincent Neary, Water Power Technologies, 25 October 2019

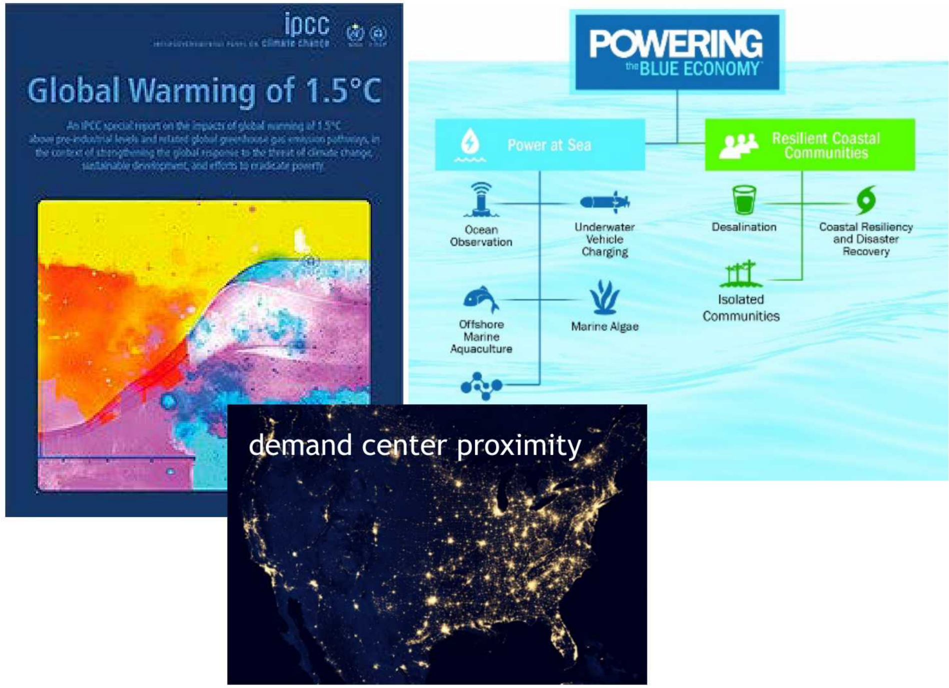
Marine Science Seminar, University of Connecticut

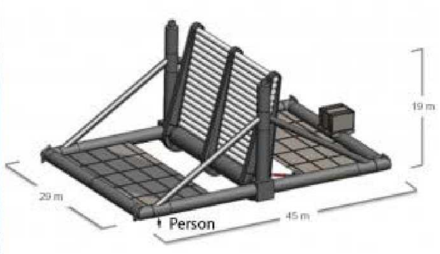
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2019-

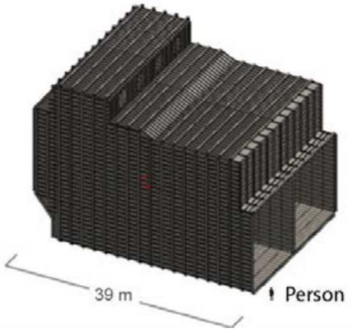
Ocean renewable energy: Opportunities & challenges

Ocean renewable energy; Opportunities and challenges

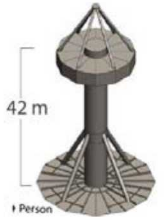




RM5, 10 MW, 0.87€ /kWh



RM6, 10 MW, 1.35€/kWh



RM3, 10 MW, 0.87€/kWh

USDOE's Reference Model WECs [Neary et al. 2013]

Opportunities

Urgency to move to renewable energy dominant portfolios [IPCC 2018]

Large power densities close to population centers [NASA 2012]

Blue economy – local energy sources for maritime markets, e.g., desalinization, aquaculture, observation & navigation[USDOE 2019]

Challenges

Difficult engineering - Harsh marine environment

High capital, installation, operation and maintenance (IO&M) costs [Neary et al. 2013]

Infrastructure for testing and IO&M

Complex and costly permitting process

Market opportunities unclear, and no established supply chains

USDOE R&D Program

2015 LCOE ~1€/kWh

Technology development

- Early stage concepts
- Component & subsystem innovations
- Test infrastructure
- Open source models
- Demonstration projects
- Performance & LCOE assessment

Resource characterization & assessment

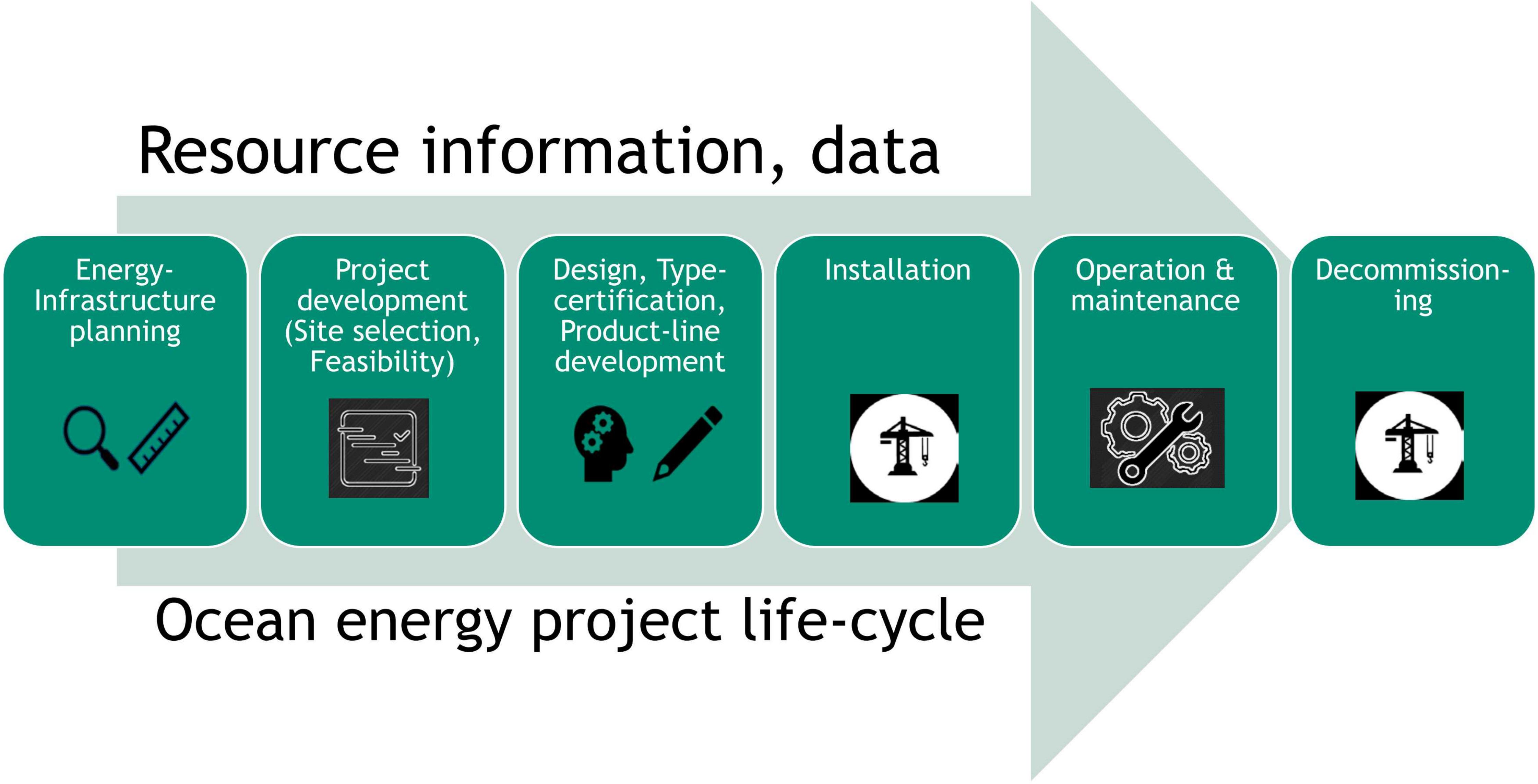
- National resource and regional distribution
- Resource statistics characterizing average and extreme conditions

Market acceleration

- Potential markets and supply chains
- Environmental compliance
- Stakeholder/user conflict avoidance and mitigation
- Standards and certification

2030 Target LCOE ~0.1€/kWh

Resource characterization needs in project life cycle



Wave resource characterization, US case study

Background

- National resource assessments quantified potential contribution of wave energy to electricity production nationally and regionally [EPRI 2011, Chawla et al. 2013]
- More refined and comprehensive characterization needed to support energy planning, project development and WEC design
- Three assessment levels (area, Δx, Δt)
  - Reconnaissance (>300 km), 5 km, 3 h ☑
  - Feasibility (20-500 km), 500 m, 3 h ☐
  - Design (<25 km), 50 m, 1 h ☐

The MHK Atlas wave power density map.
Source:[NREL 2019].https://maps.nrel.gov/mhk-atlas/

Resource	Theoretical Resource
Waves	1,594-2,640 TWh/year
Tidal streams	445 TWh/year
Ocean currents	200 TWh/year

Source: USDOE 2015 Quadrennial Technology Review, http://energy.gov/qtr

Goals/Objectives

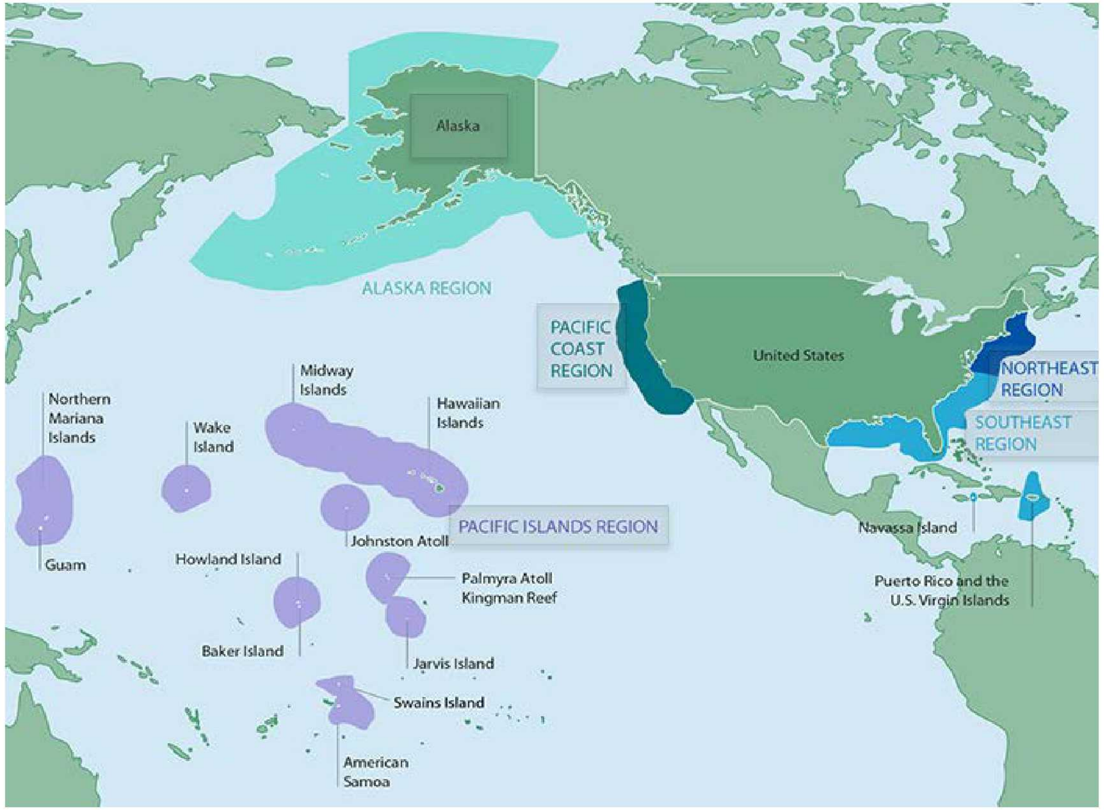
Generate high-resolution resource data source covering all US economic exclusion zones (EEZ) from 32-40 year wave model hindcast

Improve data source ☑

Characterize resource attributes ☑

Disseminate data and information ☑

Region	Area, km²	Status
West Coast	825,549	Complete
East Coast	915,763	Complete
Alaska	3,770,021	Complete
Hawaii Islands	1,579,538	2019
Gulf of Mexico	707,832	2019
Pacific Islands	3,328,925	2020
Puerto Rico, US Virgin Islands	211,429	2020



US Economic Exclusion Zones (EEZ)

U.S. EEZ consists of following sub-regions: (a) Pacific West Coast; (b) East Coast (Northeast and Southeast regions); (c) Alaska; (d) Gulf of Mexico; (e) Puerto Rico and U.S. Virgin Islands; (f) Hawaii and Pacific Islands. EEZ is defined as a sea zone that extends 370 km (200 nmi) offshore from its coastal baseline. The image is obtained from NOAA National Ocean Service. https://www.worldatlas.com/articles/countries-with-the-largest-exclusive-economic-zones.html

Methods: Spectral wave modeling (SWAN)

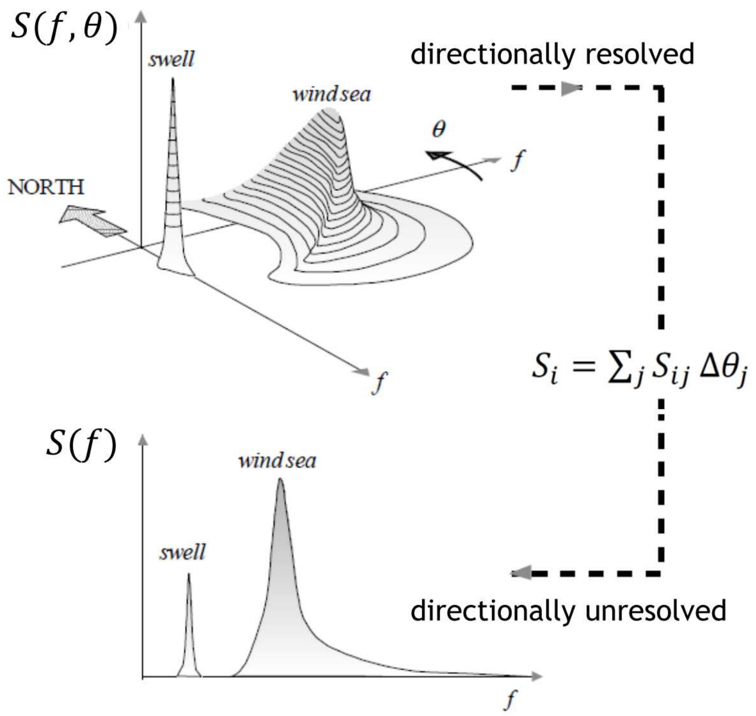
Emphasis on validated spectral wave model hindcast data

Evolution of wave action density (N) in space and time for all frequencies ($\sigma = 2\pi f$) and directions (θ) (LHS)

Source and sink terms that generate, transfer and dissipate wave energy

Feasibility/Design level Δx = 200-300 m, Δt =1 h

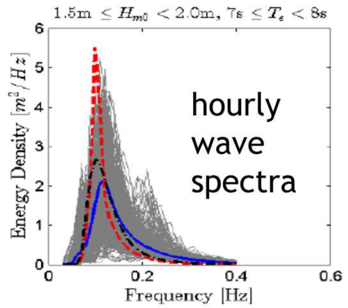
Source: SWAN Technical Manual



$$N = S(f,\theta)/\sigma$$

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{\mathrm{tot}}}{\sigma}$$

$$S_{\mathrm{tot}} = S_{\mathrm{in}} + S_{\mathrm{nl3}} + S_{\mathrm{nl4}} + S_{\mathrm{ds,w}} + S_{\mathrm{ds,b}} + S_{\mathrm{ds,br}}$$



Resource metrics: IEC parameters [IEC TS 62600-101:2015-06]

Omnidirectional wave power, *J*

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij} \, \Delta f_i \Delta\theta_j$$ [kW/m]

- Total wave energy flux at point of interest
- Directionally unresolved

Directionally resolved wave power, J_θ

$$J_\theta = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \cos(\theta - \theta_j)\delta$$ [kW/m]

- Wave energy flux through vertical plane of unit width

Direction of max J_θ

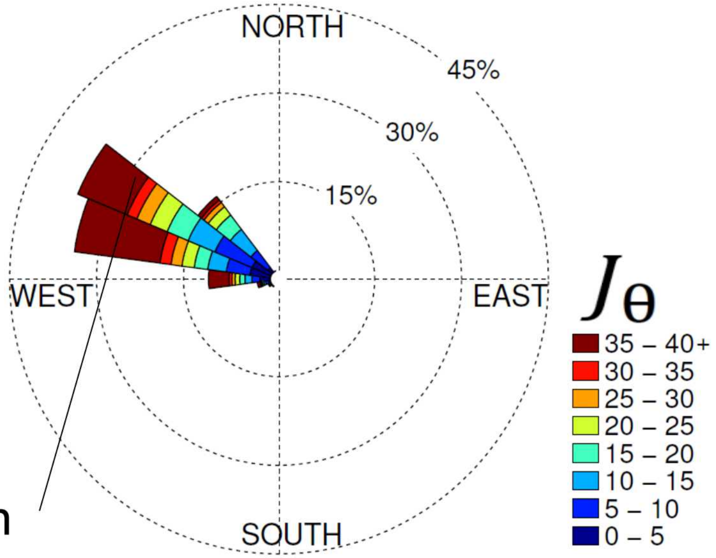
$$\theta_{\mathrm{Jmax}}$$ [deg]

- Bearing where most of the incident wave power coming from

Directionality coefficient, *d*

$$d = \frac{J_{\theta_{\mathrm{Jmax}}}}{J}$$ [-]

- Measure of directional spreading



$J_{\theta max}$ ~36 kW/m
θ_{Jmax} ~300 deg.

Resource metrics: IEC parameters [IEC TS 62600-101:2015-06]

Spectral moments

$$m_n = \sum_i f_i^n S_i \Delta f_i$$

- Used to derive important wave statistics

Significant wave height

$$H_{m0} = 4\sqrt{m_0}$$ [m]

- Proxy for H_s, combined with T_e to define sea states in scatter plots

Energy period

$$T_e \equiv T_{-10} = \frac{m_{-1}}{m_0}$$ [s]

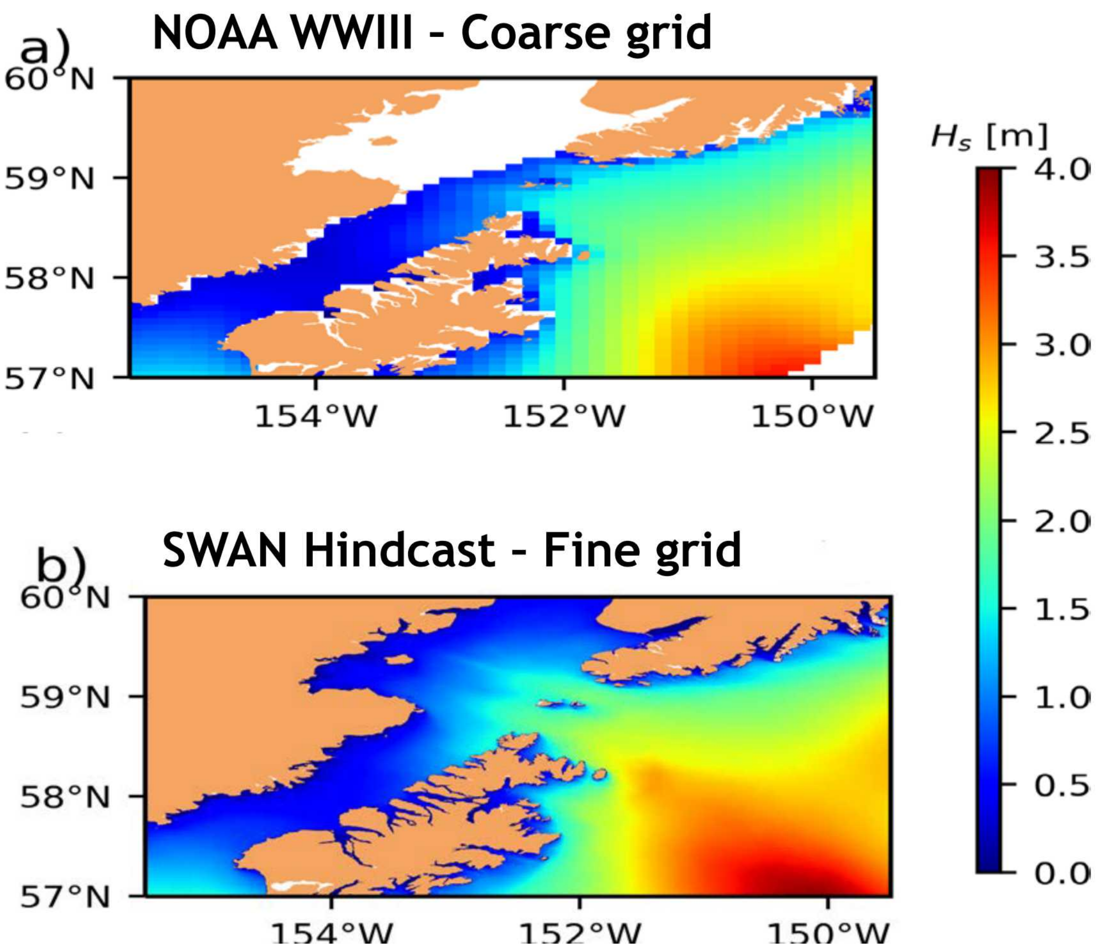
- Centroid of wave power spectrum, with H_{mo} to define sea states in scatter plots

Spectral width

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}^2} - 1}$$ [-]

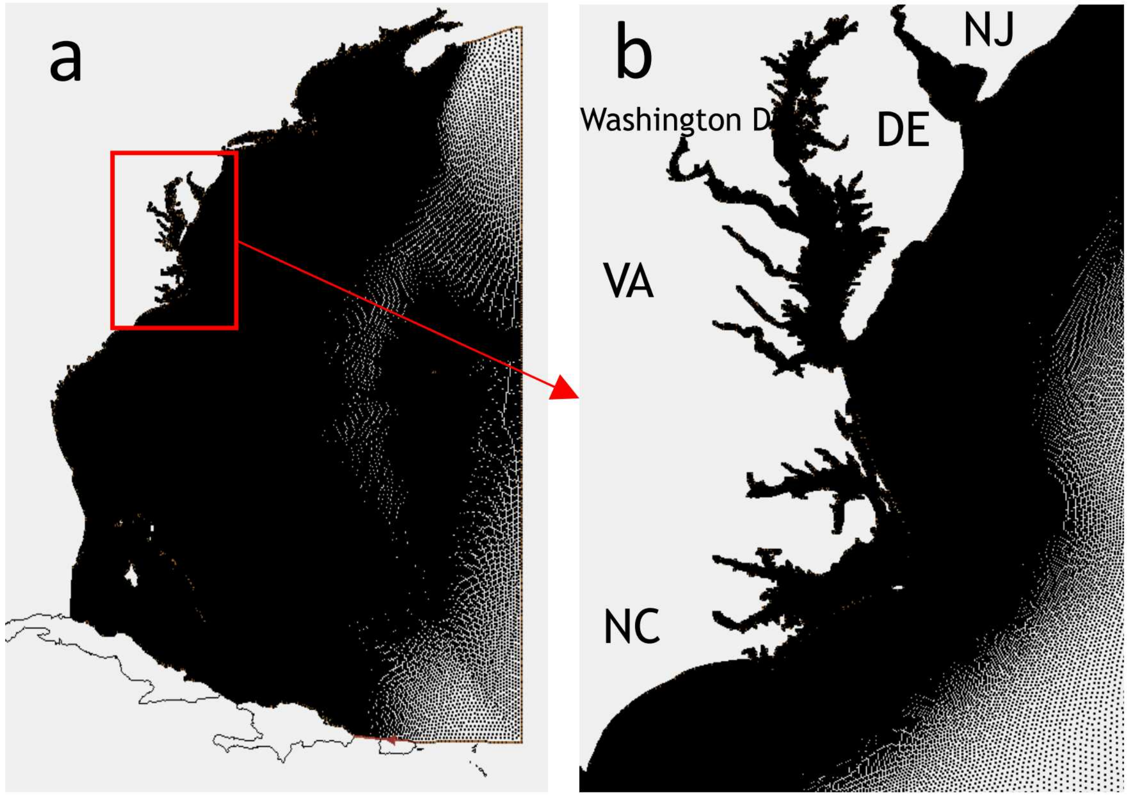
- Characterizes energy spreading in wave spectrum.

Results: Model mesh refinement [Yang & Neary 2019]



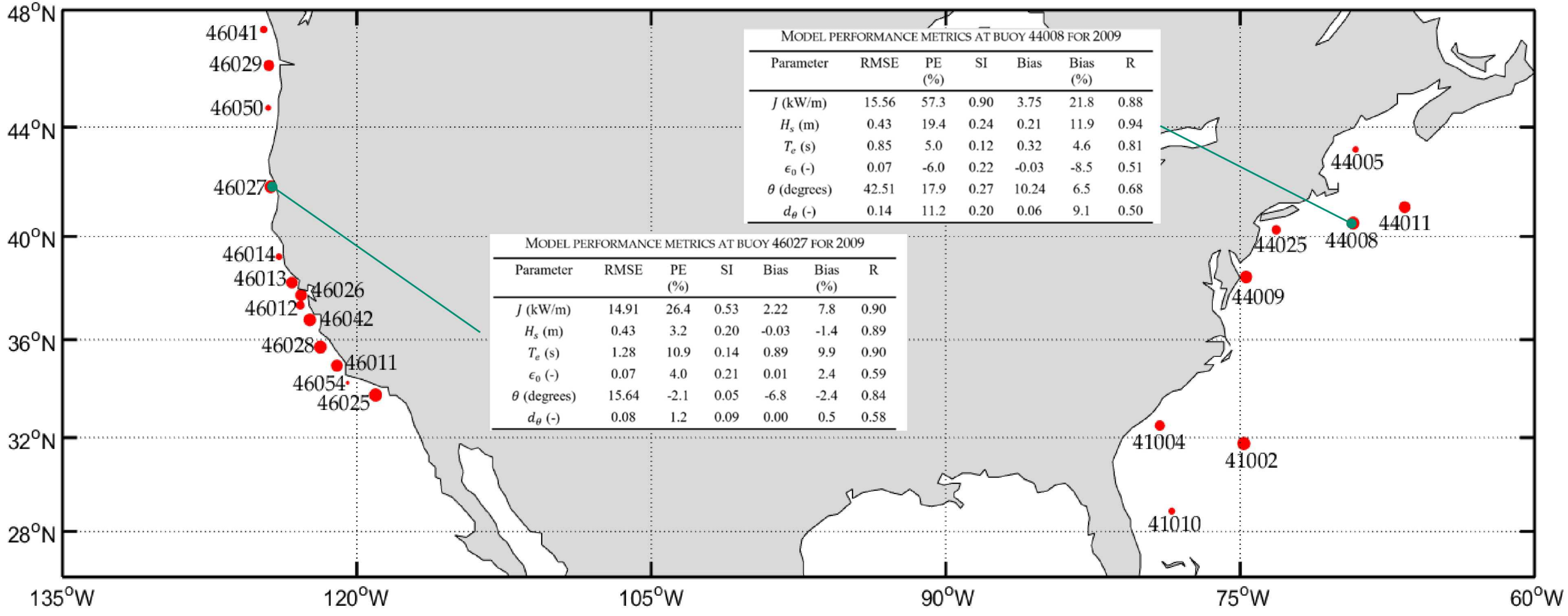
Significant wave height near Kodiak, Alaska, simulated by NOAA WWIII (a) and UnSWAN (b) [Yang & Neary 2019]

SWAN East Coast Region Hindcast



SWAN model grid for U.S. East Coast (a) and zoomed-in near the Chesapeake Bay region (b) [Allahdadi et al. 2019, Yang & Neary 2019]

Results: Better accuracy, IEC metrics [Yang et al. 2017; Allhadadi et al. 2019; Yang and Neary 2019]



MODEL PERFORMANCE METRICS AT BUOY 44008 FOR 2009

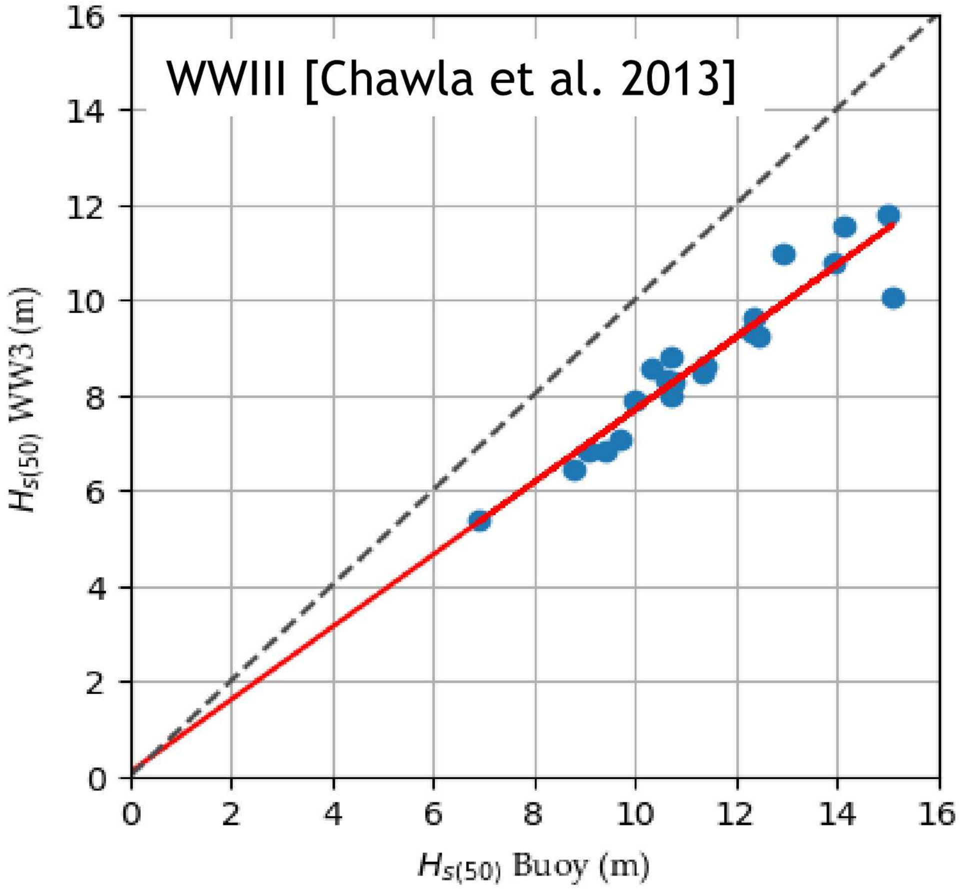
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	15.56	57.3	0.90	3.75	21.8	0.88
H_s (m)	0.43	19.4	0.24	0.21	11.9	0.94
T_e (s)	0.85	5.0	0.12	0.32	4.6	0.81
ϵ_0 (-)	0.07	-6.0	0.22	-0.03	-8.5	0.51
θ (degrees)	42.51	17.9	0.27	10.24	6.5	0.68
d_θ (-)	0.14	11.2	0.20	0.06	9.1	0.50

MODEL PERFORMANCE METRICS AT BUOY 46027 FOR 2009

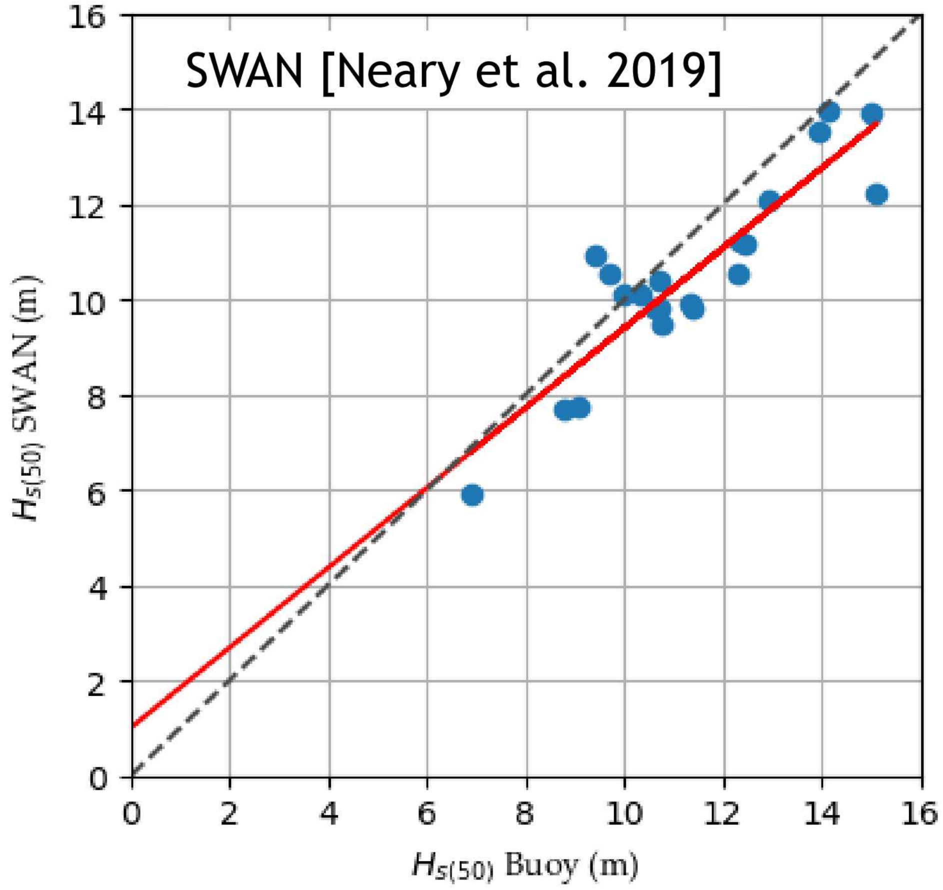
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	14.91	26.4	0.53	2.22	7.8	0.90
H_s (m)	0.43	3.2	0.20	-0.03	-1.4	0.89
T_e (s)	1.28	10.9	0.14	0.89	9.9	0.90
ϵ_0 (-)	0.07	4.0	0.21	0.01	2.4	0.59
θ (degrees)	15.64	-2.1	0.05	-6.8	-2.4	0.84
d_θ (-)	0.08	1.2	0.09	0.00	0.5	0.58

Results: Better accuracy, $H_{s(50)}$ [Neary et al. 2019]

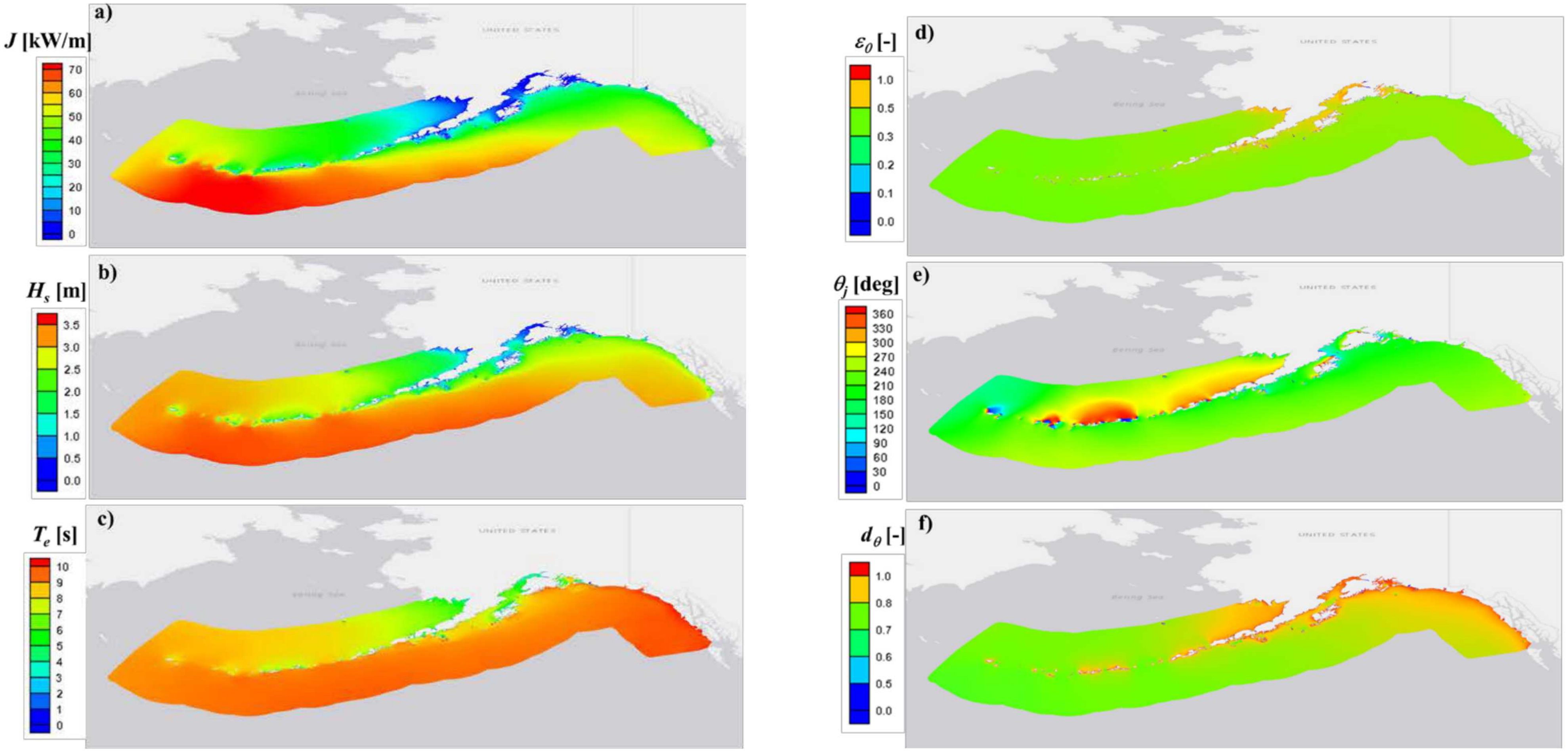
NOAA WWIII – Coarse grid



SWAN Regional- Fine grid



Results: 6 IEC parameters at 200-300 m resolution [Yang & Neary 2019]



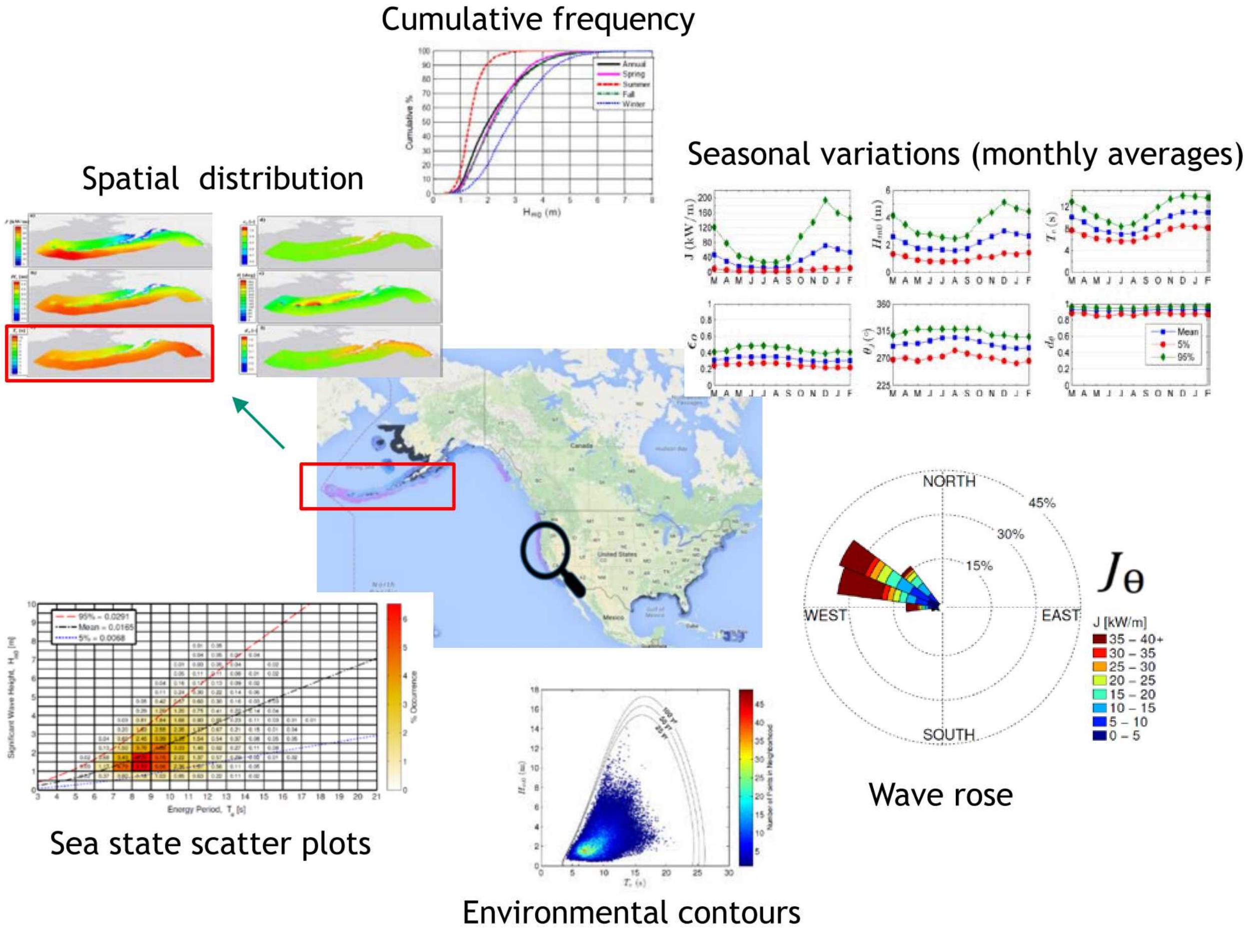
Simulated annual averages of six IEC metrics for year 2009 in Alaska region: (a) omnidirectional wave power; (b) significant wave height; (c) energy period; (d) spectral width; (e) direction of maximum directionally resolved wave power, and (f) directionality coefficient [Yang & Neary 2019]

Results: Resource data archiving & dissemination (In progress)

MHK ATLAS upgrade (In-progress)
- All 6 IEC parameters, monthly averages and average annual values
- Hs(50, 5, 1-year)
- 200-300 m resolution within US EEZ
- Includes shallow nearshore waters

MHK Data Repository (TBD)
- 2D spectra, *O*(100) points each region
- Partitioned bulk parameters, *O*(1,000) points each region
- IEC parameter time series, *O*(1M) points

Functional GIS dissemination platforms (TBD)
- Bureau of Ocean Energy Management (BOEM), US Dept. of Interior (USDOI)
- NOAA, Ocean Project Planning Tool,
- US Dept. of Commerce (USDOC)
- Private vendor, e.g., Open Ocean (Marine data intelligence) http://www.openocean.fr/en/



BOEM Bureau of Ocean Energy Management

U.S. DEPARTMENT OF ENERGY

NOAA

Concluding remarks

US experience demonstrates trend towards improved resource characterization and assessment through:

- High-resolution wave model hindcasts validated with buoy measurements
- Improved data dissemination through functional GIS platforms (MHK Atlas) and on-line data repositories.

Ongoing R&D:

- Augmenting characterization with additional metrics
- Investigating inter-annual and non-stationary trends

ACKNOWLEDGEMENTS:

Contributors to this work include Sandia colleagues Bibiana Seng, Sara Bredin, Dr. Seongho Ahn; Pacific Northwest National Laboratory researchers Dr. Zhaoqing Yang, and Dr. Taiping Wang; Georgia Tech researcher Dr. Kevin Haas; and North Carolina State University researchers Dr. Nabi Allahdadi and Dr. Ruoying He. The model test bed study benefited from review and input from steering committee members including Dr. Bryson Robertson, University of Victoria, Dr. Arun Chawla of NOAA.

Thank you

Contact: vsneary@sandia.gov

Extra slides

Resource metrics: Extreme conditions [Neary et al. 2017, 2019]

Extreme wave height

$H_{s(50)}$	$H_{s(5)}$	$H_{s(1)}$	[m]

- Characterizes wave load [DNV RP-C205 2014]

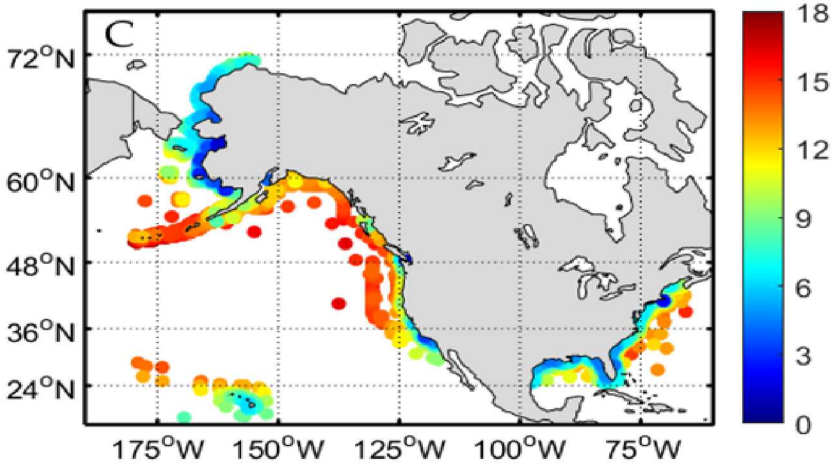
Relative risk ratio

$$R = \frac{H_{s(50)}}{H_{s(mean)}} \quad [-]$$

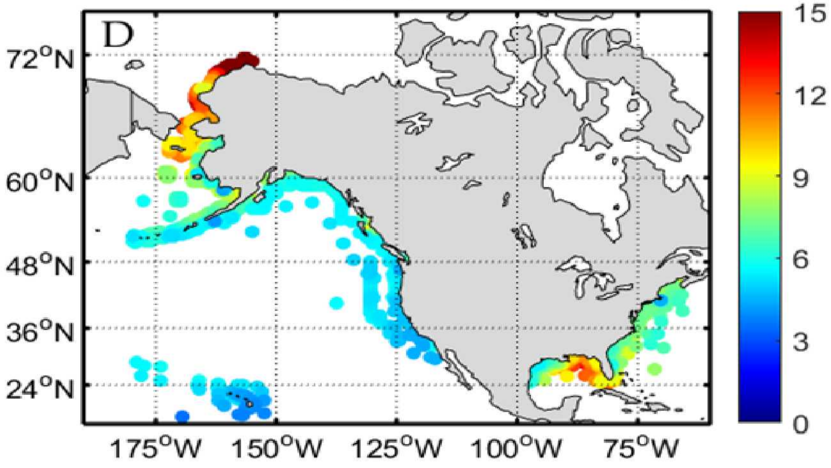
- Characterizes risk relative to opportunity [Neary et al. 2017

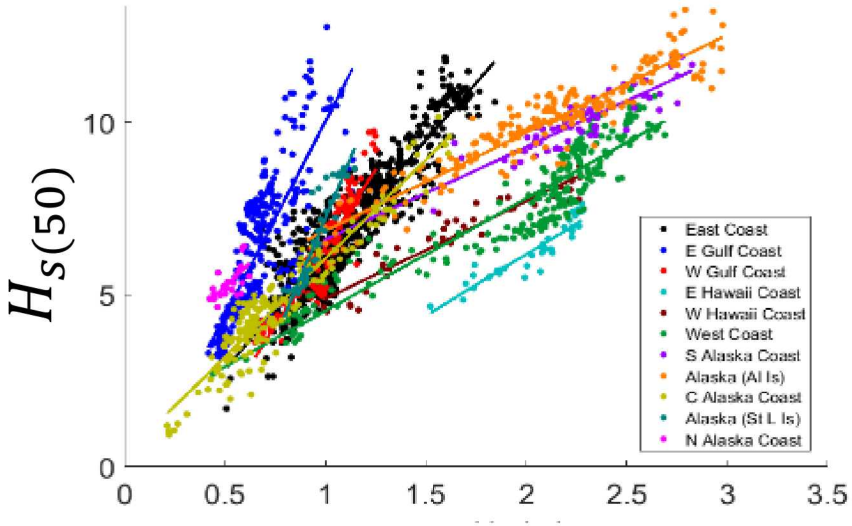
Results: Additional metrics, extreme wave height, relative-risk ratio [Neary et al. 2019]

$H_{s(50)}$



$R = H_{s(50)}/H_{s(mean)}$





Regional correlations: extreme and mean wave heights [Neary et al. 2017]

Resource metrics: Temporal variability [Haas et al. 2019]

Temporal coefficient seasonal variability

$$t_s = \frac{J(max) - J(min)}{J_{avg}}$$ [-]

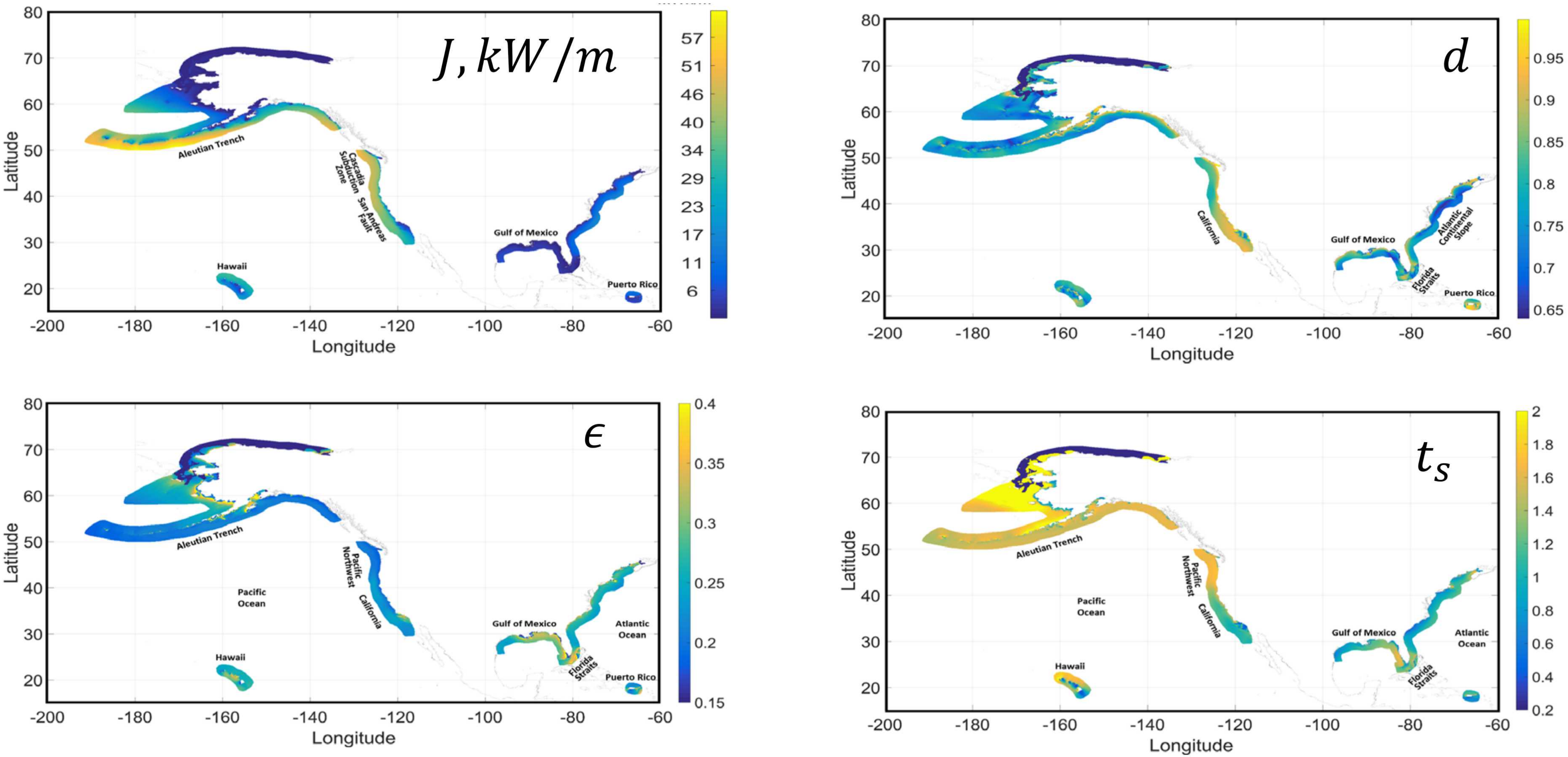
- Characterizes seasonal variability/constancy of resource

Temporal coefficient inter-annual variability

$$t_i = \frac{\sigma\left[AAE(Y) - (S_1 Y + S_2)\right]}{AAE} \times 100\ \%$$

- Characterizes inter-annual variability/constancy of resource

Results: Geographic distribution of resource metrics [Haas et al. 2019]



References: Opportunities & challenges

The Special Report on Global Warming of 1.5 °C (SR15) was published by the Intergovernmental Panel on Climate Change (IPCC) on 8 October 2018

USDOE 2019. Powering the blue economy: Exploring opportunities for marine renewable energy in maritime markets. USDOE, Office of Energy Efficiency and Renewable Energy (EERE), April 2019. https://www.energy.gov/eere/water/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets

NASA Earth Observation Group at NOAA's National Geophysical Data Center. USA Night Map, April 18 - October 23, 2012. Data acquired by the Suomi NPP satellite. https://earthobservatory.nasa.gov/images/79800/city-lights-of-the-united-states-2012

Neary, V.S., M.Previsic, R.A. Jepsen, M. Lawson, Y. Yu, A.E. Copping, A.A. Fontaine, K.C. Hallett and D.K. Murray (2014). Methodology for design and economic analysis of Marine Energy Conversion (MEC) technologies. SAND2014-9040, Sandia National Laboratories, March 2014. 261 pages.

References: Background US resource assessment

EPRI, Mapping and Assessment of the United States Ocean Wave Energy Resource, in EPRI 2011 Technical Report to U.S. Department of Energy2011, Electric Power Research Institute: Palo Alto, California.

NREL, MHK Atlas, web site accessed 26 June 2019: https://maps.nrel.gov/mhk-atlas/

USDOE 2015 Quadrennial Technology Review: An assessment of energy technologies and research opportunities. USDOE, p. 489, September 2015. https://www.energy.gov/quadrennial-technology-review-2015-omnibus

Chawla A, Spindler DM, Tolman HL. Validation of a thirty year wave hindcast using the Climate Forecast System Reanalysis winds. Ocean Model 2013;70:189–206. doi:10.1016/j.ocemod.2012.07.005.

References: Methods (SWAN modeling)

Allahdadi, M.N., Gunawan, J. Lai, R. He, V.S. Neary (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. https://doi.org/10.1016/j.renene.2019.01.020

Allahdadi, M. N., He, R., and Neary, V. S.: Predicting ocean waves along the US East Coast during energetic winter storms: sensitivity to whitecapping parameterizations, *Ocean Sci.*, 15, 691-715, https://doi.org/10.5194/os-15-691-2019, 2019.

Z. Yang, V. S. Neary, "U.S. regional wave model hindcasts for wave resource characterization, classification and assessment," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019

Yang, Z., V.S. Neary, T. Wang, BGunawan, A.R. Dallman, W. Wu (2016). A wave model test bed study for wave energy resource characterization. Renewable Energy, Available online 23 December 2016 (2017) 1 – 13. http://dx.doi.org/10.1016/j.renene.2016.12.057

References: Methods (characterization, metrics)

W. Cooper, A.Saulter, P. Hodgetts, Guidelines for use of metocean data through the life cycles of a marine renewable energy development, C666, RP 742, ©CIRIA 2008.

Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization, IEC TS 62600-101:2015-06.

Det Norske Veritas, Recommended Practice - Environmental conditions and environmental loads, DNV-RP-C205:2014.

K. A. Haas, S. Ahn, V. S. Neary, "Wave energy resource classification system as characterization and assessment tool," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019

V. S. Neary, R. G. Coe, J. Cruz, K. Haas, G. Bacelli, Y. Debruyne, S. Ahn, V. Nevarez, "Classification systems for wave energy resources and WEC technologies," *Int. Marine Energy Journal*, vol. 1, no. 2, pp. 71-79, 2018.

V. S. Neary, B. E. Seng, Z. Yang, N.Allahdadi, R. He, T. Wang, "Model performance predicting extreme wave heights for project risk assessment and WEC design," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019.

References: Results

Allahdadi, M.N., Gunawan, J. Lai, R. He, V.S. Neary (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. https://doi.org/10.1016/j.renene.2019.01.020

Z. Yang, V. S. Neary, "U.S. regional wave model hindcasts for wave resource characterization, classification and assessment," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019

V. S. Neary, B. E. Seng, Z. Yang, N.Allahdadi, R. He, T. Wang, "Model performance predicting extreme wave heights for project risk assessment and WEC design," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019

K. A. Haas, S. Ahn, V. S. Neary, "Wave energy resource classification system as characterization and assessment tool," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019