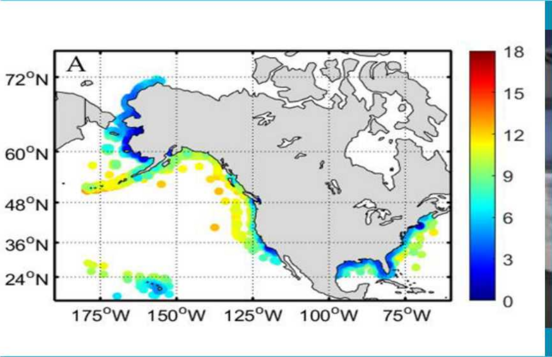
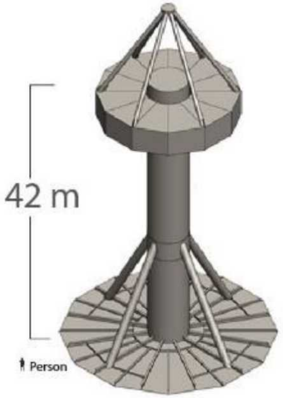
Sandia National Laboratories

SAND2019-7598C

Trends in met-ocean characterization for project development and design: US wave energy perspective





PRESENTED BY

Vincent Neary, Water Power Technologies, 4 July 2019

Stakes and trends in the future structures at sea

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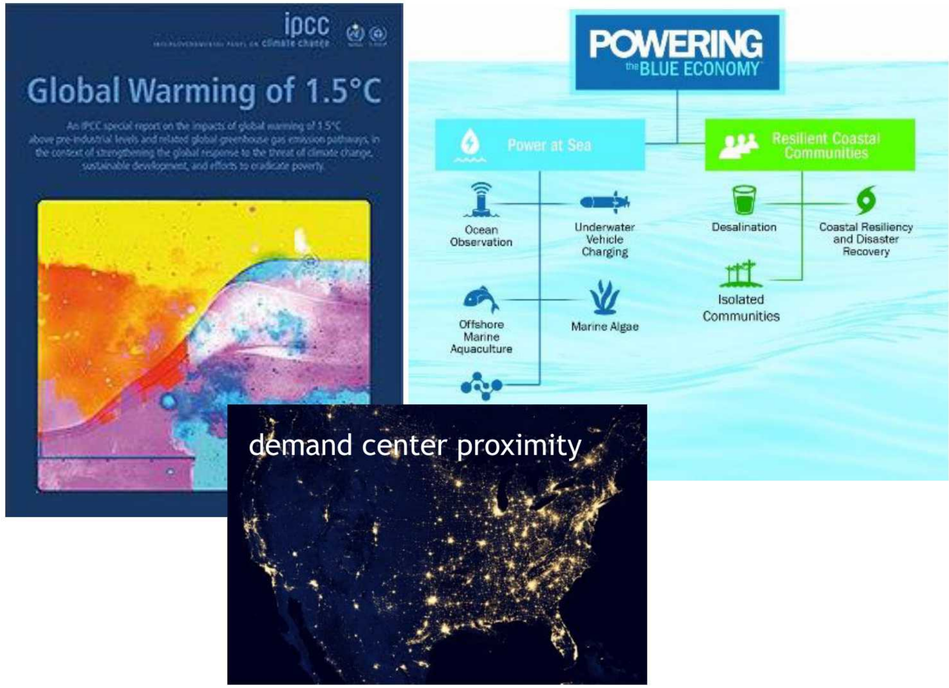
Agenda

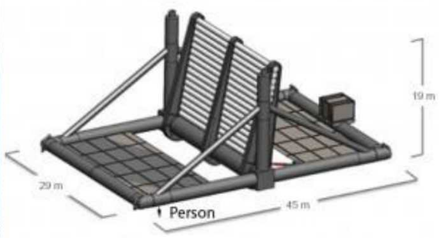
Wave energy converters (WEC) as next generation renewable energy generation technologies
- Opportunities and challenges
- The USDOE R&D program

Wave resource characterization, classification and assessment
- Motivation, Goals & Objectives
- Methods
- Results
- Conclusions

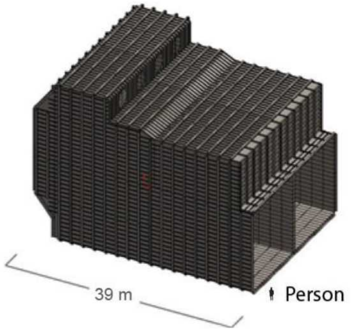
Ocean renewable energy: Opportunities & challenges

Ocean renewable energy; Opportunities and challenges

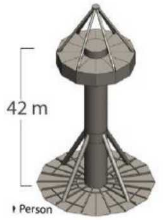




RM5, 10 MW, 0.87€ /kWh



RM6, 10 MW, 135€/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

Wave resource characterization

Background

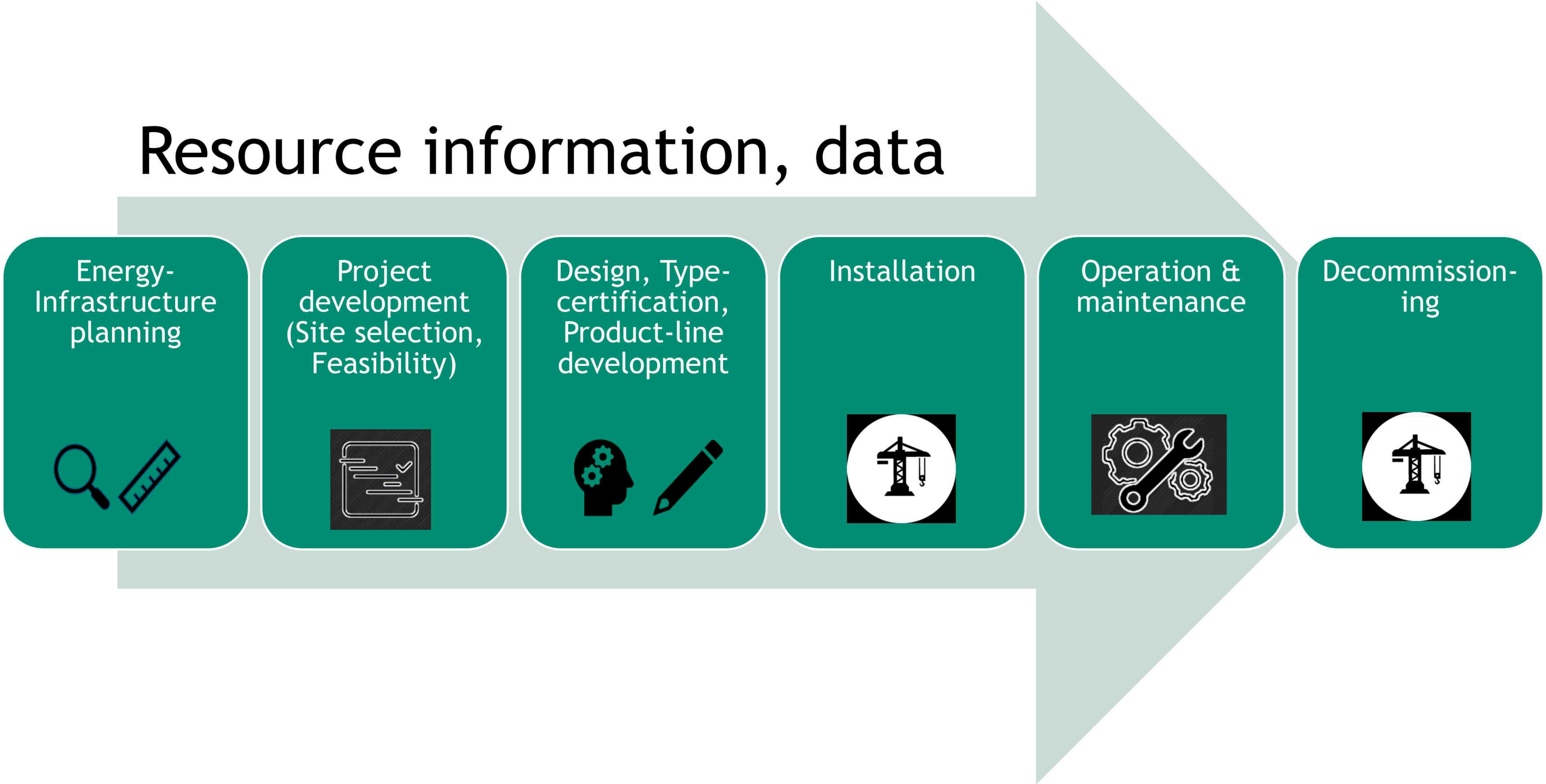
- National resource assessments quantified potential contribution of wave energy to electricity production nationally and regionally [EPRI 2011, Chawla et al. 2013]
- More refined and comprehensive characterization needed to improve national assessments and to support energy planning, project development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

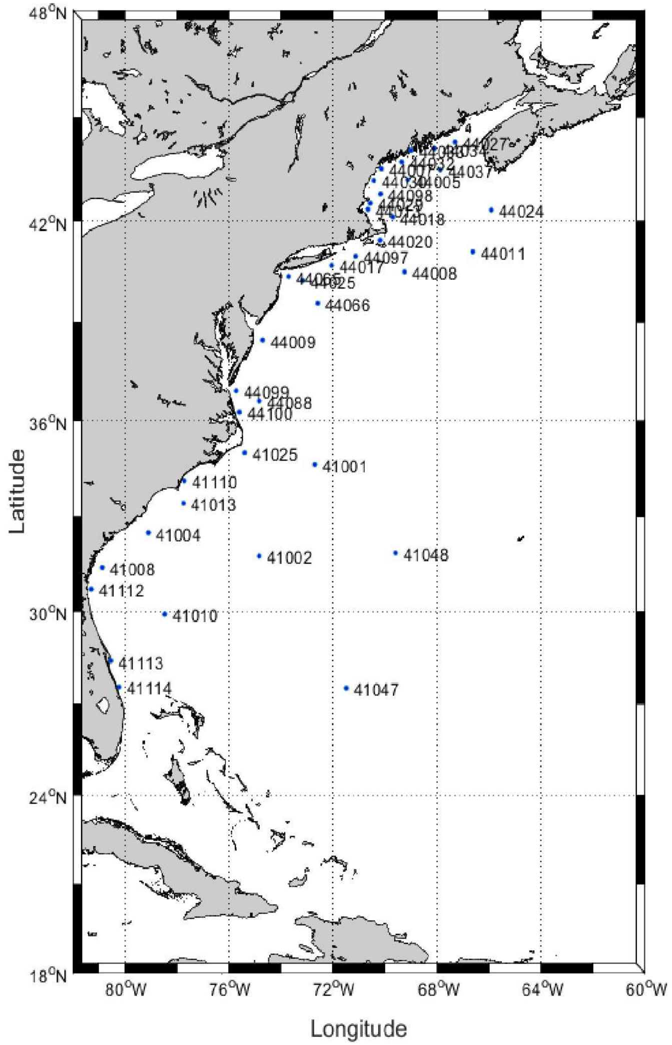
Resource	Theoretical Resource
Waves	1,594–2,640 TWh/year
Tidal streams	445 TWh/year
Ocean currents	200 TWh/year

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

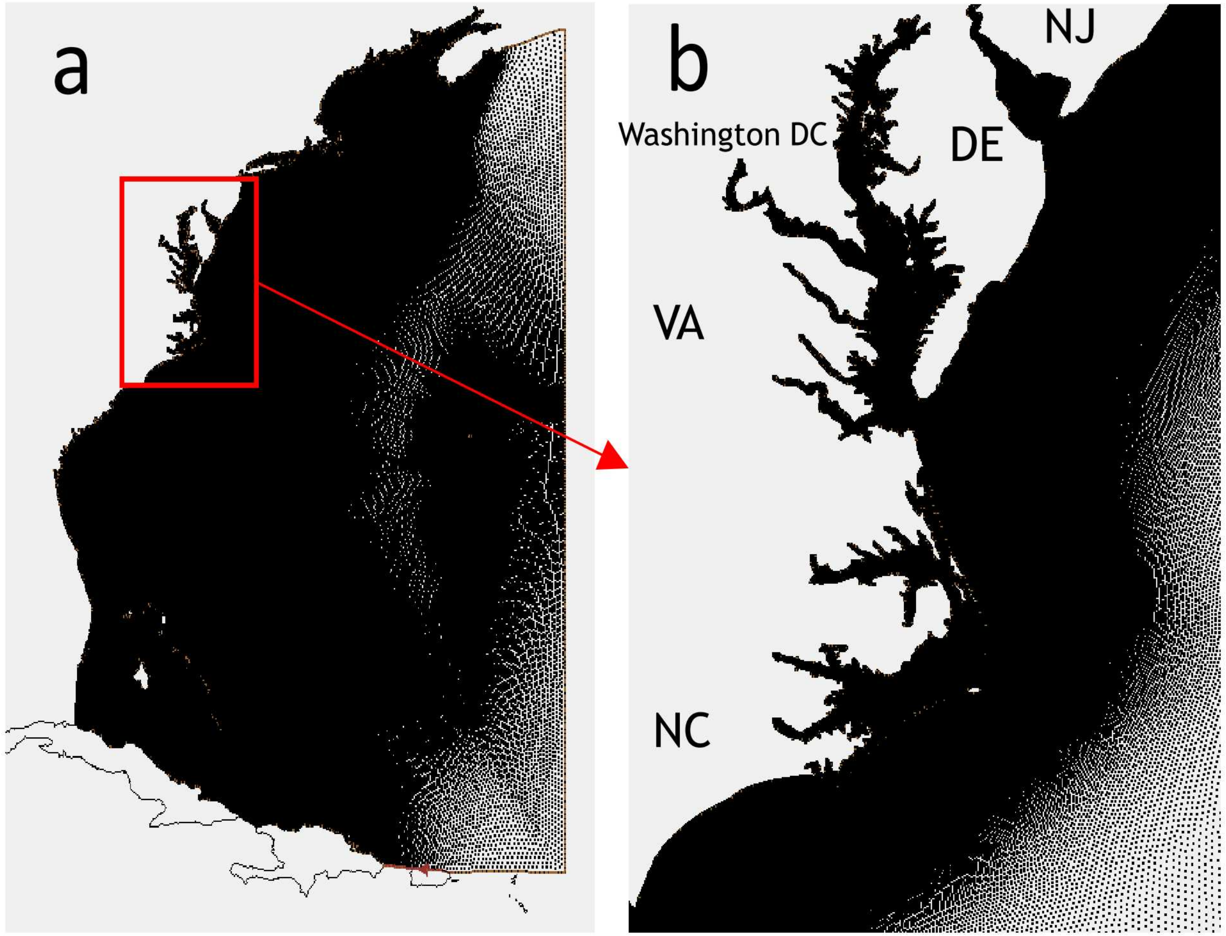
Background: Information and data needs for ocean projects



Motivation: Resource data sources limited



Validation buoys US East Coast [Allahdadi et al. 2019]
Sparse coverage, limited period of record (POR)



SWAN model with over 4 M grid cells [Allahdadi et al. 2019]
High-resolution coverage (200 m), 32-year POR vs. NOAA WWIII model (4 arc-minute = 5-7 km), 30-year POR [Chawla et al. 2013]

Motivation: Characterization metrics limited

Guidelines for met-ocean data use for marine energy project development [Cooper et al. 2008]

6 standard metrics for assessing wave energy resource [IEC TS 62600-101:2015-06]

IEC Wave Resource Metric
Power, J
Sea state (H_s, T_e**)**
Spectral width, ϵ_0
Directionality coefficient, d
Direction of max power, θ_{Jmax}

No metrics for temporal variability/constancy (monthly, inter-annual)

No metrics on extremes

- High-percentile values, e.g., Hs(95-percentile)
- n-year events, e.g., Hs(50-year)

MHK Atlas showing spatial distribution of average annual omni-directional power density computed From NOAA WWIII 30-y hindcast [NREL 2019]

Motivation: Data archiving & dissemination limited

MHK ATLAS currently limited to four IEC parameters calculated from 30-year NOAA hindcast

Coarse resolution 4 arc-minute, 5-7 km

Hindcast accuracy poor

Shallow nearshore waters not resolved

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

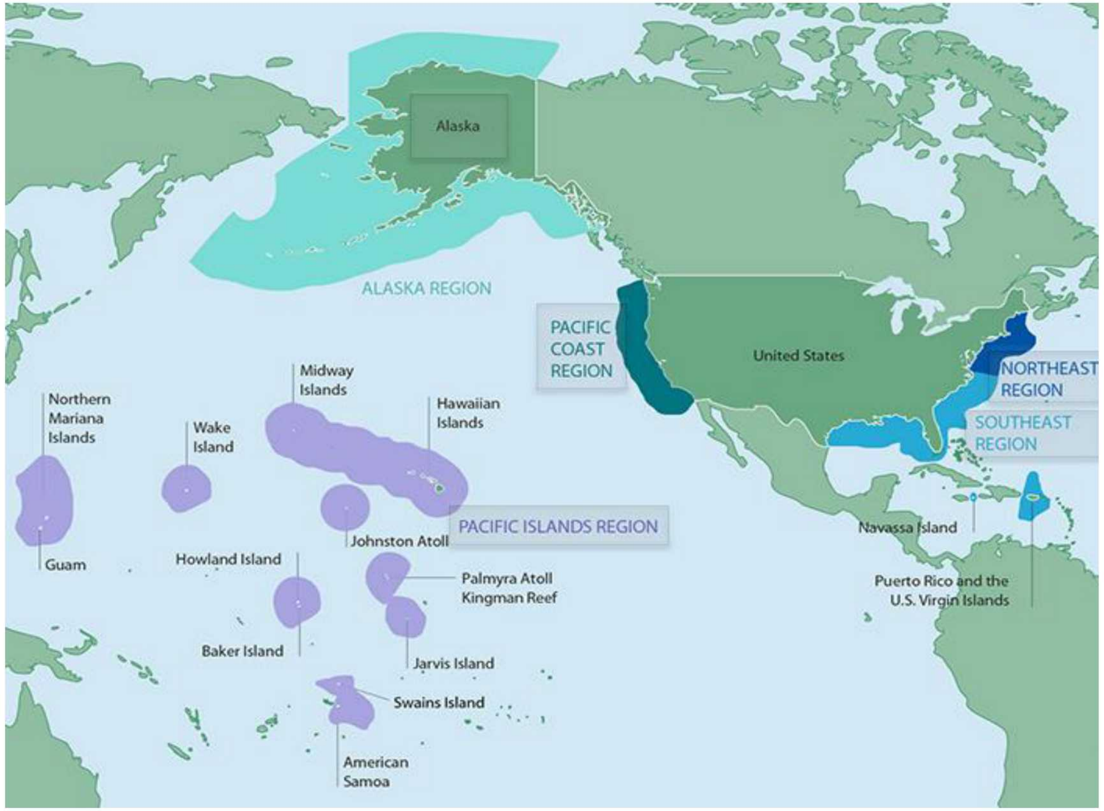
Goals/Objectives

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

Improve data source and augment resource metrics

Improve dissemination through MHK ATLAS upgrade

Region	Area, km^2	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

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

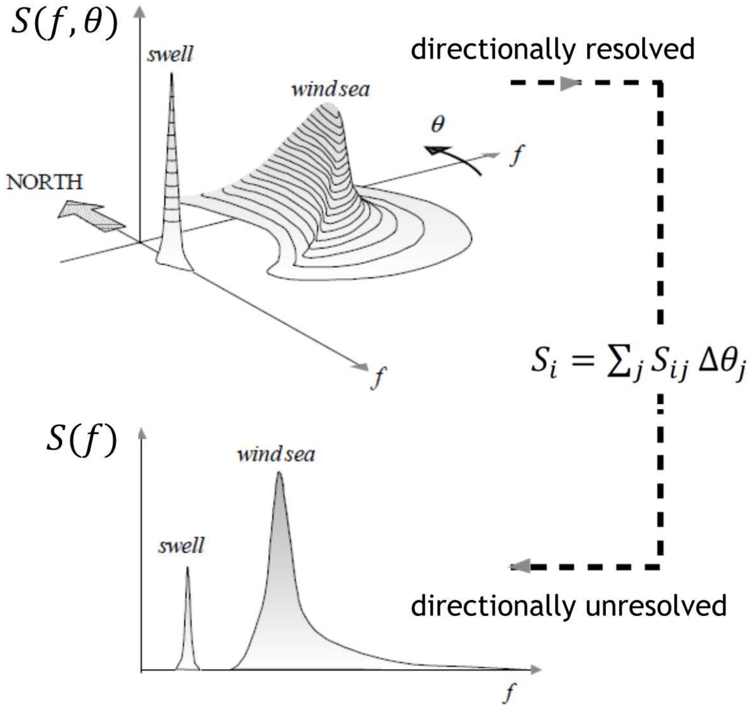
Evolution of wave action density (N) in space and time for all frequencies (σ=2πf) and directions (θ) (LHS)

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

3 assessment classes, area, Δx, Δt:

- Reconnaissance (>300 km), 5 km, 3 h
- Feasibility (20-500 m), 500 m, 3 h
- Design (<25 km), 50 m, 1 h

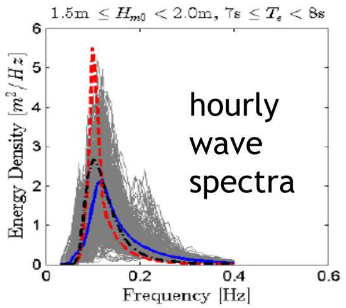
Source: SWAN Technical Manual



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

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

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



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

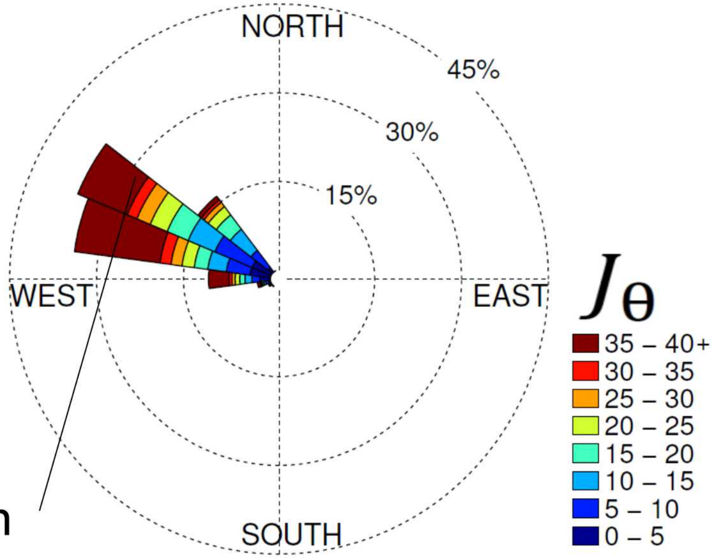
$$\theta_{\mathrm{Jmax}}$$ [deg]

- 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

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

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

Energy period

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

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

Spectral width

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

- Measure of energy spreading in wave spectrum.

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

Coefficient of monthly variability

$$C_m = \frac{J(max) - J(min)}{J} \quad [-]$$

- Measure of seasonal variability/constancy of resource

Coefficient of inter-annual variability

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

- Measure of inter-annual variability/constancy of resource

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

Extreme wave height

$H_{s(50)}$	$H_{s(5)}$	$H_{s(1)}$

[m]

- Measure of wave load [DNV RP-C205 2014]

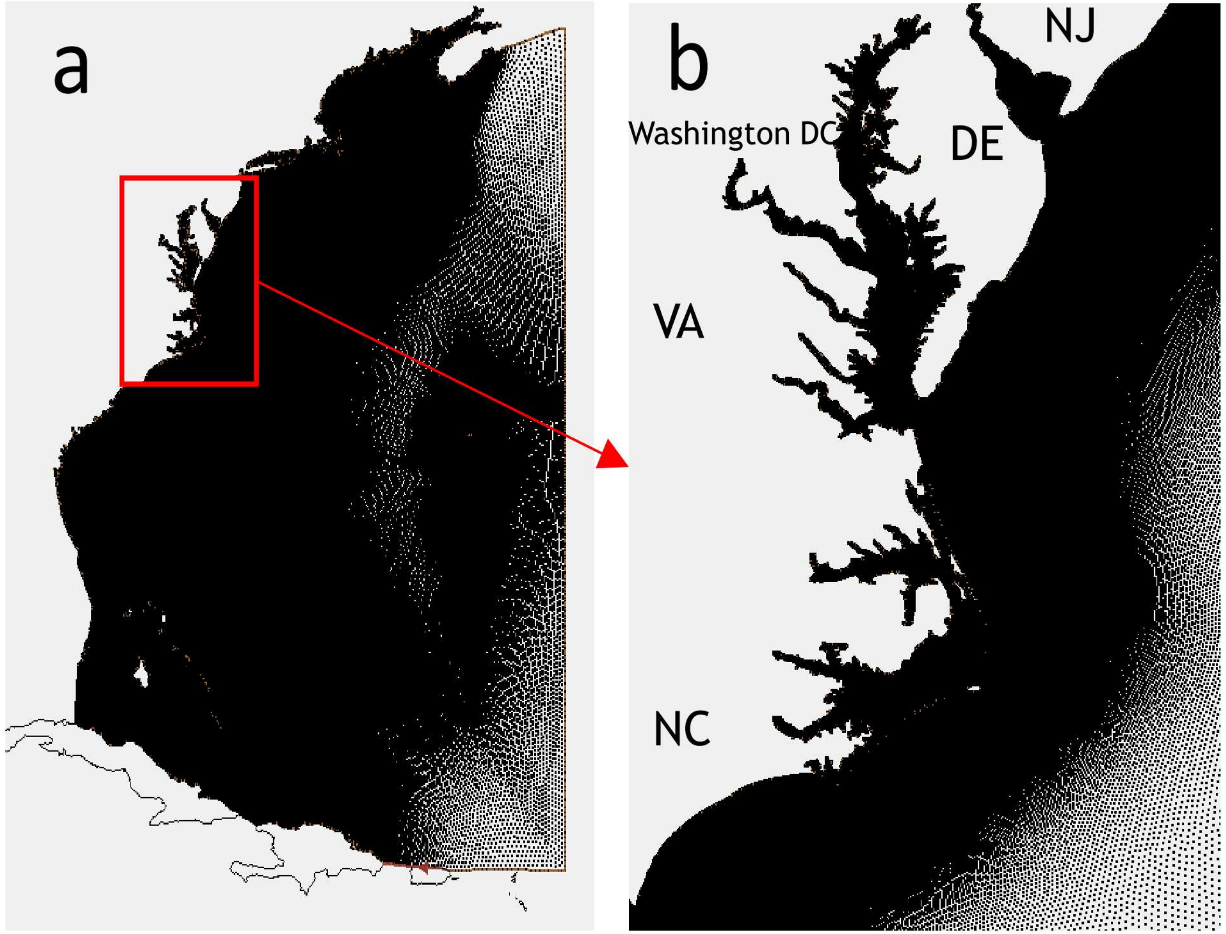
Relative risk ratio

$$R = \frac{H_{s(50)}}{H_{s(mean)}}$$

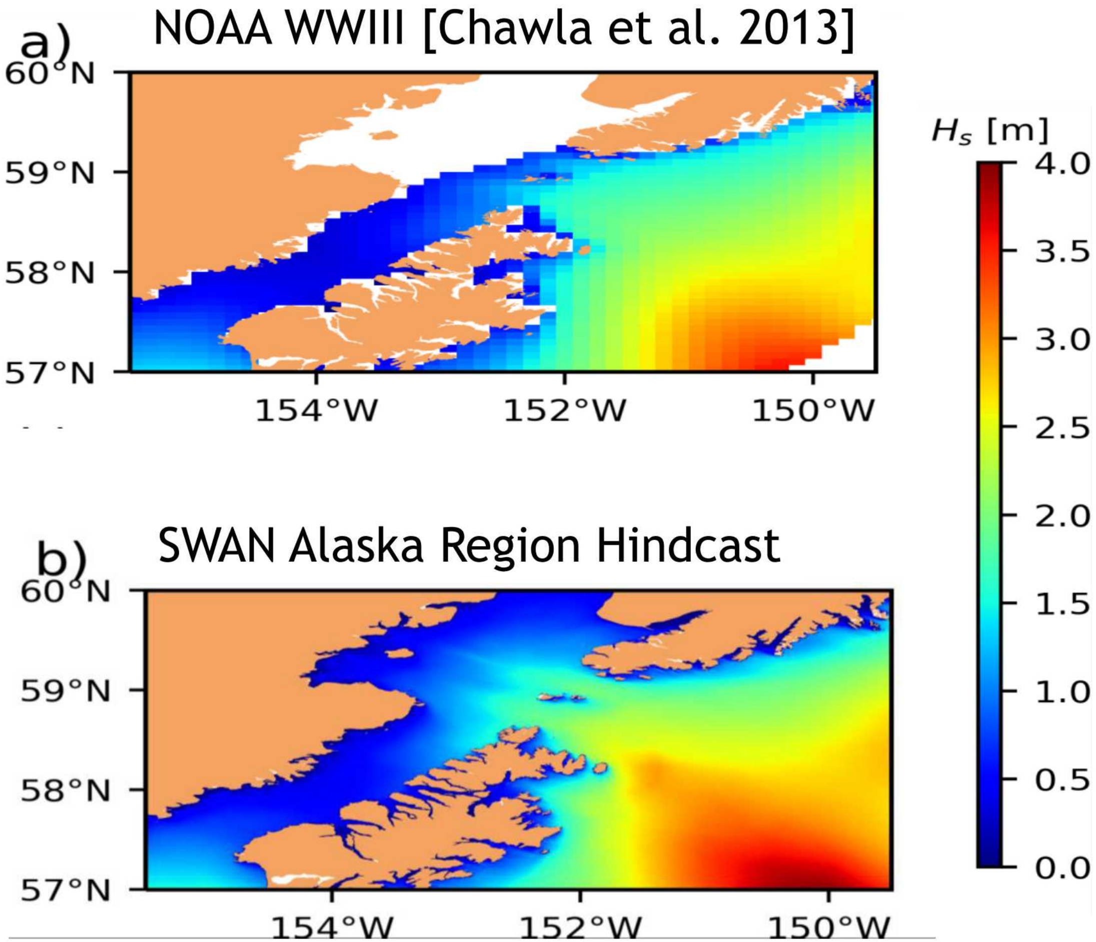
[-]

- Measure of risk relative to opportunity [Neary et al. 2017

Results: Model mesh refinement

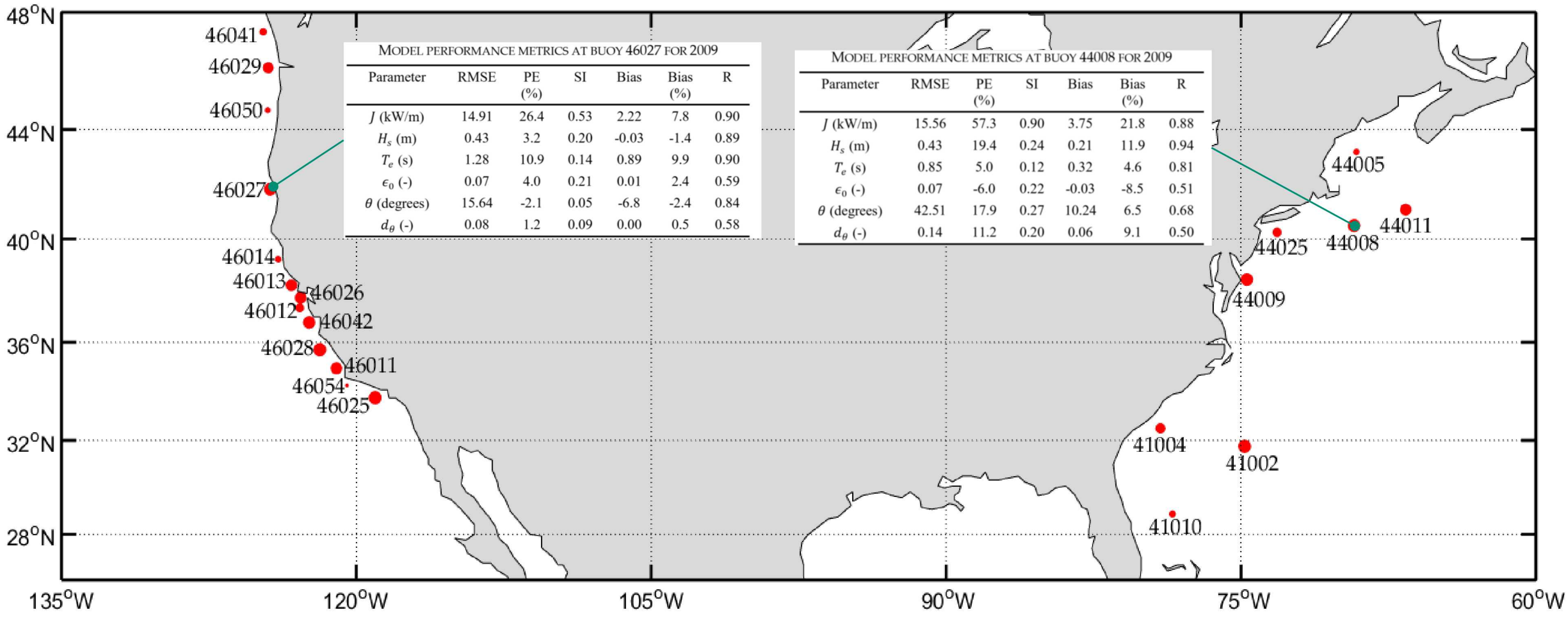


SWAN model grid for U.S. East Coast (a) and zoomed-in near the Chesapeake Bay region (b) [Allahdadi et al. 2019]



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

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



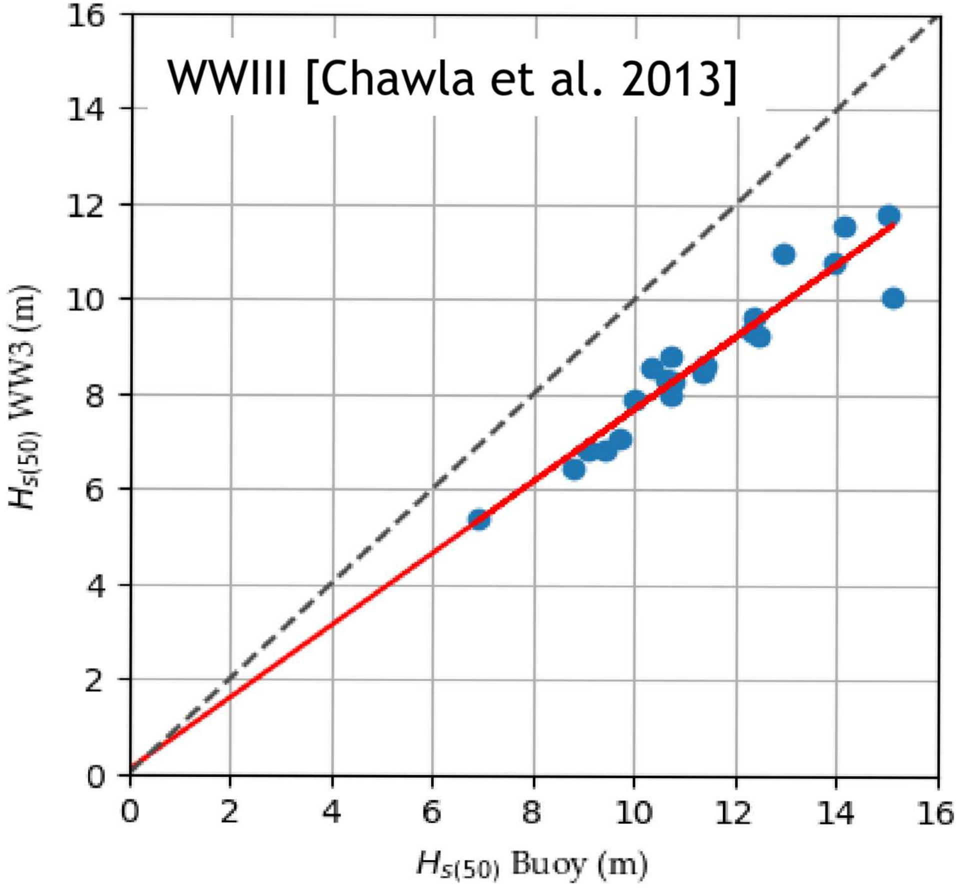
MODEL PERFORMANCE METRICS AT BUOY 46027 FOR 2009

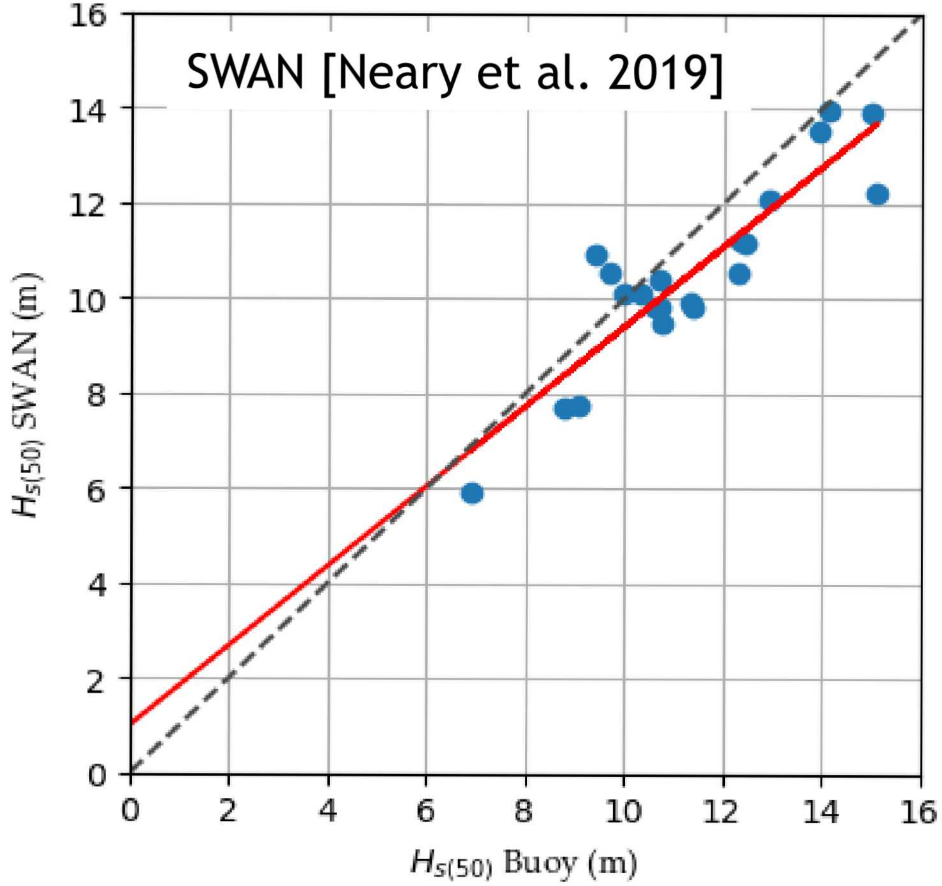
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	14.91	26.4	0.53	2.22	7.8	0.90
H_s (m)	0.43	3.2	0.20	-0.03	-1.4	0.89
T_e (s)	1.28	10.9	0.14	0.89	9.9	0.90
ϵ_0 (-)	0.07	4.0	0.21	0.01	2.4	0.59
θ (degrees)	15.64	-2.1	0.05	-6.8	-2.4	0.84
d_θ (-)	0.08	1.2	0.09	0.00	0.5	0.58

MODEL PERFORMANCE METRICS AT BUOY 44008 FOR 2009

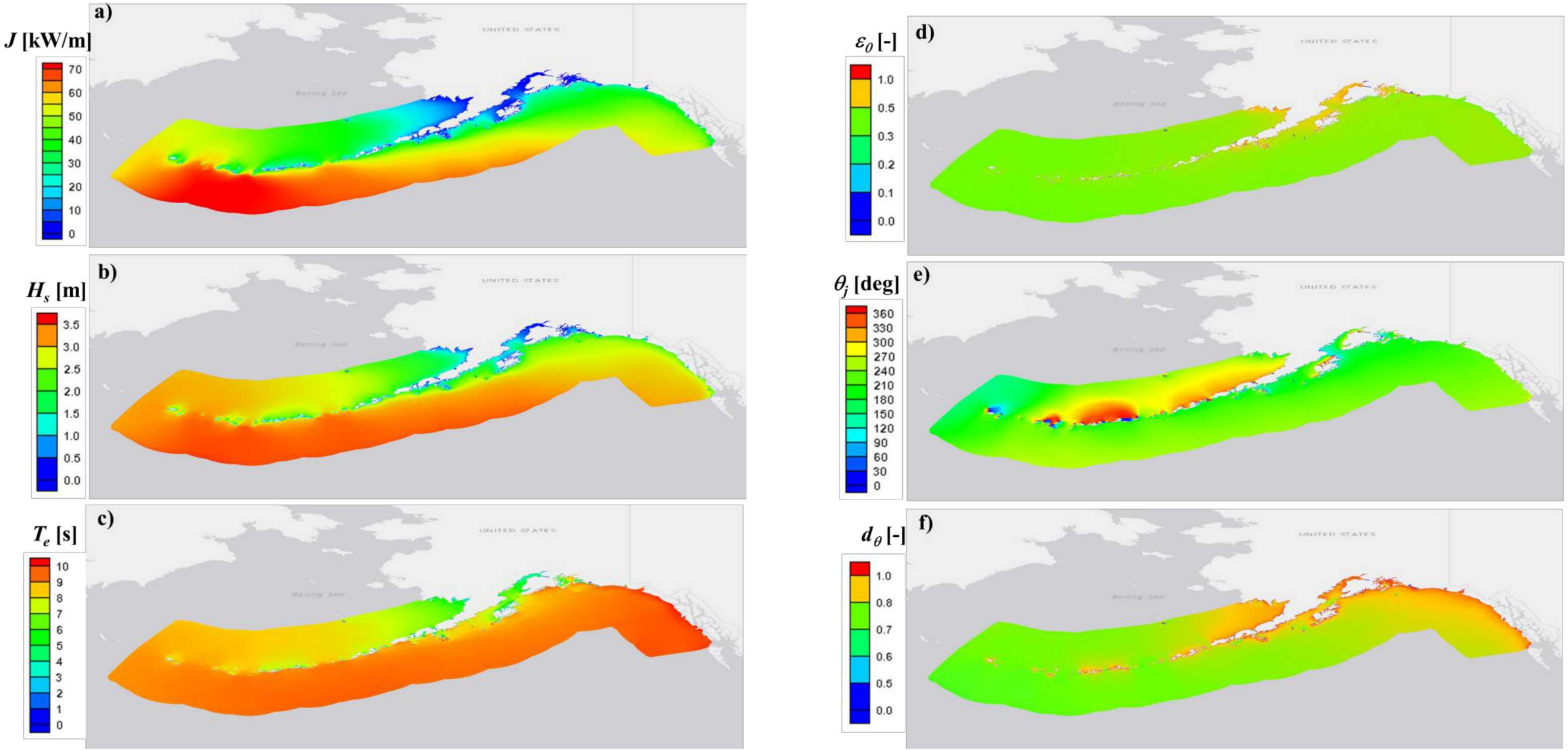
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	15.56	57.3	0.90	3.75	21.8	0.88
H_s (m)	0.43	19.4	0.24	0.21	11.9	0.94
T_e (s)	0.85	5.0	0.12	0.32	4.6	0.81
ϵ_0 (-)	0.07	-6.0	0.22	-0.03	-8.5	0.51
θ (degrees)	42.51	17.9	0.27	10.24	6.5	0.68
d_θ (-)	0.14	11.2	0.20	0.06	9.1	0.50

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



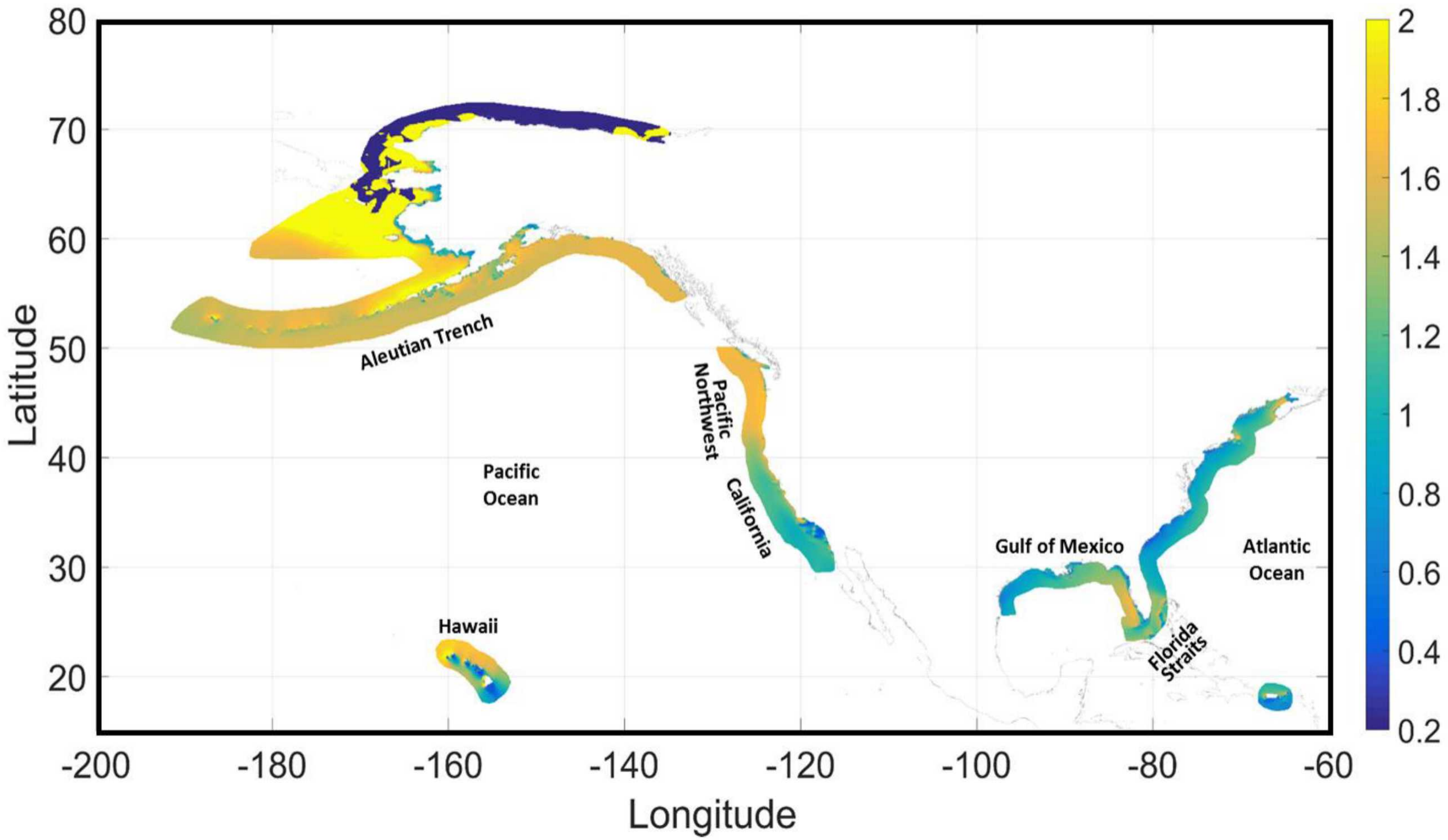


Results: 6 IEC parameters mapped at 200-300 m resolution

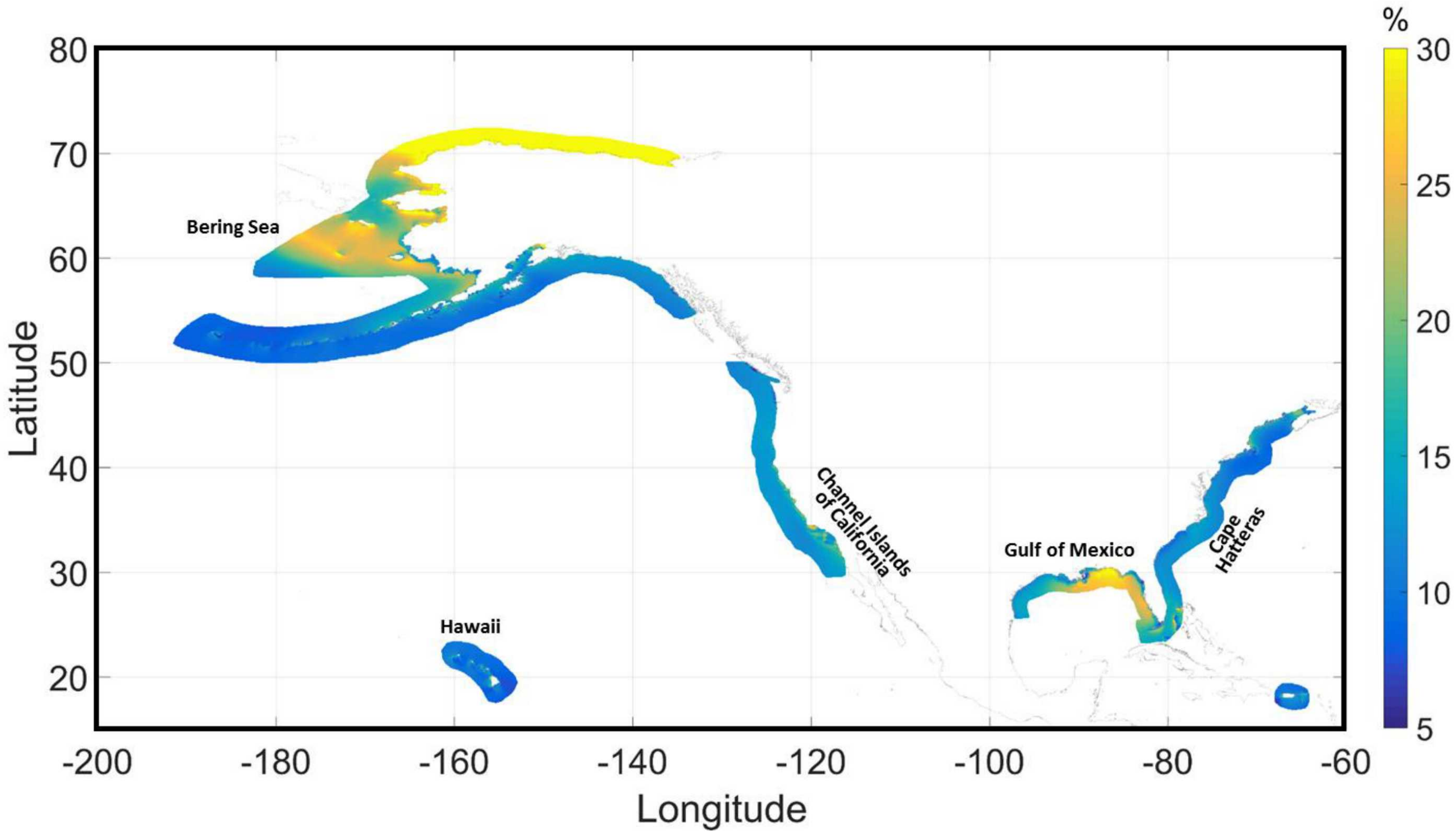


Simulated annual averages of six IEC metrics for year 2009 in Alaska region: (a) omnidirectional wave power; (b) significant wave height; (c) energy period; (d) spectral width; (e) direction of maximum directionally resolved wave power, and (f) directionality coefficient [Yang & Neary 2019]

Results: Additional metrics, monthly variability, C_m

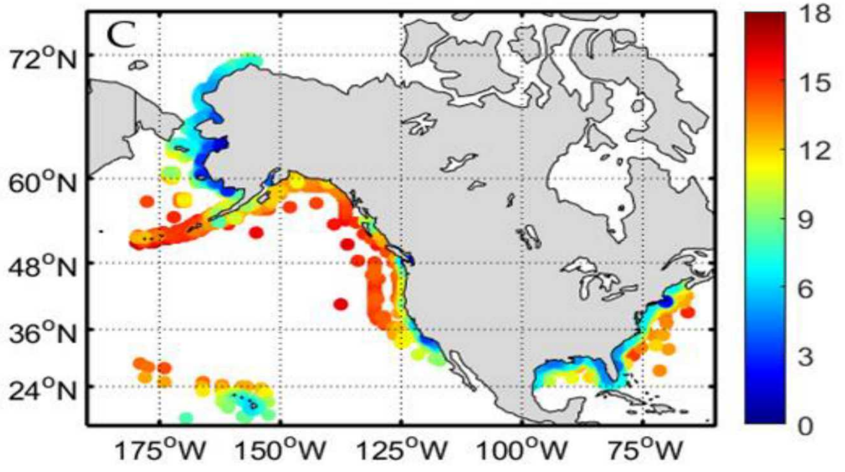


Results: Additional metrics, inter-annual variability, C_{ia}

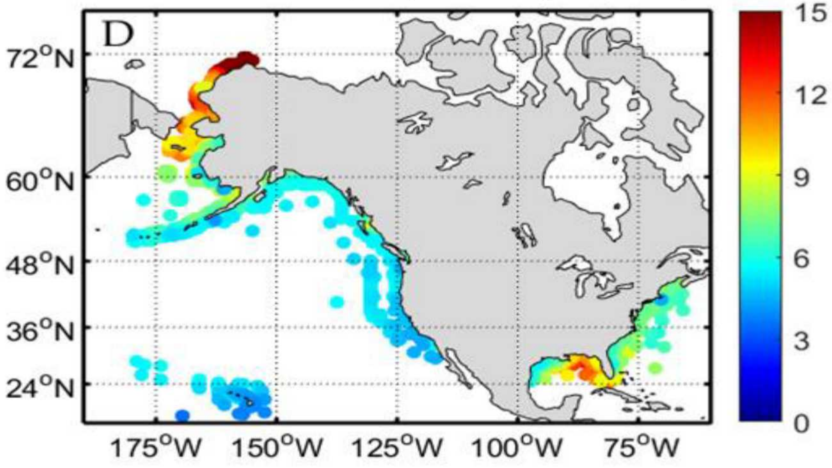


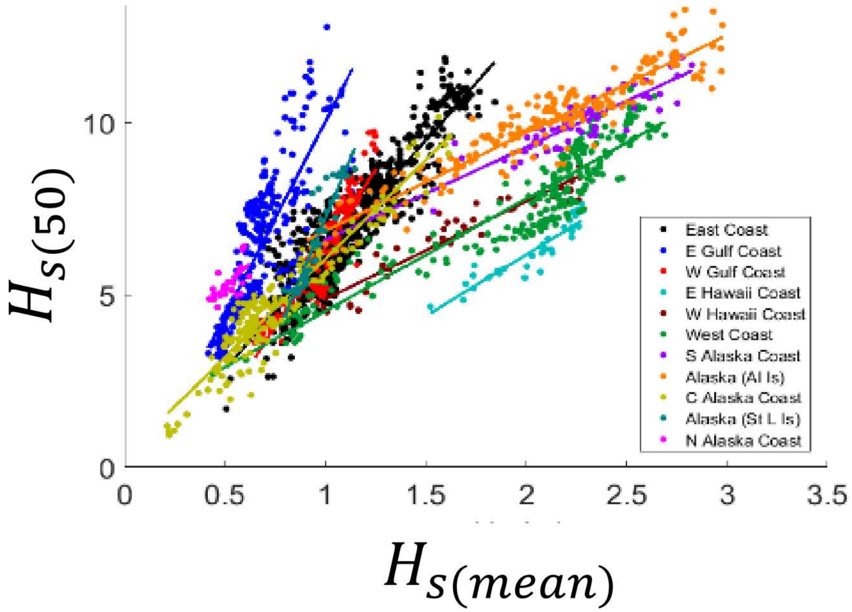
Results: Additional metrics, extreme wave height, relative-risk ratio [Neary et al. 2019]

$H_{s(50)}$



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





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

Results: Resource data archiving & dissemination (In progress)

MHK ATLAS upgrade (In-progress)

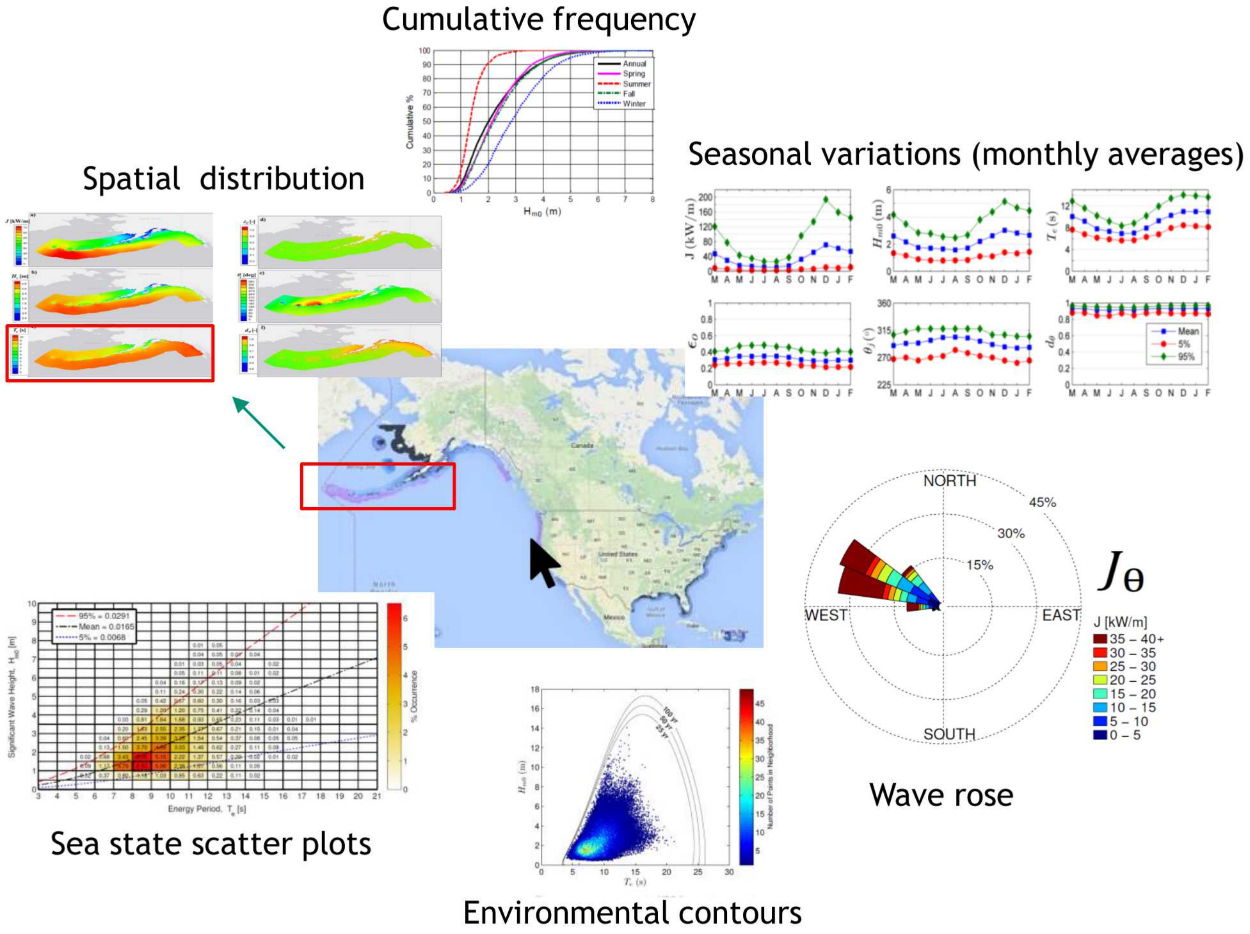
- All 6 IEC parameters, monthly averages and average annual values
- 200-300 m resolution within US EEZ
- Includes shallow nearshore waters

MHK Data Repository (TBD)

- 2D spectra, O(100) points each region
- Partitioned bulk parameters, O(1,000) points each region
- IEC parameter time series, 3h intervals, O(1M) points
- Hs(50, 5, 1-year)

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/



Concluding remarks

Successful ocean development requires best available data sources and metrics to characterize the opportunities, risks and constraints for all phases of project life cycle.

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

- High-resolution validated wave model hindcasts
- Additional metrics to characterize extreme conditions and temporal variability
- Improved data dissemination through functional GIS platforms (MHK Atlas) and on-line data repositories

High-quality resource data/information accessible on web-based functional GIS platforms can significantly reduce costs for ocean development

Ongoing R&D will introduce better data sources, improved model hindcasts and knowledge on non-stationary trends due to climate change that will require periodic upgrades to metocean data and information

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Thank you

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