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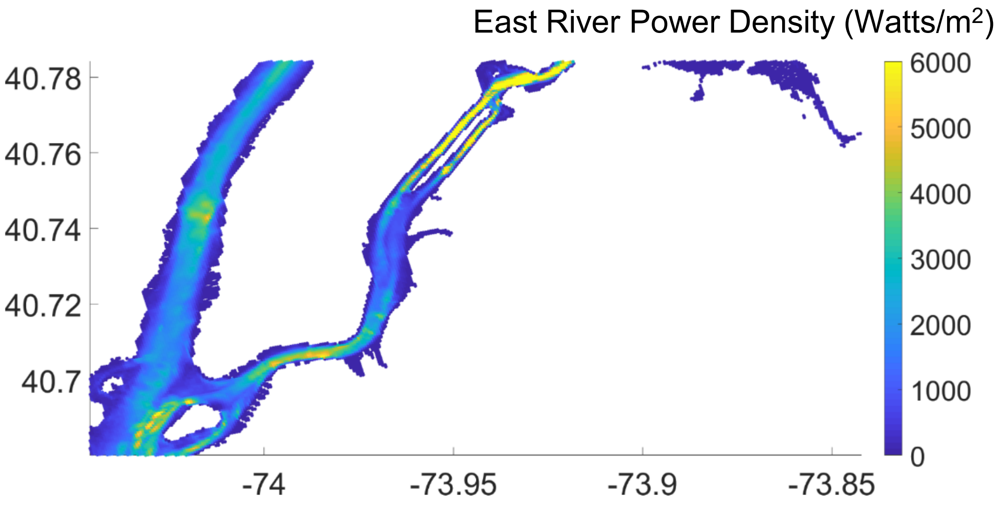

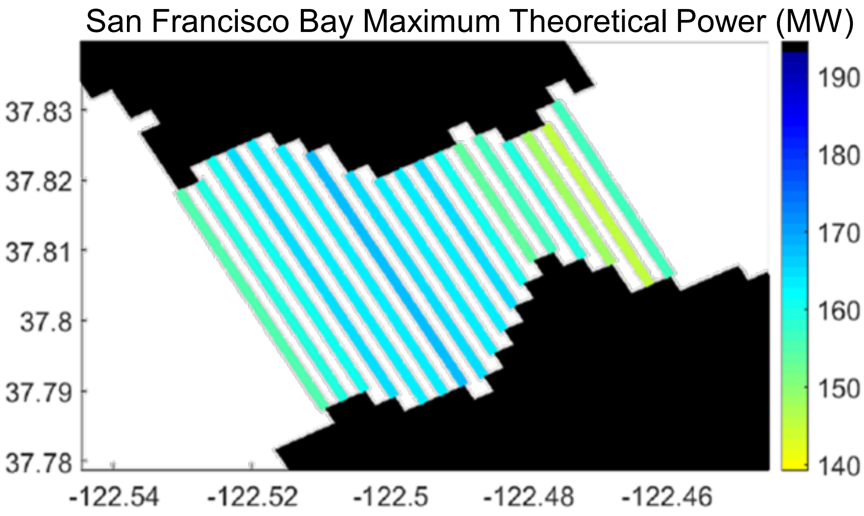

Tidal Gaps Resource Analysis

2.1.5.403

Marine and Hydrokinetics Program

October 10, 2019

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National Renewable Energy Laboratory

Kevin Haas and Alexandra Muscalus
Georgia Institute of Technology

Project Overview

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Project Summary

The tidal resource gaps project was created to address a growing body of evidence that models underpredict tidal current speeds compared to measurements at a number of top-ranking tidal energy sites. This led to industry and DOE concerns that the U.S. tidal energy resource assessment, which is based primarily on models, may be an underestimate. The goal of this project, therefore, is to perform a systematic review of the tidal energy resource assessment methodology—including a detailed investigation of the model validation data sets and procedures—and to propose changes or update results where possible.

Project Objective & Impact

The goal of this project is to resolve discrepancies between current speed measurements at top-ranking tidal energy sites and resource models of those sites. This will provide DOE and the tidal energy industry with a clearer understanding of the accuracy of the existing tidal energy resource assessment. This will improve confidence in tidal energy resource estimates and will provide the data needed to undertake more detailed tidal energy site-identification and market assessment studies. Ultimately, the refined resource assessments will help guide the U.S. tidal energy industry to the most promising tidal energy sites.

Project Information

Project Principal Investigator

Levi Kilcher
National Renewable Energy Laboratory

WPTO Lead

Steve Dewitt

Project Partners/Subs

Kevin Haas
Georgia Institute of Technology

Project Duration

- Started: Oct. 1, 2016
- Ends: Sept. 30, 2019

Alignment with the Program

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Marine and Hydrokinetics (MHK) Program Strategic Approaches

Data Sharing and Analysis

Foundational and Crosscutting R&D

Technology-Specific Design and Validation

Reducing Barriers to Testing

Alignment with the MHK Program

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Foundational and Crosscutting R&D

- Drive innovation in components, controls, manufacturing, materials and systems with early-stage R&D specific to MHK applications
- Develop, improve, and validate numerical and experimental tools and methodologies needed to improve understanding of important fluid-structure interactions
- **Improve MHK resource assessments and characterizations needed to optimize devices and arrays, and understand extreme conditions**
- Collaboratively develop and apply quantitative metrics to identify and advance technologies with high ultimate techno-economic potential for their market applications

The primary objective of this project is to resolve discrepancies between measurements and the models used to estimate national/regional/state tidal energy resource totals and site details.

This will help the MRE industry, DOE, and other MRE stakeholders to better identify, prioritize, and design tidal energy sites and projects.

Alignment with the MHK Program

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Data Sharing and Analysis

- **Provide original research to assess and communicate potential MHK market opportunities, including those relevant for other maritime markets**
- **Aggregate and analyze data on MHK performance and technology advances, and maintain information sharing platforms to enable dissemination**
- Support the early incorporation of manufacturing considerations/information into design processes
- Leverage expertise, technology, data, methods, and lessons from the international MHK community and other offshore scientific and industrial sectors

This project conducts original research on the tidal energy resource, which is critical to assessments of its market opportunity.

It has also updated the MHK Atlas with new model results that provide a more accurate picture of the U.S. tidal energy opportunity.

Alignment with the MHK Program

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Technology-Specific Design and Validation

- Validate performance and reliability of systems by conducting in-water tests of industry-designed prototypes at multiple relevant scales
- Improve methods for safe and cost-efficient installation, grid integration, operations, monitoring, maintenance, and decommissioning of MHK technologies
- **Support the development and adoption of international standards for device performance and insurance certification**
- Evaluate current and potential future needs for MHK-specific IO&M infrastructure (vessels, port facilities, etc.) and possible approaches to bridge gaps

Because the team involved in this project is actively involved in International Electrotechnical Commission standards on marine energy resource assessment (IEC TC114), the methods and approaches developed in this project are designed to be consistent with international standards, and/or to be proposed as improvements to them.

This approach maximizes the probability that results will be accepted and adopted by the international scientific and MRE community.

Project Budget

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FY17	FY18	FY19 (Q1 & Q2 Only)	Total Project Budget FY17–FY19 Q1 & Q2 (October 2016–March 2019)	
Costed	Costed	Costed	Total Costed	Total Authorized
$186K	$36K	$13K	$235K	$273K

- Variances from planned budget due to project leaders being diverted to higher-priority projects
  - This project remained dormant for 1.5 years
- Scope increased due to project leaders working closely with DOE to maximize the project impact as it evolved

Management and Technical Approach

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- **Collaboration between NREL and Georgia Tech**

NREL (Levi Kilcher)	Georgia Tech (Kevin Haas)
Expertise Tidal resource measurement **Background** Market analysis	**Expertise** Tidal resource modeling **Background** U.S. tidal resource assessment

- **Managed in coordination with the "*Model Validation and Site Characterization for Early Deployment MHK Sites and Establishment of Wave Classification Scheme*" project (Pacific Northwest National Laboratory)**
  - Modeling efforts of both projects maximize spatial coverage of refined modeling
  - PNNL coordination leverages high-performance computing resources
  - Coordination strengthens standards and best-practices in tidal resource assessment

Management and Technical Approach

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1) **Identify discrepancies between modeled and measured tidal energy power density at tidal hot spots using the resource assessment and C-MIST data**

2) **Investigate sites with larger discrepancies to identify source of discrepancy**
   A. Examine shortcomings of the theoretical resource calculation method
   B. Examine shortcomings of the model for that site

3) **Improve models at hot spot sites with large discrepancies or high priority**
   A. Increase model grid resolution
   B. Incorporate new/updated bathymetry
   C. Couple models (couple Long Island Sound to New York Bight)
   D. Use unstructured grids (Cook Inlet, Western Passage, and Salish Sea)
   E. Use nested grids (Florida Keys and Portsmouth Harbor)

Milestone 1: Present model-measurement discrepancy analysis, how sites were selected for modeling, and preliminary model results

Milestone 2: Report results for the Long Island Sound and Portsmouth models

Management and Technical Approach

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4) **Revise the theoretical resource calculation method (based on the Garrett and Cummins 2005 method, GC05)**
   A. Use fine-scale tidal constituent interpolation to reduce the sensitivity of the resource calculation to the precise transect location
   B. Incorporate nonuniform tidal constituent phase into the resource calculation to better reflect real, nonuniform flow conditions

5) **Add resulting changes in resource estimates to the MHK Atlas**

6) **Update hot spot ranking results**

7) **Publish project report for the public, DOE, and tidal energy industry (to be completed in FY20)**
   A. Provide clearer understanding of the resource assessment accuracy
   B. Provide list of measured tidal energy power densities at promising early-market sites

<u>Milestone 3</u>: Deliver report to DOE with projecting summary and findings, as well as the updated hot spot rankings.

End-User Engagement and Dissemination Strategy

- **Improved resource assessment methods and results will benefit the entire U.S. tidal industry**
  - Improved accuracy and decreased uncertainty in resource estimates
- **Marine Energy Council input has been actively solicited through the project**
  - Project was motivated by the U.S. Marine Energy Council (MEC) over concerns about discrepancies between resource assessment estimates and measurements
  - After its commission, the project leaders presented to the MEC in August 2017
  - Project leaders have actively solicited input from MEC members interested in tidal energy
- **Dissemination of results**
  - Presentations to the “Resource Characterization” project’s steering committee
  - Preliminary results presented to the MEC
  - Marine Energy Technology Symposium (2017, 2018)
  - Ocean Sciences conference (2018)
  - Updated model results added to the MHK Atlas (2019)
  - NREL technical report (2019)

Technical Accomplishments

- **Technical accomplishments overview**
  - Comparison of resource estimate to measured resource
  - Identification of discrepancies and site prioritization
  - Improvement of models at prioritized sites
  - Improvement of theoretical method application for calculating the maximum theoretical power of a site
  - Updated tidal energy hot spots list with new rankings

- **Technical target: publication of an academic journal paper**
  - To be completed in 2020

Technical Accomplishments (Cont.)

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Comparison of Resource Estimates to Measurements

Model Overprediction

- Seven Mile Bridge, FL (+1,128%)
- Key West, FL (+244%)
- Woods Hole Passage, MA (+411%)
- Quicks Hole, MA (+176%)
- Tacoma Narrows, WA (+134%)
- Portsmouth Harbor, ME (+53%)

Model Underprediction

- East River, NY (-51%)
- Craig, AK (-45 %)

Good Agreement Between Model and Measurements (within 20%)

- Western Passage, ME
- Kodiak, AK
- San Francisco Bay, CA
- St. Mary's River, GA/FL

Technical Accomplishments (Cont.)

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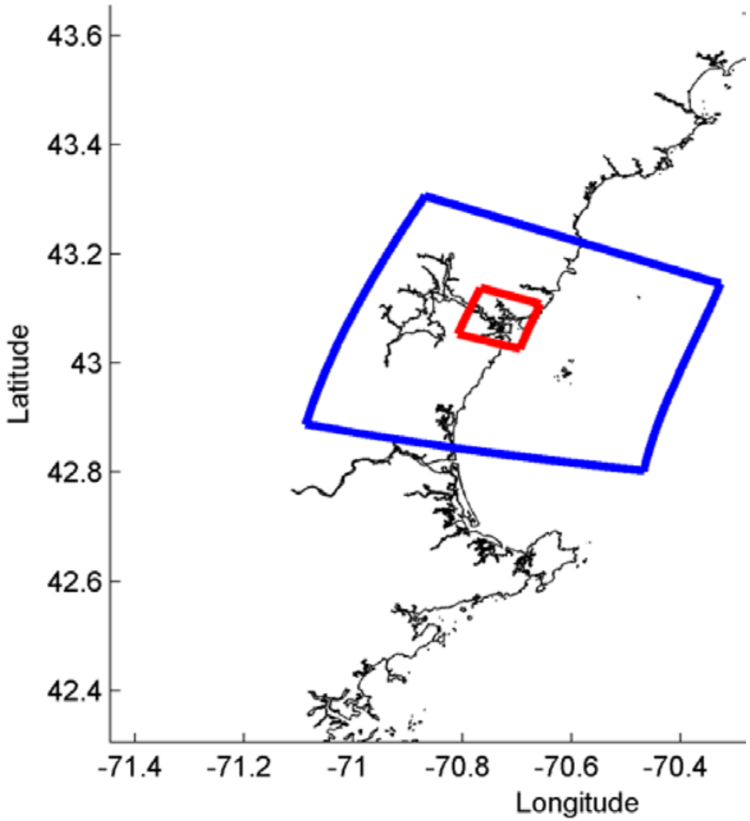
Model Improvement

Improved Models:

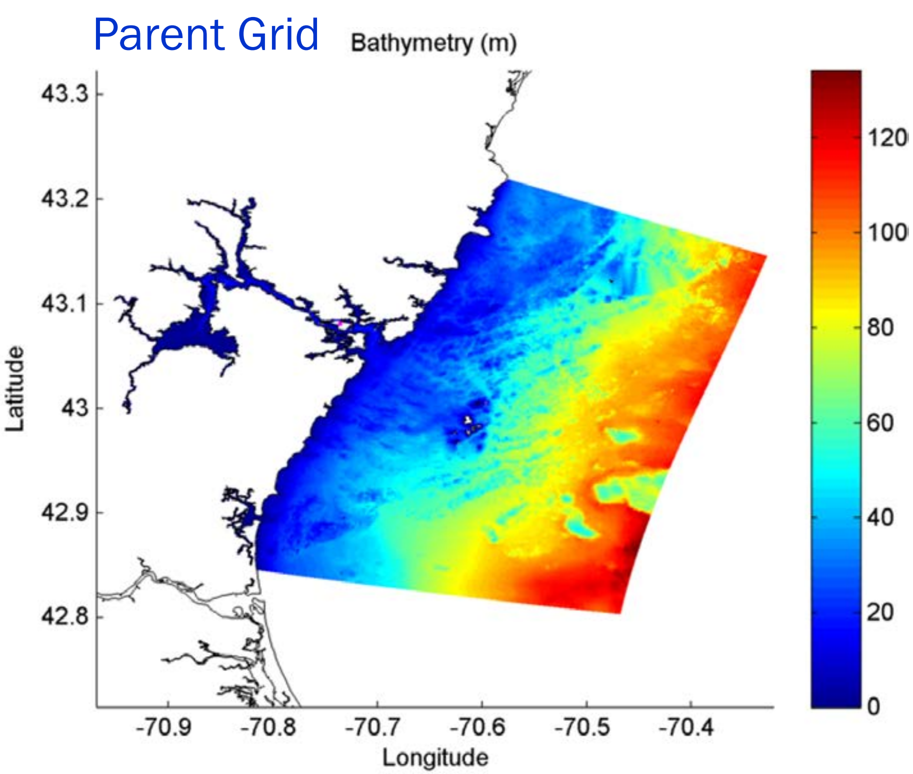
- Cook Inlet, AK—*unstructured grid*
- Delaware Bay, DE—*new data available*
- Florida Keys, FL—*nested grids*
- Massachusetts—*new data available*
- Portsmouth Harbor, ME—*nested grids*
- Long Island Sound, NY—*coupled to New York Bight, higher resolution*
- Western Passage, ME—*unstructured grid*
- Salish Sea, WA—*unstructured grid*

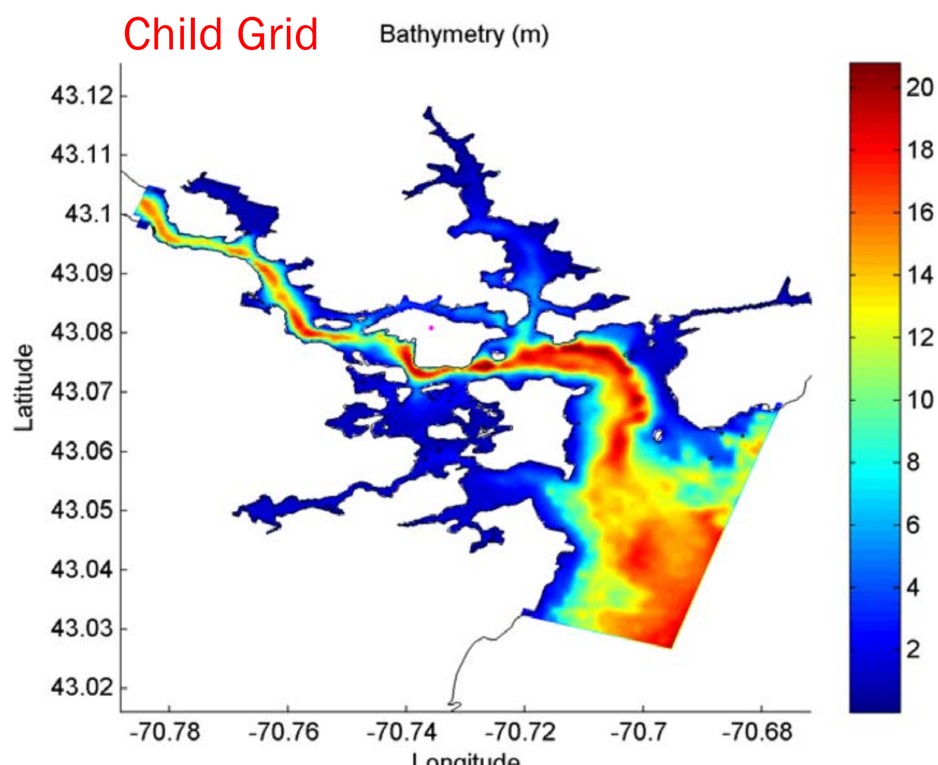


Portsmouth Harbor grid nesting

Technical Accomplishments (Cont.)

Model Improvement Example:
Portsmouth Harbor—Grid Nesting





Technical Accomplishments (Cont.)

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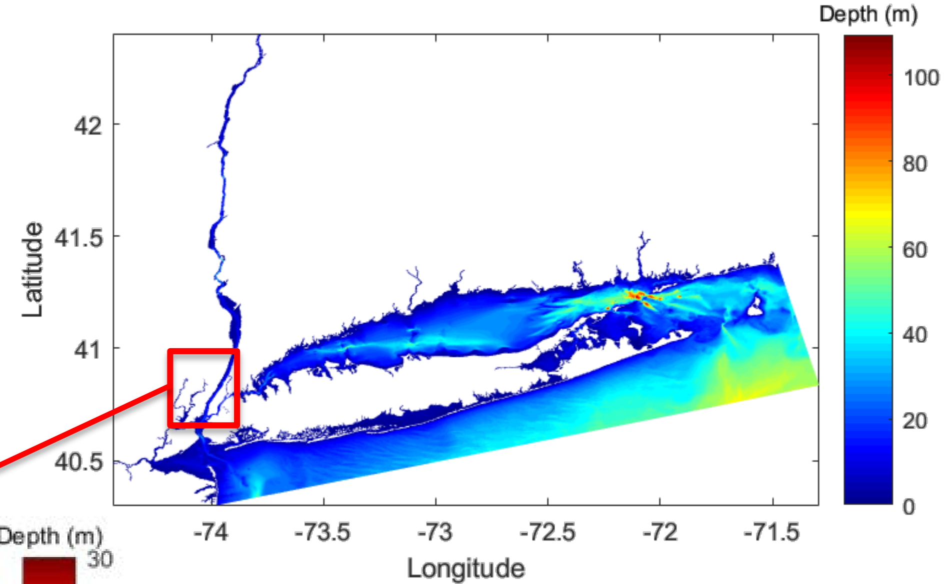
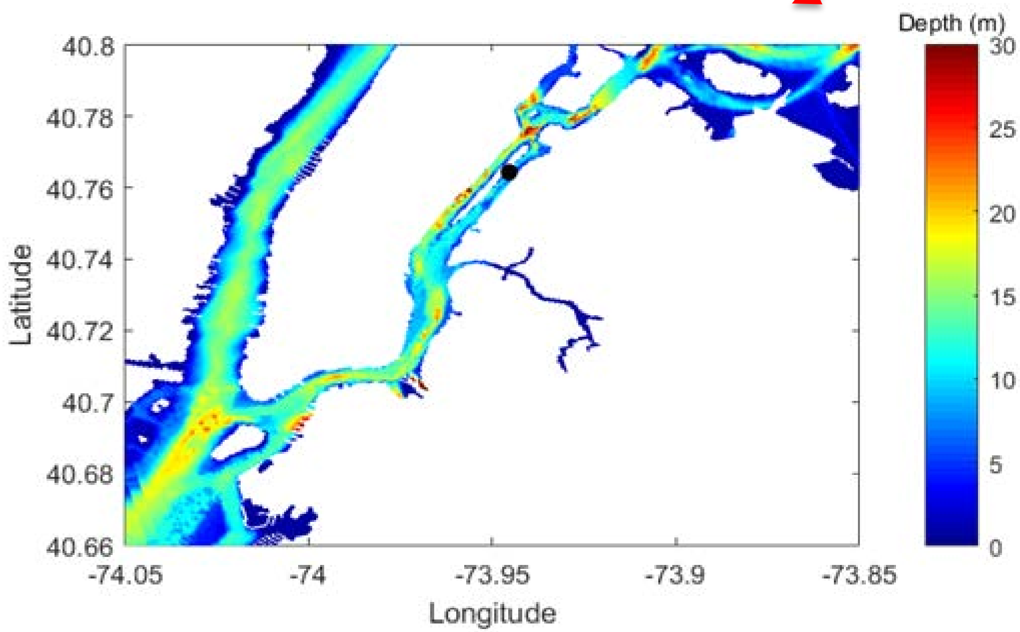
Model Improvement Example: East River, NY—Grid Coupling

Improved East River model is coupled with the New York Bight





Technical Accomplishments (Cont.)

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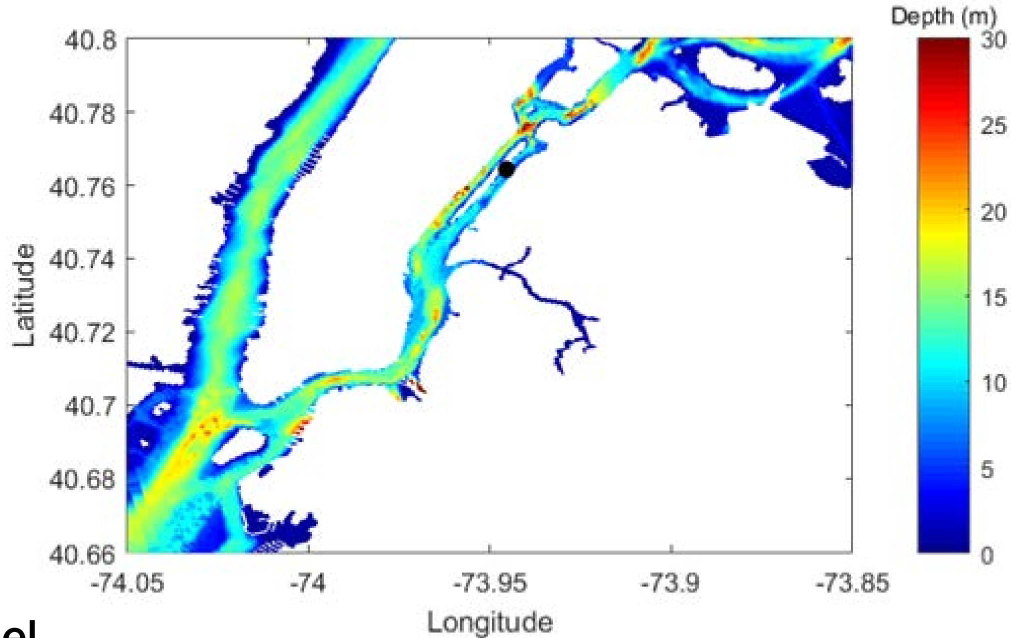
Model Improvement Example: East River, NY—Grid Coupling



<u>**Power Density**</u>

Old Model – 0.5 kW/m^2

New Model – 1.8 kW/m^2

ADCP – 2.0 kW/m^2

Old Model

Const	Amp (m/s)		
	Obs	Mod	Diff
M2	1.982	0.834	-1.148
N2	0.291	0.134	-0.157
S2	0.307	0.069	-0.237
K1	0.026	0.014	-0.012
O1	0.054	0.018	-0.036
M4	0.097	0.017	-0.081

New Model

Amp (m/s)		Inclination (deg)			Phase (deg)			
Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Min
1.938	-0.044	61.3	58.5	-2.8	341.2	330.9	-10.3	-21.3
0.281	-0.010	60.8	58.5	-2.3	330.8	317.8	-13.0	-27.3
0.311	0.005	61.2	58.5	-2.7	14.5	1.7	-12.7	-25.5
0.049	0.023	63.3	58.9	-4.5	94.7	77.4	-17.3	-69.2
0.051	-0.002	61.1	59.0	-2.2	111.6	102.6	-9.0	-38.6
0.046	-0.050	64.4	53.3	-11.1	335.6	329.0	-6.6	-6.9

Technical Accomplishments (Cont.)

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Theoretical Resource Calculation Method Improvement

- **Revised method for assigning model data to a precise transect along which the resource is calculated**
  - High resolution interpolation produces more consistent results
- **Incorporation of the spatial variation of tidal constituent phase into the resource calculation**
  - Decreases spatial sensitivity of the estimate
  - Better accounts for nonuniform flow (G&C method developed for uniform flow)
- **Publication of a script for calculating the theoretical resource**
  - User inputs tidal constituents, bathymetry, and a transect location
  - Script outputs theoretical maximum tidal energy resource at the transect

Technical Accomplishments (Cont.)

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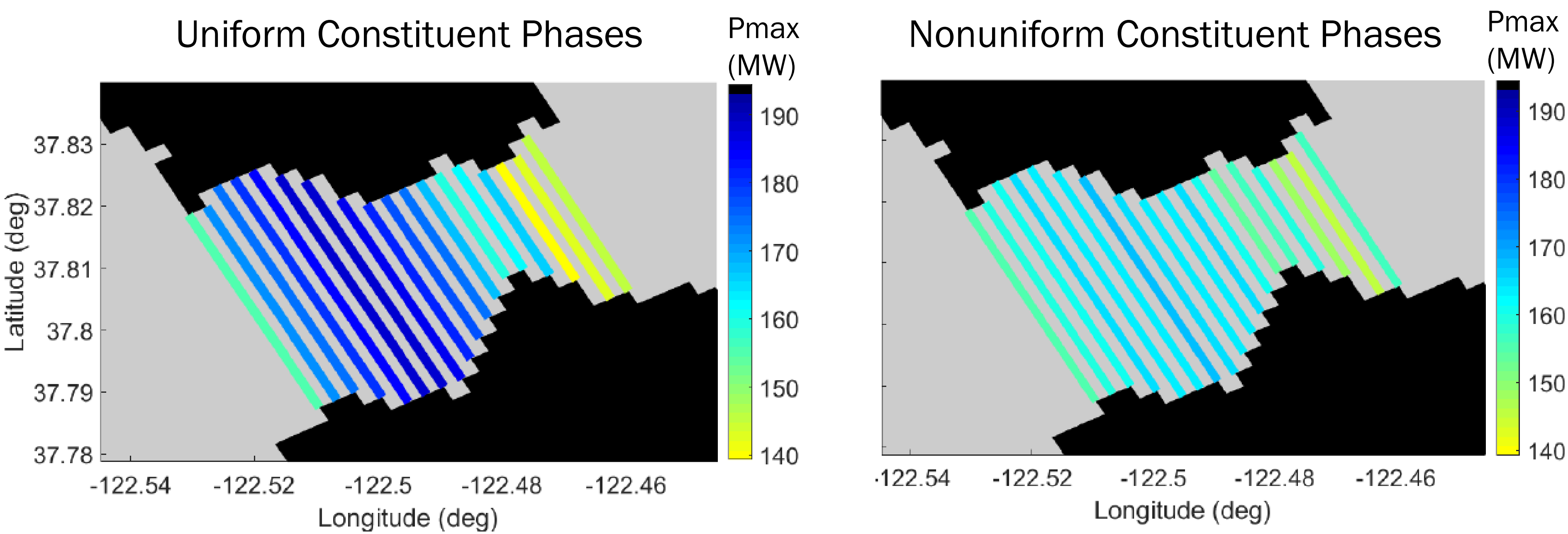
Theoretical Resource Calculation Method Improvement Example: San Francisco Bay, CA—Reduction of Spatial Sensitivity

- Tidal constituents are not perfectly in phase along a given transect
- Accounting for this variation in phase along each transect produces more consistent flow rates, and therefore power estimates, among nearby transects in a region



Technical Accomplishments (Cont.)

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New Hot Spot Rankings: Sample Selection of Updated Table

	Site	State	Lat	Lon	Resource [kW/m^2]	Market [MW]	Energy Cost	Range [km]	Shipping [$/ton]	Depth [m]	Score	Rank Change
1	Cook Inlet	AK	60.79	-151.26	2.1	500 L	0.16	2.5	91	41	8.0	0
2	Western Passage	ME	44.92	-66.99	3.0	190 R	0.14	1.1	0	35	8.0	0
3	East River	NY	40.79	-73.92	2.1	16 R	0.19	0.3	0	21	7.7	27
4	Long Island Sound	NY	41.23	-72.07	1.2	250 R	0.19	4.2	0	20	7.5	7
5	Vineyard Sound	MA	41.48	-70.64	1.7	84 R	0.16	5.1	0	23	7.4	-2
6	Muskeget Channel	MA	41.35	-70.37	2.4	90 R	0.16	8.3	0	23	7.4	-2
7	Tacoma Narrows	WA	47.28	-122.55	2.0	210 R	0.09	1.4	0	33	7.4	-2
8	Rosario Strait	WA	48.58	-122.75	2.2	420 R	0.09	3.5	0	50	7.3	-2
9	Portsmouth Harbor	ME,NH	43.07	-70.73	2.6	16 R	0.15	3.9	0	20	7.2	-1
10	Bellingham Channel	WA	48.56	-122.67	2.0	130 R	0.09	4.0	0	24	7.1	-3
11	San Juan Channel	WA	48.46	-122.95	2.0	160 R	0.09	7.0	0	56	6.9	-2
12	Kodiak	AK	57.79	-152.41	3.6	16 L	0.18	9.3	114	27	6.8	-2
13	Cape Cod Canal	MA	41.74	-70.61	1.5	5.0 R	0.16	1.6	0	20	6.7	NEW
14	San Francisco Bay	CA	37.82	-122.48	0.7	170 R	0.16	4.8	0	32	6.7	-2
15	Friday Harbor	WA	48.54	-122.98	1.0	180 R	0.09	3.5	0	48	6.4	-2
16	Admiralty Inlet	WA	48.14	-122.70	0.9	720 R	0.09	6.6	0	48	6.2	-2
17	Spieden Channel	WA	48.63	-123.12	1.4	160 R	0.09	12.7	0	30	5.9	-2
18	Nantucket Sound	MA	41.51	-69.97	2.0	260 R	0.16	17.4	0	20	5.9	-2
19	St. Mary's River	GA,FL	30.71	-81.45	0.8	13 R	0.11	3.1	0	18	5.8	-2
20	Delaware Bay	NJ,DE	38.86	-75.03	0.9	320 R	0.14	6.6	0	11	5.7	18*

Technical Accomplishments (Cont.)

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Short-Term Hot Spot Rank Changes for Sites with Updated Models

- East River: Rank 30 → Rank 3
- Long Island Sound Entrance: Rank 11 → Rank 4
- Portsmouth Harbor: Rank 8 → Rank 9
  - No significant changes in model results; ranking drop due to other sites increasing
- Cape Code (NEW): Rank 13
- Delaware Bay: Previously below ranking threshold → Rank 20