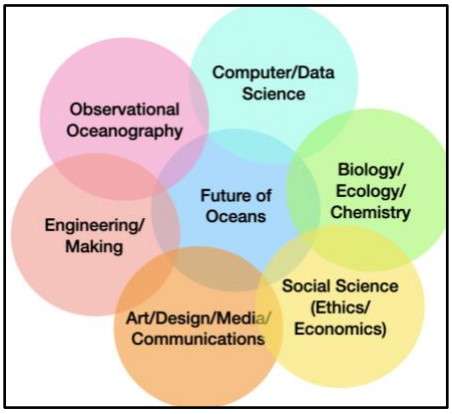
C-Accel Track Recommendation:
Ocean Internet-of-Things // Networked Blue Economy

Over the next decade, ocean industries and resources are expected to play a central role in addressing the nation's (and the world's) needs for energy, food, jobs, and sustainability. Indeed, these industries - collectively called the *Blue Economy* - already play an outsized role in the US economy. Unfortunately, despite pressing needs for innovation and integration, today's Blue Economy remains far from its full potential due to the disconnected, fragmented, and often closed nature of its different sectors, technologies, and communities.

We propose an NSF C-Accel track on "Ocean Internet-of-Things" (IoT) to interconnect the Blue Economy and accelerate convergence across ocean sectors. ***This track aims to create, within 1-3 years, a smart, integrated, connected, and open ecosystem for ocean innovation, exploration, and sustainable utilization***. Such an ecosystem is necessary to address the pressing needs highlighted by multiple national and international reports on ocean observation, mapping, and sustainability, including from the National Academy of Engineering, the White House Ocean Policy Committee, the US Department of Energy, and the UN Decade of Ocean Science. A convergent and use-inspired approach for science and technological development bridges multiple NSF's 10 Big Ideas (specifically Navigating the New Arctic, Harnessing the Data Revolution, Growing Convergence Research, INCLUDES). It advances the White House's Industries of the Future by bringing Artificial Intelligence (AI) and 5G to bear - enabling connected oceans, coastal communities, and advancing the nation's food (aquaculture, fisheries) and energy (renewable and non-renewable) industries. An integrative and open platform for oceans will also address global, unprecedented, and imminent ecological and societal ocean challenges.

This recommendation for a C-Accel track comes out of Smart Oceans 2020, an NSF-sponsored symposium with over 1,700 participants from more than **400 institutions**, spanning academia, private industry (including startups), government agencies, and nonprofits. The symposium featured plenary and lightning talks by thought leaders who highlighted the emergent paradigm of ocean IoT and convergent ideas and challenges aligned with this paradigm. The symposium included **4 convergent workshops** that facilitated discussions between representatives from 47 organizations on integrative solutions spanning emerging industries, novel tools, sustainable utilization, social engagement, policy interventions, and others. It also generated powerful **social media** engagement that resulted in building a **Slack community** of more than 300 active participants (who exchanged 2,000+ messages during the symposium) and also featured a #SmartOceansChallenge (on Twitter, Instagram, YouTube) that attracted award-winning videos, photos, and infographics from across the nation and the world.

The convergence symposium shed light on the types of cross-cutting Blue Economy partnerships capable of delivering transformative impact through accelerated and convergent activities. Ocean IoT C-Accel teams are expected to forge partnerships between stakeholders from two or more disciplines (see right Figure) as they strive to bridge the expertise of seasoned ocean researchers and practitioners with novel tools from engineers, makers, technologists, and designers. Such integrative teams will accelerate convergence toward a networked blue economy. An explicit and key factor in all decision-making involving C-Accel will be the laser focus on projects that present well-defined deliverables over the required 3 year time frame.



Convergence at the Intersection of Verticals and Horizontals in the Blue Economy:
In order to have substantive impact over the targeted, short time frame, convergent teams will span different horizontals (i.e., tools and initiatives that apply to more than one domain) and verticals (i.e., integrative solutions that focus on specific application domains). To ensure convergence, each proposal is expected to combine at least 1 horizontal (demonstrating novelty & acceleration) with 1 vertical (emphasizing the use-inspired nature of the work) though multi-disciplinary and/or multi-institutional teams. Below, we highlight the various horizontals and verticals in the context of a C-Accel Ocean IoT.

- *Horizontals:*
  - Systems & Technologies: These encompass networked infrastructures (communication, power, localization), distributed and interoperable sensors (for instrumentation, imaging, remote sensing, autonomous & uncrewed robotics), and data aggregation techniques (through standards, databases, algorithms, visualization, and modeling).
  - People & Communities: These include scalable efforts to empower communities (place-based strategies, sustainability) and educate the workforce (training, curricula, diversity, equity, inclusion, technology commercialization).
- *Verticals:*
  - Sustainable Utilization: These include utilization industries (aquaculture, fisheries, energy, mapping, tourism & recreation, shipping & maritime commerce), preservation efforts (plastics, marine debris, & unexploded ordinances), and novel instrumentation (e.g., Arctic, Polar).
  - Climate & Ecology: These focus on monitoring and forecasting processes (weather, air-sea interaction, corals, carbon/acidification, animals, currents & waves, sea ice, marine animals).
  - People & Communities: These aim to empower communities (disaster risk reduction, coastal resilience, restoration, oceans & human health) and broaden engagement (literacy, public participation in science, awareness, policy engagement, media production).

Two Subtracks for Expected Deliverables: Given the above verticals and horizontals, C-Accel integrative teams are expected to deliver practical and complementary outcomes that integrate into the overarching theme of a smart, integrated, and connected ocean ecosystem. Broadly, deliverables would fall under two main categories:

- *Sub-track 1: Networked, Cost-Effective, and Interoperable Ocean Systems & Technologies:* including ultra-low-power (or self-powered) sensor networks, low-cost underwater GPS, reliable sensors (aquaculture, waste, carbon, optical, chemical), databases and visualization tools for big ocean data; algorithms and AI for deployment, inference, and decision-making.
- *Sub-track 2: Interconnected People, Communities, and Curricula:* including video/media production for ocean/ecological challenges, affordable and accessible tools for engaging public participation in ocean STEM, hubs for engaging with local communities, curricula for policy, diversity, mentorship, and technology translation.

The future of oceans brings large societal, ecological, and industrial questions: How can we connect ocean data, technology, and resources with communities and people? How can we explore, map, monitor, and predict the ocean at scale? How can we use ocean resources sustainably? How can we help communities and people benefit from connections to ocean data, technology, and resources? How can we train the next generation of scientists and engineers to work in interdisciplinary teams to solve real-world problems?

The deliverables expected from Ocean IoT C-Accel tracks will accelerate ocean research and technology towards a *networked blue economy* that is connected, open, and accessible, and will drive convergent research and innovation towards positive impact.

Authors:
Fadel Adib, Associate Professor, Massachusetts Institute of Technology
Seth Zippel, Assistant Scientist, Woods Hole Oceanographic Institution

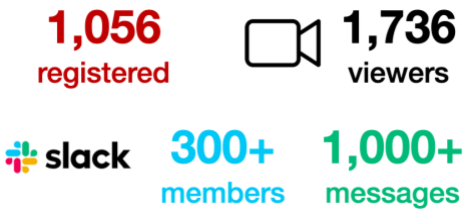
Endorsers:
Ryan Kastner, Professor, UC San Diego
Scott Lindell, Research Specialist, Woods Hole Oceanographic Institution
Jeff Kaeli, Lead Scientist, ARMADA Marine Robotics Inc.
Diane Foster, Director, School of Marine Science and Ocean Engineering, University of New Hampshire
Kristin Wilson Grimes, Research Assistant Professor, University of the Virgin Islands
Shana Lee Hirsch, Research Scientist and Associate Director, Pacific Marine Energy Center, University of Washington
Bruce Howe, Research Professor, University of Hawaii at Manoa, Chair, JTF SMART Cables
Alissa Peterson, Co-Founder & Executive Director, SeaAhead
Dawn J. Wright, Chief Scientist of Environmental Systems Research Institute (Esri); Professor of Geography and Oceanography, Oregon State University
Matthew Eisaman, Assistant Professor, Stony Brook University
Meghan Cronin, Oceanographer, NOAA Pacific Marine Environmental Laboratory
Michael S Triantafyllou, Doherty Professor & Sea Grant Director, Massachusetts Institute of Technology
Jane Chang Mi, Artist and Assistant Professor, Scripps College
Brian T. Glazer, Associate Professor, University of Hawaii, Founder & CEO of Hohonu, Inc.
Ken Kostel, Director of Research Communications, Woods Hole Oceanographic Institution
Ted Maksym, Associate Scientist w/ Tenure, Woods Hole Oceanographic Institution
Alison Macdonald, Senior Research Specialist, Woods Hole Oceanographic Institution
Subarna Basnet, Director, Design Science, Technology and Innovation, MIT International Design Center
Tamer Nadeem, Associate Professor, Virginia Commonwealth University
Brian Polagye, Associate Professor, University of Washington and Director, Pacific Marine Energy Center
Christine Ward-Paige, Founder, CEO, & Lead Scientist of eOceans

Appendices:

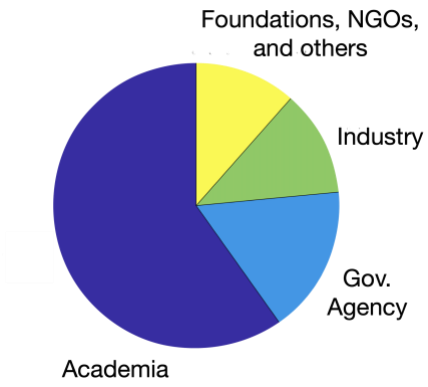
Appendix A: Participant Statistics and Interests

The symposium featured 5 plenaries, 19 lightning talks, 4 workshops, 18 breakout groups, and Q&A with NSF C-Accel.

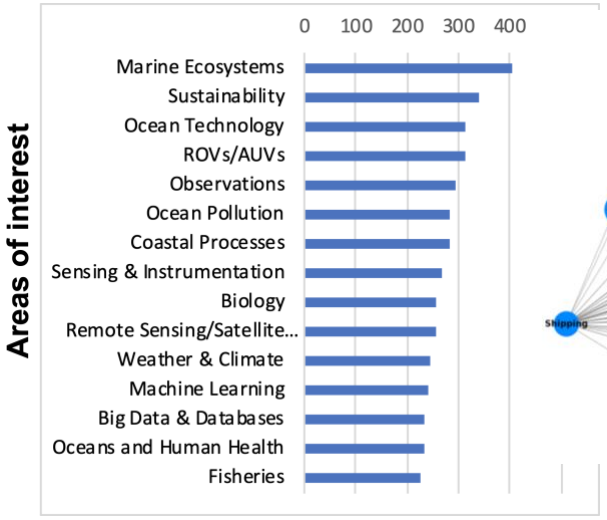
The symposium attracted broad attendance from a variety of industries. The diagrams below show the stats on pre-registration and attendance. Viewers joined us on an ***omni-channel webcast*** that streamed on MIT webcast, Twitter, Instagram, and Periscope. We also created a slack community that attracted more than 300 active members who exchanged over 1,000 messages during the conference and another 1,000 messages after it.

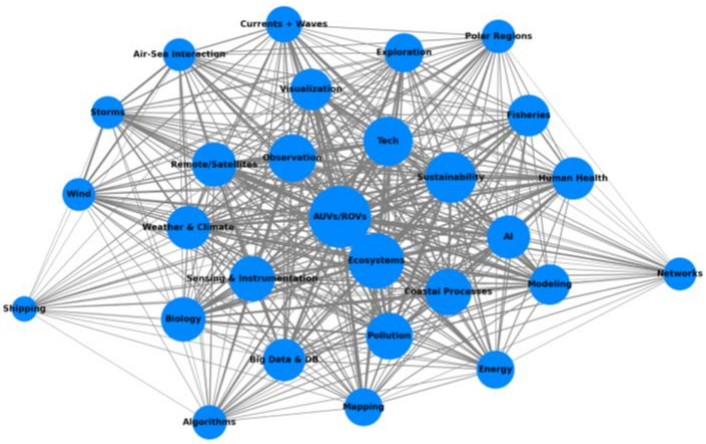


Participants and registrants represented stakeholders from various industries (as shown below) including academia, industry, foundations, NGOs, government agencies, and others. They hailed from more than 400 institutions (some of which are shown below). While we had world-wide attendance from 5 continents, 86% of participants came from the US, spanning more than 38 states.



We asked our participants to share their interests, and identified the network of overlapping interests in creating convergent workshops that can brainstorm cross-cutting partnerships. The areas and connections between these interests are shown below.





Appendix B: List of Plenary & Lightning Talks

Below we provide the schedule and links to Day 1 (Oct 5, 2020) which featured plenaries and lightning talks focused on unpacking the future of oceans. The links provide the videos of each of the talks.

12:00 pm **Opening Remarks**

12:10 pm **NSF Convergence Accelerator**

12:15 pm **Plenary Session**

- "Driving Convergence in Ocean Science" Peter de Menocal - President, Woods Hole Oceanographic Institution
- "Activating the Smart Ocean" Margaret Leinen - Director, Scripps Institution of Oceanography & Dean, School of Marine Sciences, University of California San Diego
- "The Evolution of a Paradigm" Bob Ballard - President, Ocean Exploration Trust & Director, Institute for Archeological Oceanography, University of Rhode Island
- "Geospatial as an Accelerator of Impact" Dawn Wright - Chief Scientist, Environmental Research Systems Institute (ESRI)
- David Lang Co-founder, Sofar Ocean & Co-founder, OpenROV

1:30 pm **Convergence Session I:** Harnessing the Power of Data & People

- "Making Game-Changing Air-Sea Interaction Observations for 2030" by Meghan Cronin - Oceanographer**,** Pacific Marine Environmental Laboratory, NOAA
- "Making Ocean Data Useful" by Ryan Abernathey - Professor, Lamont-Doherty Earth Observatory, Columbia University
- "eOceans: Towards Collaborative, Transparent, Real-Time Marine Science" by Christine Ward-Paige - Chief Executive Officer, eOceans
- "SeaAhead: Venture Innovation for the Ocean" by Alissa Peterson - Co-Founder & Executive Director, SeaAhead
- "SEAS Islands Alliance: Expanding Opportunities for Islands Students in the Ocean Sciences" by Kristin Wilson-Grimes - Research Assistant Professor, University of the Virgin Islands

2:05 pm **Convergence Session II:** Exploring & Mapping Unseen Worlds

- "Technologies for Studying Biological Phenomena in Deep Sea" by Kakani Katija - Principal Engineer, Monterey Bay Aquarium Research Institute (MBARI)
- "Deep-Sea Mining" by Thomas Peacock - Associate Professor & Director, Environmental Dynamics Laboratory (ENDLab), MIT
- "Meeting the Challenges of 4D Oceanography with Vehicle Swarms and Sensors" by Jules Jaffe - Research Oceanographer, Marine Physical Laboratory & Scripps Institution of Oceanography, University of California, San Diego
- "National Strategy for Mapping, Exploring and Characterizing the U.S. Exclusive Economic Zone" by Amanda Netburn - Oceanographer, Office of Ocean Exploration and Research, NOAA
- "Autonomous Operations for an Ocean Worlds Submersible" by Andrew Branch - Technical Staff, Artificial Intelligence Group, Planning and Execution Section, Jet Propulsion Laboratory, NASA

2:48 pm **Convergence Session III:** Connecting the Ocean

- "The Moana Project's Te Tiro Moana (Eyes on the Sea): Fishing Gear as an Ocean Observing Platform in New Zealand" by Julie Jakoboski - Data Scientist, MetOcean Solutions
- "Basic Infrastructure for Future Ocean: SMART Cables and Acoustic Network" by Bruce Howe - Research Professor, University of Hawaii
- CELESTE: Community Environment for Learning Eco-Science via Testbed Experiments
- by Bishal Thapa | Research Scientist, Raytheon Technologies & Helen Scott | Staff Scientist, Raytheon Technologies
- "Ocean Sensing At Scale" by Ryan Kastner - Professor, University of California San Diego

3:20 pm **Convergence Session IV:** From Protection to Sustainable Utilization

- "A Moonshot for Coral Reefs: Using Conservation Technologies to Save Coral Reefs" by David Kline - Staff Scientist, Smithsonian Tropical Research Institute
- "Pacific Marine Energy Center" by Shana Hirsch - Associate Director, University of Washington Division, Pacific Marine Energy Center (PMEC)
- "What is Needed to Deploy and Scale Direct Ocean Capture?" by Brendan Carter - Research Scientist, Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington & Matthew Eisaman - Assistant Professor, Stony Brook University
- "Channelized Optical System (CHANOS): An In-situ Sensor Technology for High-resolution Measurements of Seawater CO2 Parameters" by Zhaohui 'Aleck' Wang - Associate Scientist, Woods Hole Oceanographic Institution
- "Offshore Aquaculture" by Michael S Triantafyllou - William I. Koch Professor of Marine Technology; Professor of Mechanical and Ocean Engineering; Associate Head for Ocean Engineering, MIT

3:55 pm **Closing Remarks**

Appendix C: Convergence Workshops

The second day of the symposium featured 4 workshops with participants from 47 representative institutions. To maintain highly-dynamic and engaging conversations, the workshops were divided into 18 breakout groups (both series and parallel) to brainstorm the anticipated challenges that can be addressed, multi-disciplinary and convergent teams, and the expected deliverables within 1-3 years through NSF C-Accel funded project.

Workshop	Breakout Session	Participants
Real-time, High-Resolution, and Large-Scale Observations	Big Data: Organization, Algorithms, Visualization, Standards	23
	Sensor Networks: Powering, Communications, and Networking	11
	Autonomous Systems: Navigation, Observation, Communication	15
Emerging Industries & Sustainable Utilization	Startups & Technology Commercialization	8
	Aquaculture & Fisheries: Sensing, Sustainability, Policy	N/A
	Energy: Renewables, Models	16
	Plastics & Marine Debris: Sensing, Collection, Policy, Engagement	11
Exploration via Novel Imaging, Navigation & Sensing Tools	Mapping: Seafloor, Autonomous Systems	10
	Extreme Environments (Artic, Polar, & Space): Instrumentation, Navigation, Sensing	19
	Imaging: Coral Reefs, Marine Animals, Ecosystems	15
	Acidification: Carbon Measurements, Capture, Modeling, Ecological Impact	9
Social Engagement & Policy Interventions	Diversity, Equity, & Inclusion: including education	10
	Coastal communities & resilience	6
	Citizen science & science literacy & awareness	11
	Engagement between decision makers & scientists	10

Appendix D: Example Teams

We have already identified various examples of cross-cutting partnerships such:
(1) Physical Oceanographers + Sensor Makers
(2) Marine Biologists + Machine Vision (AI)
(3) Video Producers + Marine Ecologists + NGOs
(4) Mobile Developers + Coastal Community Organizers + Ethicists
(5) Blue Tech Startups + Statisticians + Gov Agencies

These teams are primed to tack specific projects in our two proposed sub-tracks, such as:

- *Sub-track 1: Networked, Cost-Effective, and Interoperable Ocean Systems & Technologies:*
    - *Co-design of marine energy generation systems with blue economy uses*
    - *Demonstrating and deploying open standards for underwater e-communications*
    - *Cost-effective and extensible underwater GPS for location tagging and navigation*
    - *Novel databases for aggregating, querying, visualizing and the web's dark ocean data*
    - *Biodegradable framework for expendable scientific instruments and blue economy equipment.*

- *Sub-track 2: Interconnected People, Communities, and Curricula:*
    - *Citizen science + blue economy ocean monitoring networks: Fishing vessels as observing systems in remote regions*
    - *Mapping socio-cultural uses of the ocean, coastlines, and coastal resources for policy and decision makers*
    - *Accelerator/incubator environment to reframe academia as innovation for all, not for innovation for self, to make non-academic jobs visible, to provide diverse mentorship*

In addition, we had participation from an active NSF C-Accel Team that has highlighted below how they may integrate with an Ocean IoT Track.

NSF Award 2033521, C-ACCEL Track A, KnowWhere Graph: Enriching and Linking Cross-Domain Knowledge Graphs Using Spatial-Explicit AI; Lead PI, K. Janowicz, UCSB; Industry Partner, Esri.
This new NSF Convergence Accelerator Pilot Phase II Active project, led by geographers, greatly desires to integrate with Smart Oceans because of the value add that it is building for a host of domains. Knowledge graphs power search engines, catalogs, apps, helping to build a new, much more open web of structured scientific data in an open Open Knowledge Network (with semantics, ontologies, vocabularies, standards). This project also focuses on the emerging technology of "geoenrichment" (as powered by Esri), which is the enhancing of EXISTING data with additional location-based context. This could be demographics, infographics, blue economy financials, fisheries stock assessments, movement data, migrations, even parameters from climate models. It fills in needed attributes that are currently missing. The project will build AI-powered geoenrichment services with an open cross-domain knowledge graph. It is seeking to add value to a host of domains, currently to climate data and models, digital humanities data, commodity trading, Linked Open Data, but including in the future, Smart Oceans! This team will also be the first to incorporate satellite data, drone imagery, and maps (soil maps) into a knowledge graph.

Appendix E: Submission Form

1. First Name:
2. Last Name:
3. Email:
4. Affiliation:
5. Position (Professor, PI, CEO, VP, Director, Engineer, Student, etc.):
6. Stakeholder Group:
    - ❒ Academia
    - ❒ Foundation
    - ❒ Governmental Agency
    - ❒ Industry
    - ❒ Other (Please Specify Below)
7. If you are a student, are you interested in volunteering for this event?
    - ❒ Yes
    - ❒ No
8. What is your primary area of interest? Please check all that apply.

Algorithms	Exploration	Ocean Technology, ROVs, AUVs	Shipping
Big Data & Databases	Fisheries	Oceans and Human Health	Sustainability
Biology	Machine Learning	Oceanography	Weather & Climate
Coastal Processes	Marine Ecosystems	Polar Regions/Sea Ice	Wind, Storms, and Air-Sea Interaction
Computer Networks & Systems	Modeling	Remote Sensing/Satellite Data	Sensing & Instrumentation
Currents and Waves	Observation	Robotics	Visualization
Energy	Ocean Pollution	Seafloor and Seafloor Mapping	

9. If your primary area of interest is not listed above, please list here:

10. Describe your work in 1-2 sentences:

11. The conference will be open to all registrants to attend, observe, and ask questions. We also have a limited number of slots for lightning talks on the Monday, October 5. The lightning talks (3-5 minutes) are expected to blue sky ocean problems (climate, observation, energy, biology, etc.), emerging solutions that can be applied to ocean problems (visualizations, machine learning, big data, sensing, computing), and/or ongoing efforts by researchers/industry/foundations/government agencies. If you are interested in and willing to participate as a speaker, please describe, in 200 words or less, what you would be interested in presenting.

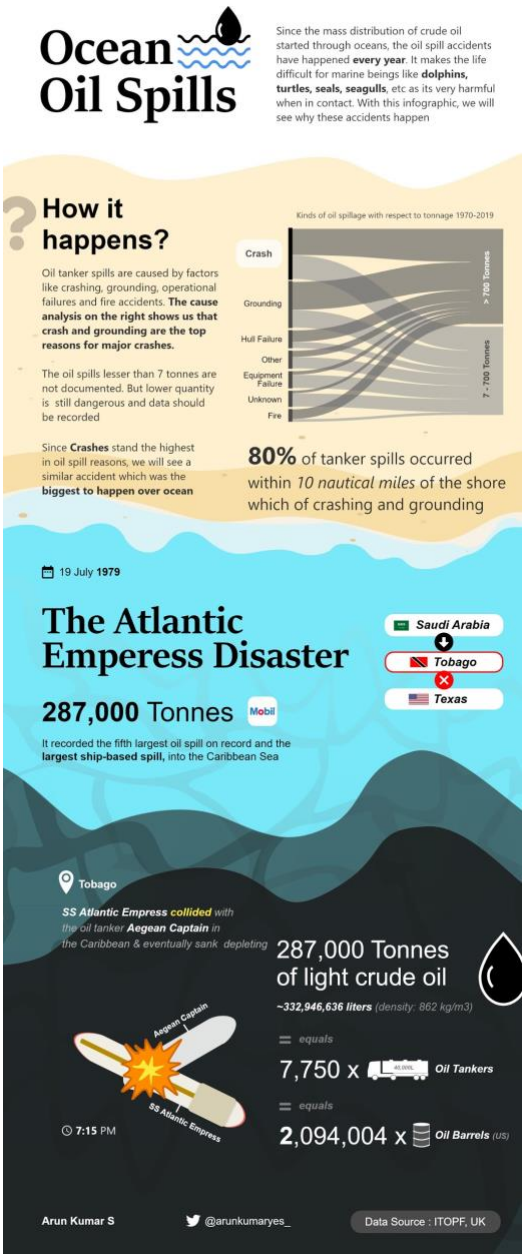
12. The conference will feature workshopping sessions on Wednesday, October 7. These sessions are expected to be interactive and focused on identifying pathways to ocean solutions and team formations. If you would like to be an active participant in these sessions (as opposed to an observer), please describe, in 200 words or less, what you think is the most pressing/critical problem facing the ocean and how society would benefit from addressing it.
If you are looking for collaborators, what kind of collaborators are you looking for?

Appendix F: Social Media Engagement & #SmartOceansChallenge Competition

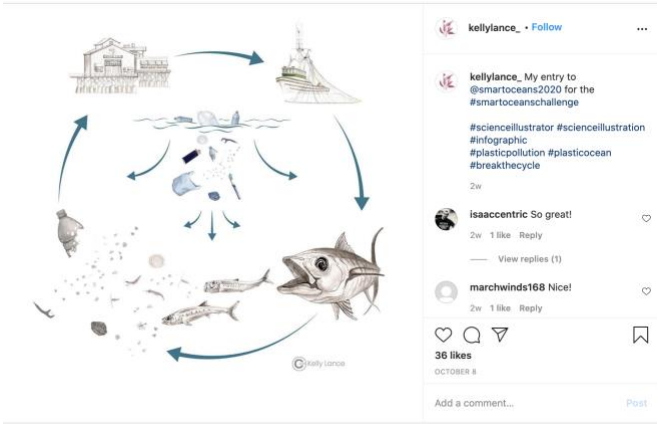
In conjunction with Smart Oceans 2020, we ran a social media campaign. The goal of the campaign was two-fold: (1) increase public engagement through a smart oceans challenge and (2) identify the level of interest in convergent research targeted in the C-Accel.

Below, we highlight the social media competition winners:

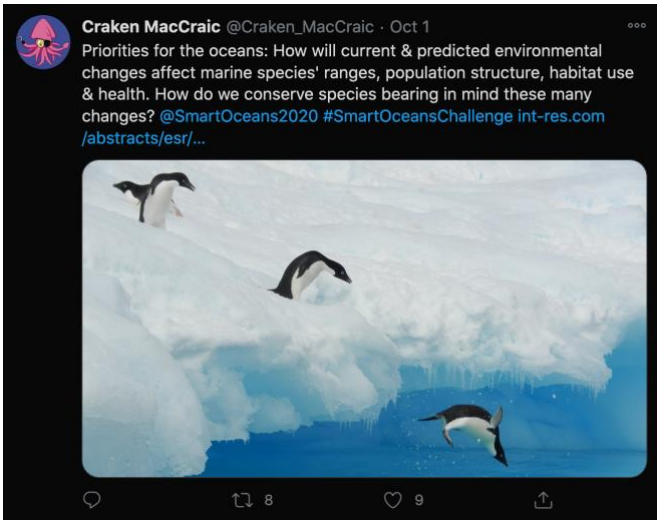
[Infographic Challenge Winner](#) ($500):



[Infographic Challenge Runner-Up](#) ($250)

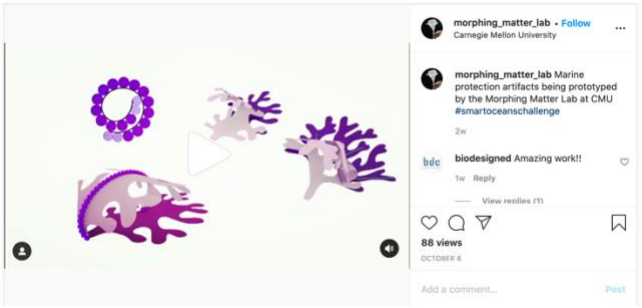


[Photo Challenge Winner](#) (Cannot accept prize)



Video Challenge Winner ($1000)

Video Challenge Runner-Up ($500)



Moreover, to identify interest beyond the conference, PI Adib tweeted asking researchers from maker/engineering/computer science backgrounds about their interest in joining forces with ocean researchers and practitioners on tackling the types of problems an NSF C-Accel would be funding. Within a few hours, the post was retweeted around 200 times, demonstrating the level of excitement in cross-disciplinary partnerships in ocean IoT.