DARPA Ocean Synoptic Sensing Roundtable

DARPA Ocean Synoptic Sensing Roundtable Report

October 2024

The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Table of Contents

Background

The Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO), led by Director Jinendra Ranka, is investigating how improved ocean circulation models and characterization of ocean variables might prevent strategic or tactical surprise for national security. To assist DARPA/DSO in its investigations, a small experts group was formed.

On August 1, 2024, the **DARPA Ocean Synoptic Sensing Roundtable** was held at Stanford University. The primary goal of the DARPA Stanford Roundtable was to gather a group of experts to evaluate existing ocean models, identify unmet needs, and explore high-risk research areas aligned with DARPA's risk-reduction mission.

Organized by Ann Kerr (DSO) and Steven Koonin (Hoover Institution, Stanford), the Roundtable Discussions were structured around six key Topics and Questions, with experts contributing ideas and materials before and after the meeting. A dedicated database was created to house these contributions, including meeting materials and post-meeting updates. Access is provided via links within the Report.

This report captures both the Roundtable and subsequent informal discussions among the participants. It includes comments, and materials prepared and submitted in advance of the Roundtable Discussions and those arising from follow-up discussions. The body of the Report captures the essence of the Roundtable Discussions; detailed comments and supporting material are in the Appendices. The Roundtable was limited to invited experts to facilitate discussions. After the Roundtable, DARPA/DSO held an RFI Workshop, Advancements in Ocean Modeling and Monitoring, organized and chaired by Dr. Rebecca Chmiel, DARPA Innovation Fellow. The Workshop was held on October 29, 2024, in Arlington, Virginia

Ann Kerr and Steven Koonin
Convenors

Contributors

James (Jim) Bishop
John Colosi
Kristen Davis
Peter De Menocal
Emanuele Di Lorenzo
Matthew Dzieciuch
Marquay Edmondson
Bran Ferren
Kai Gemba
David Halpern
Nancy Hann
Douglas Horner
Benjamin Horton
Fiorenza Micheli
Stephen Monismith
John Orcutt
Randy Pugh
Venkatachalam Ramaswamy
D. Benjamin Reeder
Kevin Smith
Thomas Wagner
Carl Wunsch

Overview

Oceans cover two-thirds of the earth's surface and so are important in several dimensions. They facilitate the transportation of goods and are a source of food. But they are a theater for geopolitical and military engagement. And, uniquely, they are the long-term component of the earth's climate system, exchanging energy, water, and greenhouse gases with the atmosphere.

For these reasons, the capability to monitor the ocean and model its dynamics across a variety of spatial and temporal scales is essential to avoid strategic or tactical surprise impact on national security and to anticipate future changes in the earth's climate system. Accurate models, validated by observations over extended periods of time are the tools for doing that, but there are challenges in observing the ocean at depth and in constructing models with sufficient resolution. There are a variety of promising sensing technologies and systems, but there is a *lack of sufficient data* to evaluate and validate their value to improve models. They reside in separate systems and experimental projects, which make it difficult to integrate and evaluate the data to assess their potential value improving models and other capabilities.

Our lack of ability to accurately model key areas of the ocean and ability to predict may hold the potential for Strategic or Tactical Surprise on our National Security.

- Lack of knowledge of currents, temperatures, and salinity in key areas of interest
- Inability to accurately predict extreme and/or ordinary weather events with certainty needed for operational missions.
- Insufficient information on the Arctic, especially Ice Melt and its impacts.
- Inability to accurately model local areas strategic to operational missions.

The Roundtable reviewed these key areas and others, framed by a set of Discussion Topics and Questions which were provided in advance of the Roundtable. The comments and material provided by the experts were posted to a Collaborative platform, facilitating information sharing and the discussions during the one-day meeting.

The meeting's goals, agenda, and list of invited experts are provided on the following pages. The meeting summary and the materials presented by various experts are organized by topic and speaker. Comments submitted by experts before the meeting to foster discussion are summarized in Appendix 1A. A detailed document, addressing the key questions, was prepared by Emanuele Di Lorenzo, drawing on discussions with other experts, and is included in Appendix 1B.

This report summarizes the knowledge gained before, during, and after the Roundtable, organized by discussion topics and key questions, with an emphasis on their relevance to DARPA's risk-reduction goals.

Discussion Topics

DARPA Ocean Synoptic Sensing Roundtable

August 1, 2024 | Stanford University | Meeting Purpose & Discussion Topics

Meeting Purpose

New technologies open the possibilities of acquiring such data. These include autonomous platforms, fixed and mobile sensing platforms, remote observations; but the question remains - *how do you collect and utilize multi-modal data to substantially improve Ocean Models and forecasting capabilities?*

Discussion Topics

Climate & Ocean Models

- What are the inadequacies of current models?
- What are the consequences?
- If better models are accomplished – what difference would it make?

Problems unique to Ocean vs Atmosphere

- What are the limits of predictability in ocean weather forecasting?
- How to distinguish between ocean and atmospheric climate?
- Data transmission, computation, and storage challenges
- Monitoring the deep ocean

Acquisition of Data

- How would more data help?
- How would you acquire it?
- How would you use it?

Integration & Management of Data

- Data assimilation
- Machine learning interpolation processes

Modalities – Sensors, Sensor Platforms

- What coverage is needed?
    - Depth?
    - Area?
    - Time?
- What is the required precision of the measurements?

Would a basin-scale demonstration be valuable? If so, what would it look like?

Invited Experts

Last Name	First Name	Attendance	Affiliation
Baggeroer	Arthur	Virtual	Massachusetts Institute of Technology
Bishop	James (Jim)	In Person	University of California, Berkeley
Chmiel	Rebecca	In Person	DARPA
Colosi	John	In Person	Naval Postgraduate School
Davis	Kristen	Virtual	Stanford University
De Menocal	Peter	In Person	Woods Hole Oceanographic Institution
Di Lorenzo	Emanuele	In Person	Brown University
Dzieciuch	Matthew	In Person	UCSD/Scripps Institution of Oceanography
Edmondson	Marquay	In Person	Hoover Institution, Stanford University
Ferren	Bran	Virtual	Applied Minds
Gemba	Kai	In Person	Naval Postgraduate School
Halpern	David	In Person	Scripps Institution of Oceanography
Hann	Nancy	In Person	NOAA
Horner	Douglas	In Person	Naval Postgraduate School
Horton	Benjamin	Virtual	Nanyang Technological University
Kerr	Ann	In Person	DARPA DSO Subject Matter Expert
Koonin	Steven	In Person	Hoover Institution, Stanford University
Micheli	Fiorenza	Virtual	Stanford University
Monismith	Stephen	In Person	Stanford University
Orcutt	John	In Person	UCSD
Pugh	Randy	In Person	Naval Postgraduate School
Ramaswamy	Venkatachalam	In Person	NOAA/Geophysical Fluid Dynamics Laboratory
Ranka	Jinendra	In Person	DARPA DSO Director
Reeder	D. Benjamin	In Person	Naval Postgraduate School
Smith	Kevin	In Person	Naval Postgraduate School
Wagner	Thomas	In Person	NASA
Wunsch	Carl	Virtual	Massachusetts Institute of Technology

DARPA Questions

- ***What are the unknowns in the ocean reservoir relevant to national security?***

The DARPA Ocean Synoptic Sensing Roundtable covered multiple themes relevant to oceanographic science, technology, data integration, and advanced modeling. This roundtable emphasized the need for innovative ocean sensing technologies and improved models to better understand the ocean's complex dynamics, while balancing military needs with scientific exploration.

Key Findings and Conclusions

Unknowns in Oceanography

A major theme was the lack of understanding of ocean processes on various timescales and how this affects national security. The ocean's role in climate impact and fluid dynamics needs better modeling and observation across both short-term (weather) and long-term (climate) scales.

Modeling Ocean Dynamics

Carl Wunsch highlighted the need for high-resolution models to cover large-scale energy dynamics down to centimeter-scale dissipation. Ocean circulation is a key area of study, and future ocean sensing requires improved computational power and space-based observations (e.g., altimetry, gravity sensing). Small scale experiments are needed, as the ocean is 'regional'. The Arctic is both essential to our national security and an excellent candidate for basin-scale experiments that would provide essential parameters for models. With the anticipated further sea ice melt, it is critical to accurately model this strategic environment, which is a growing concern for national security. Link to **Kerr DoD 2024 Arctic Strategy Document**.

Models like NOAA's MOM6 are advancing in sea-level rise predictions and regional observations. However, fundamental physical processes and boundary conditions (e.g., coastlines, carbon budgets) remain unresolved, requiring more data to refine ocean models.

Emerging Technologies for Ocean Sensing

Acoustic thermometry, remote sensing, and satellite communications were discussed as critical tools for improving ocean current and thermal data collection. Acoustic "GPS" may well be quite important. A lot of ocean observations are drifters. Acoustic GPS can locate a vehicle with an accuracy of 1-10m. ARGO floats greatly understate temperature changes by a factor of 2, based on seismic measurements from stations like the IDA Network operating since the 70's.

Acoustics can measure temperature profiles and resolve mixing layers in the Arctic, while satellite data enhance global ocean monitoring systems.

Tomographic sensing and reconstruction have been valuable understanding the solid earth and thereby improving model fidelity. Similarly, Acoustic Tomography employing the hydrophones in the International Monitoring System (CTBT) has proven valuable.

National Security Implications

Randy Pugh, Director of Naval Warfare Institute, emphasized the importance of competitive advantage in ocean sensing for military operations, including underwater systems for tracking submarines and anti-ship missile threats. The Arctic was identified as a key strategic area, with ice melt presenting both challenges and opportunities for adversarial activity.

Ocean Discovery and Exploration

A key concept discussed was the need for collecting, integrating and making accessible Ocean data from various platforms (fixed, floating, historical) to users such as the military, civilian agencies, and scientific communities. While building operational systems is not within DARPA's primary mission, a proof of concept is needed to support follow-on research and demonstrate its proof of concept. Other funding agencies philanthropic and commercial funding sources are needed to explore and discover the ocean, 70% of the planet.

Challenges in Data Integration and Sharing

Oceanographic data, particularly classified data, faces bureaucratic obstacles in sharing between military and scientific communities. Improved coordination between data collection systems, including the integration of acoustic data, was proposed to enhance modeling and prediction efforts. A testbed to collect experimental data from a variety of sensors, integrate them into a database and make the available for testing is an essential tool. Some work has started to develop a Concept for such an Operational Testbed, illustrated in Figure 1. on the next page.

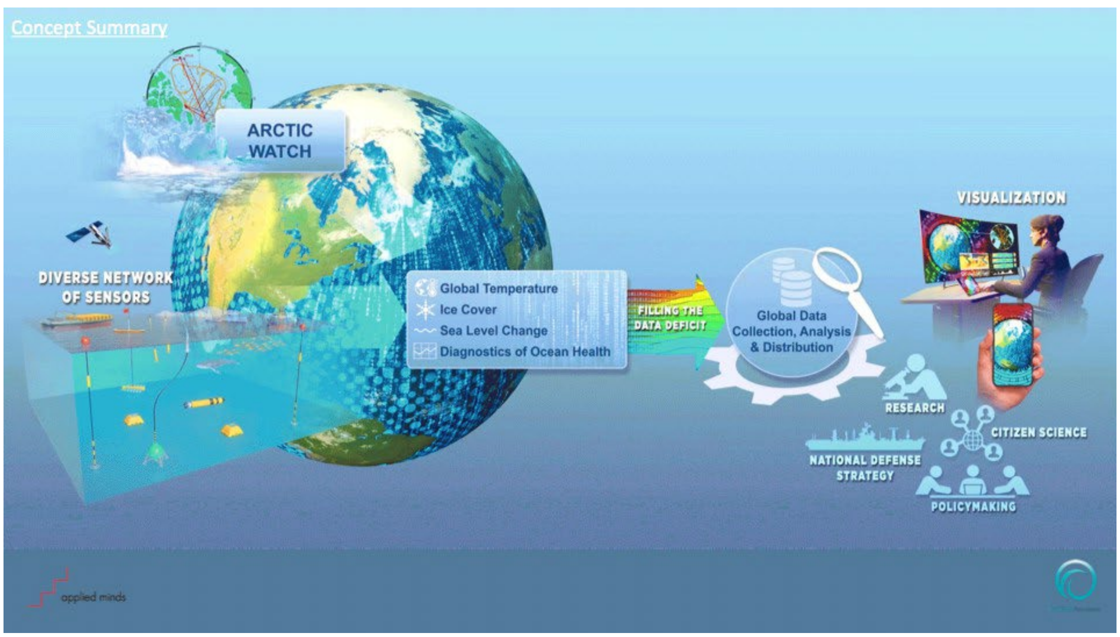
Focus Areas Recommended to DARPA

- High-resolution, region-specific ocean current predictions.
- Acoustic thermometry for deeper ocean monitoring.
- Integrating advanced AI models for adaptive ocean sensing systems.
- Testbed to evaluate research and data from experiments.

An ***Ocean Challenge***, with specific well-defined parameters, modeled after previous DARPA Grand Challenges, fits well within DARPA's de-risking mission and is highly recommended.

(Note: Such a challenge and future oceanographic modeling research would build on results and lessons learned from DARPA's previous Ocean of Things program, which conducted a small challenge in 2021 called Forecasting Floats in Turbulence.)

Figure 1: Concept for Ocean Watch Operational Testbed



Roundtable Discussions and Presentations

Status & Prospects of Ocean Modeling	Carl Wunsch | Animation
Needs, Capabilities & Gaps	Randy Pugh, NPS
	Nancy Hann, NOAA
	Venkatachalam Ramaswamy, NOAA
Status & Prospects of Ocean Data	Ann Kerr
	John Orcutt, USCD
	Bran Ferren, Applied Minds
Integrated Basin-Scale Demonstration(s)	
Concept, Area and Scope	Matthew Dzieciuch, UCSD
	John Colosi, NPS
	Kai Gemba, NPS
What Drives Progress in Oceanography?	Peter de Menocal, WHOI
Satellite Measurements	Tom Wagner, NASA
	Emanuele di Lorenzo, Brown
Challenges Relevant to DARPA/Wrap-up	Dave Halpern, UCSD

Click on the speaker's name to access the materials presented at the Roundtable

Summary of Roundtable Talks and Discussions

DARPA’s Focus and Key Considerations

DARPA’s Involvement: The workshop was held to consider ocean sensing technologies due to their implications for national security. However, the agency must clearly define the scope and timescales for its involvement. DARPA's primary mission is to pursue disruptive technological innovations rather than commit to long-term funding.

Scientific and Modeling Challenges

Ocean Models: Current Ocean models vary widely, covering timescales from seconds to decades. Although advances in computational power can improve model accuracy, challenges such as data scarcity and resolution constraints remain. Carl Wunsch emphasized the need to precisely define both spatial regions and timescales for future modeling efforts.

AI in Oceanography: The discussions highlighted the growing importance of AI in oceanographic modeling. However, AI applications in ocean models lag their more advanced use in weather forecasting.

Acoustic Sensing: There is considerable potential for utilizing acoustics in remote ocean sensing, particularly in high-energy environments where traditional float-based methods are ineffective. Acoustic technologies could offer more detailed measurements of ocean circulation and temperature stratification; an accelerated effort to increase the bandwidth of acoustic modems fits within DARPA’s mission and would change the landscape.

National Security Needs

Navy’s Priorities: The Navy prioritizes long-range precision, unmanned systems, and seabed monitoring technologies, which are essential for maintaining a competitive advantage, particularly against peer adversaries.

Impact of Climate Change: Climate driven disruptions, including mass migrations and oceanic changes, present significant national security risks.

Data Collection and Integration

NOAA’s Capabilities: NOAA is making significant strides in unmanned ocean monitoring, particularly in forecasting extreme events such as hurricanes. Innovations in technologies like saildrones and gliders are advancing their ability to gather critical oceanic data.

Global Ocean Monitoring System: A concept was proposed for a Global Ocean Monitoring System that integrates data from various sources (fixed, floating, and historical) to serve military, civilian, and scientific communities. However, the sustainability of such a system would require commercial viability to offset operational costs.

Technological Innovations

Acoustics in the Arctic: There is increasing interest in employing acoustic systems for ocean sensing, including underwater systems akin to GPS. However, a lack of infrastructure and specialized expertise—particularly in the Arctic—presents obstacles. We still have no US Icebreaker unlike our adversaries.

Satellite Measurements: NASA's advances in satellite technologies, including ocean color measurements and surface phenomena monitoring, have been used to map the seafloor however, the integration of in-situ data with satellite observations remains limited.

Future Directions

Focus Areas: Key areas of focus included regional ocean current prediction, the definition of appropriate time and space scales, and the integration of acoustics into ocean models. Discussions prioritized the physical processes of the ocean over biological or chemical processes in the short term. The emphasis was placed on the need for precise and integrated data systems, the use of advanced technologies such as AI and acoustics, and a strong focus on security driven ocean research.

Expert comments submitted prior to the Roundtable

As noted, the Discussion Topics and Questions were posed before the Roundtable and invited experts were asked to provide comments and relevant materials in advance of the meeting to facilitate discussions. The following comments reflect the insights provided by various experts, highlighting the ongoing challenges in ocean modeling and the potential solutions for improving predictability and national security strategies related to climate impact and ocean changes. A breakdown of the main points is provided here. The full set of comments are found by topic and expert are found in Appendix 1A.

Ocean Modeling Challenges

- Current ocean models have several inadequacies, such as limited high-resolution data, tidal forcing, and computational challenges. These issues affect predictability, especially for short-term forecasting in upper ocean layers.
- Improvements are needed in how models handle fine-scale processes like eddy dynamics, mixing, and biogeochemical interactions.
- The need for high-resolution models and multiscale approaches is critical, particularly for understanding the impact of ocean heat and carbon uptake.

Data Gaps and Collection

- There's a scarcity of data, particularly below 2000 meters and in the Arctic, which limits accurate ocean model calibration.
- The expansion of systems like Bio-ARGO floats, improved satellite coverage, and increased deployment of robotic sensors are recommended to better monitor ocean systems.
- Advanced machine learning and AI can help interpolate and enhance sparse data sets, improving model predictability.

Integration with National Security

- Oceanic changes, like sea-level rise and Arctic ice melt, pose strategic risks, affecting military operations, resource management, and environmental planning.
- A Global Ocean Monitoring System is proposed to integrate data from various sources and support stakeholders, including the military, scientific community, and policymakers.

Strategic Recommendations

- Long-term, large-scale experiments, such as basin-scale demonstrations, are necessary for improving the accuracy of ocean circulation and dynamics models. These efforts require coordinated data collection across multiple regions and timeframes.
- Machine learning and exascale computing are identified as future solutions to address the computational demands of high-resolution models.

Importance of Model Integration

- Coupled models that incorporate both ocean and atmospheric data are essential for improving long-term climate predictions, including phenomena like El Niño and sea-level rise.
- There's a focus on the need for better integration of model data with real-time observational data through advanced data assimilation techniques.

“Comments for DARPA/DSO Climate and Ocean Modeling Roundtable”

Emanuele Di Lorenzo submitted a document titled "Comments for DARPA/DSO Climate and Ocean Modeling Roundtable" which comprehensively addressed each Topic and sub-questions. It discusses current limitations in ocean models, such as inadequate tidal forcing, insufficient observational data, and computational limitations. Di Lorenzo highlights how these issues affect the accuracy of predictions, shifting focus from process-based studies to statistical analyses. It is briefly summarized below, and the full document is found in the Appendices.

The document addresses the following key topics:

Inadequacies of Ocean Models: Problems include tidal representation, the need for high-resolution data, and issues like spurious mixing and digital elevation map (DEM) inaccuracies.

Consequences: These inadequacies have led to a reliance on multi-model statistical studies and present challenges in data assimilation, which limits the predictability of ocean weather.

Limits of Predictability: Initial errors in ocean forecasts grow rapidly, limiting predictability for mesoscale features. While machine learning and better observations offer potential improvements, fundamental limits persist.

Distinguishing Ocean and Atmospheric Climate: Ocean climate responds more slowly than atmospheric systems, affecting long-term climate regulation.

Data Acquisition: Di Lorenzo emphasizes the need for more data from satellite and in-situ observations and advanced remote sensing to improve model calibration, process studies, and climate monitoring.

Basin-Scale Experiments: He advocates for large-scale observational campaigns to improve understanding of general ocean circulation and enhance model accuracy.

Impact of Better Models: Improved models would enhance understanding of the Earth's climate, improve predictions, reduce uncertainty in projections, and support better decision-making in environmental policy.

The document calls for significant advances in data collection, model refinement, and the integration of machine learning to improve predictability and climate projections.

Post meeting discussions and comments

Some Rough Notes. Carl Wunsch with Dave Halpern Comments (12 Sept 2024)

Carl Wunsch and Dave Halpern

A great need exists for better understanding of the ocean as it exists today, and as it might be in the future. Both aspects require a considerable, quantitative, discussion of what that means in practice. The ocean is important in climate, in national security (including both military operations and the transits of material and people), and in multiple biological systems, etc. In discussions of these and other elements, it is essential to specify a timescale of interest. Known physics shows that the ocean changes globally and regionally on *all* time scales from hours to millennia. So, for example, predicting sea level change at some position is very different on a one-year timescale and on a 20-year timescale. Crucial physical elements are very different---depending upon the time-scale choice. Long-term goals must accommodate the short-term ones to avoid potentially serious sampling problems and, pragmatically, satisfy funding agency demands for short-term results.

From the Stanford/DARPA meeting it seems plausible that there would be support for a focused effort to greatly improve understanding and predictability of ocean circulation in some, probably sub-basin, scale volume. What does that mean? Some of the climate issues involve the physics of air-sea coupling, the rate of change of the global volumetric mean temperature, salinity, carbon, oxygen, etc. Naval problems focus on the sound speed profiles and their predictability---over time scales that need to be discussed (hours? days? months? years?). *All* of these and other questions need to be rendered in quantitative fashion: How accurately do sound speed profiles need to be known? What error can be tolerated in the volume mean temperature as a function of an averaging time, or...? Do we have technologies already available, or perhaps available in the next 3-5 years that would address these questions sufficient to fulfil the needs for the results?

Can one choose areas so that the lessons learned could lead eventually to near-global observation and modelling systems which would also prove quantitatively adequate? Are there newer technologies whose development times extend beyond 5-10 years that could sensibly be accelerated? Discussion needs to distinguish places of important regional physics (and chemistry, biology,) such as the Arctic or the equatorial Pacific, but that are unlikely to serve as representative of the wider ocean. Perhaps western or eastern boundary areas are sufficiently generic—the question needs well-informed discussion.

DARPA is the logical agency to initiate this type of program because of its highly experimental nature. National and international partners will be required to sustain a successful program. Co-mingling of data for civilian and non-civilian activities will be a challenge; a role model exists in GEOSAT and elsewhere. Decisions about collaboration with other agencies is again dependent upon timescale and geography: the Navy for example, is likely only interested in the oceans above circa 1000m depth. But on long timescales, the upper and lower oceans are coupled and many of the high frequency changes occupy the full water column (e.g., baroclinic eddies and planetary waves). The Navy is likely very interested in parts of the North Atlantic but is unlikely to be willing to put resources into an equatorial or Southern Ocean region. Perhaps it can be assumed that NOAA/NASA and international partners will continue the near-global satellite coverage we now have(?), but again one needs to know whether newer satellite technologies will become available on the different future time-horizons.

Models also need analysis particularly as applied to some more specific region. That involves an understanding of the extent to which the inevitable open boundary conditions of sub-global domains can be adequately known? Models e.g., of the high latitude North Atlantic would also require useful land and sea ice components. Presumably that would not be necessary e.g., for a sub-tropical Pacific Ocean focus. It's another area where full understanding of the regional versus the global needs to be carefully and quantitatively laid out.

(A personal interest is the extent to which the complete ocean ambient noise spectrum can be used to deduce its state? Acoustics is one of the more obviously under-explored techniques outside its military and purely biological uses. It would likely require deploying vertical and horizontal arrays of hydrophones. Numerical modeling of the large-scale, lower frequency components of the acoustic field is in its infancy.)

My experience in getting a wider community to agree to what became the World Ocean Circulation Experiment (WOCE) and other collective efforts such as those leading to the launch of satellites, suggests that a small group (order ~6+ people) each with a strong interest, needs to convene to develop a statement of goals, a scientific/technical strategy for meeting them, and a strategy for convincing the wider community that it is both important and makes sense. A scientific and a DARPA leader who really wants to see it done is essential. Thus, my interpretation of the outcome of the Stanford/DARPA meeting is agreement that much more focused, more technical, discussion needs to take place. Consider delaying wide-spread community involvement until a small (6+) group, as mentioned above, prepares a 5- to10-page document for DARPA approval on challenges to improved understanding and predictability of ocean circulation. Examples of challenges worthy of DARPA consideration are an observing system, models, and data assimilation leading to prediction systems and evaluation. One might solicit brief proposals from individuals and small groups for support of discussions of sub-basin experiments in the context of the global ocean.

Key Considerations for an Effective Beaufort Gyre Acoustic System

John Colosi, NPS

1) The basin wide navigation system would be best served using the ultra-low frequency 35 Hz sources Matt has been deploying over the last 5 years. However higher frequency sources (200 -1000 Hz) will be required to resolve the upper ocean vertical heat content distribution as well as the pH fluctuations. These frequencies may also be useful for ACOMMs and more precise navigation.

2) Realtime data is a critical requirement if models are trying to provide synoptic arctic ocean state estimates. This means platforms like Ice Tethered Profilers (ITPs) equipped with hydrophones should be a high priority. Other platforms that have less reliable access to the sea surface and data exfiltration (Arctic Argo, RAFOS and other floats, gliders, etc.) will still be extremely valuable as both acoustic and oceanographic sensing systems but a lot of work will be needed to develop effective data compression systems as described by Baggeroer and Ferren.

3) Not sure if people are thinking about cabled systems but having a cabled region especially in the vicinity of Barrow canyon would be important for quantifying the pacific summer and winter water heat inputs into the gyre via acoustic remote sensing and UUVs. Maybe there are other good places where cables could be used.

4) Currents. David Halpern considers this an important topic and Jinendra seemed to pick up on this too. Acoustically, currents are observed using reciprocal transmissions (out and back) and an even more difficult observable vorticity can be measured with reciprocal transmissions along a closed circuit (or say the edges of a square or a pentagon). Currents are difficult because they depend on the isopycnal slopes, and this is probably why the data is harder to assimilate (as Manu DeLorenzo mentioned). In my opinion currents would be best observed acoustically using the higher frequencies that get trapped in the surface layer and pacific/atlantic layers: here the sound does not spread out so much in depth so the current in those layers is better constrained….. so, another case for dual frequencies.

5) Turbulence and mixing: David also mentioned this as a key topic that numerical models don't get right especially in the Arctic. At WHOI we are working on an acoustic scintillation observable for mixing but this is a high risk undertaking since the receiver system needs to quantify weak scintillation patterns and there are timing and navigation questions. In any case maybe this is something for DARPA?

Framing the Ocean Health Monitoring and Observation Problem: Advances in SmallSat Technology

Lt Col Marquay Edmondson, National Security Affairs Fellow, Hoover Institute, Stanford University

A few objective takeaways as an observer from the DARPA meeting in framing ocean health monitoring and observation.

1) From a space point of view, initial research was conducted to explore some of the advances in information collaboration and data fusion among DOD and commercial industry. There is a long-term and more sustained approach for climate change monitoring and forecasting: the adoption of SmallSat technology. This technology presents new opportunities for extended dwell-time forecasting and provides more mission opportunities to DOD, commercial organizations, and most importantly, the science community. This capability dependent on sensory payload and how it's employed improves spatial and temporal coverages while closing scientific and data-return gaps hindered by larger traditional satellites.

2) The Defense Innovation Unit (DIU) presented a new approach on data integration for commercial and legacy space-based capabilities known as Hybrid Space Architecture (HSA)—information-based architecture and framework that can deliver on various mission sets. This network architecture has the capability to integrate SmallSat sensor data, communications, and capabilities on a larger scale in accordance with optimal orbital coverage to enhance scientific study for the oceans and coastal regions. This opens the space-based ecosystem door for scientific study, data sharing, and discovery for non-traditional users and allies. The HSA framework, likely in its initial phases, is a multi-layer information-based architecture with the capability to incorporate and disseminate low-latency data and communications from SmallSat sensors across commercial and DOD domains according to DIU reporting.

3) SmallSat technology conducting data collection for Earth Science applications involves radar altimeter sensors, these sensors are one of the primary options to measure ocean variables, surface, sea level, and circulation, but mostly for short-term forecasting likely due to low-earth orbit observation. However, long-term monitoring of the ocean's temperature may be a better option to support the long-term problem of ocean health and monitoring, thus closing the data deficit on measuring and studying the interior dynamics of the ocean. Measuring the temperature of our oceans with SmallSat capabilities will likely provide key estimates for the temperature of the earth and help improve our analysis of climate change and prediction modeling.

4) Some baseline satellite sensor technology designed to measure ocean temperature produces sea surface temperature (SST) and synthetic aperture radar data. SmallSat constellations equipped with these multi-source sensors can collect SST data through satellite microwave radiometers and infrared radiometers. Moreover, SST data measured from space can provide key ocean depth measurements based on specified satellite instrumentation, resulting in various application opportunities and products that represent temperatures at different depths.

5) Data Points

- SmallSat capabilities can be a resource to employ within a constellation or a hybrid network combined with small and large-scale satellites. These satellites can operate at various orbits, but likely more efficient within an HSA ecosystem tasked to incorporate and disseminate science community objectives and data across commercial and DOD domains. SmallSats operating at different orbital planes can provide improved spatial resolution coverage across the ocean surface or operate on the same orbital plane to provide increased temporal resolution coverage at different points over time.
- SmallSat capabilities incorporated among a collaborative network of commercial, DOD, and science community users can be a cost-effective approach to integrate innovative technology with Earth Science applications. This space-based ecosystem of networks and sensors could enable traditional and non-traditional users across the National Reconnaissance Office (NRO), DOD, National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and various agencies across the science community to pursue both technology demonstration and long-term applications for the ocean problem set.
- The HSA program could branch out as a strategic opportunity for DARPA to address the long-term problem and national security requirements on forecasting Earth's climate change. Lastly, this framework and technological capability can address the information gap in dealing with periodic data that is currently limited on a global scale to measure current values of and characteristic changes in our oceans accurately for Navy and Earth Science applications.

Current Stakeholders:
Defense Innovation Unit (DIU)
National Oceanic and Atmospheric Administration (NOAA)
National Oceanographic Partnership Program (NOPP)

Collaborating Stakeholders w/ Defense Innovation Unit:
United States Space Force (USSF)
USSF Space Systems Command
Space Warfighter Analysis Center (SWAC)
Air Force Research Laboratory (AFRL) Space Vehicles Directorate

A. G. C. Guerra, F. Francisco, J. Villate, F. A. Angelet, O. Bertolami, and K. Rajan, “On Small Satellites for Oceanography: A Survey,” *Acta Astronautica* 127 (2016): 404–23, https://doi.org/10.1016/j.actaastro.2016.06.007.

Brasnett, Bruce. "The impact of satellite retrievals in a global sea-surface-temperature analysis." Quarterly Journal of the Royal Meteorological Society 134, no. 636 (2008): 1745-1760. https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/qj.319.

Emery, William J. 2017. *Introduction to Satellite Remote Sensing: Atmosphere, Ocean, Land and Cryosphere Applications / William Emery, Adriano Camps*. Amsterdam [etc.]: Elsevier. https://www.sciencedirect.com/book/9780128092545/introduction-to-satellite-remote-sensing.

L. Wang, Tianbiao Yang, Xuekuan Li, and Genqin Li. 2020. “Design of Hainan Satellite Constellation and Applications for Ocean Observations.” *IOP Conference Series: Earth and Environmental Science* 502 (May): 012002. https://iopscience.iop.org/article/10.1088/1755-1315/502/1/012002.

Margaret Srinivasan and Vardis Tsontos, “Satellite Altimetry for Ocean and Coastal Applications: A Review,” *Remote Sensing* 15, no. 16 (2023): 3939. https://doi.org/10.3390/rs15163939.

National Academies of Sciences, Engineering, and Medicine, National Academies of Sciences, Engineering, and Medicine (U.S.), Committee for the Assessment of Partnership Options for a Small Satellite System for Collecting Scientific Quality Oceanic and Coastal Data, National Academies of Sciences, Engineering, and Medicine (U.S.), Intelligence Community Studies Board, and National Academies of Sciences, Engineering, and Medicine (U.S.). Division on Engineering and Physical Sciences, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=7013910.

National Academies of Sciences, Engineering, and Medicine, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://doi.org/10.17226/26380.

Nicolo Boschetti, Johan Sigholm, Mattias Wallen, and Gregory Falco, “A Hybrid Space Architecture for Robust and Resilient Satellite Services,” 2023 IEEE 9th International Conference on Space Mission Challenges for Information Technology (SMC–IT), Space Mission Challenges for Information Technology (SMC–IT), 2023 IEEE 9th International Conference on SMC–IT, July 14–22. https://doi.org/10.1109/SMC-IT56444.2023.00021.

Two Takeaways: National security concerns and Accurate Prediction of Variables important to Climate

James Bishop, UC Berkeley

There seemed to be two major concerns:

(1) An immediate need to address national security concerns relating to the ocean.

a) Immediate identification and neutralization of Autonomous vehicle threats to Naval battle sphere operations.

b) Identification and neutralization of Small Autonomous Systems parked in areas of the ocean that could represent a future threat to marine traffic, Naval operations, and North America, particularly near ocean fronts, where passive acoustic methods (sound channel) fail. For example, the subarctic front 1000 km west of Seattle.

Tools: Float based active Acoustics, GPS of the sea, improved models – informed by real time hydrographic profiling (air dropped cheap ARGO floats).

(2) Accurate Prediction of Variables important to Climate.

a) Physical circulation of ocean and atmosphere. Heat budget, currents…
a comment. I heard was that current velocities near fronts are poorly represented in models (Halpern). It is often said that the physical regime sets the stage for all biological processes in the ocean.

b) Improved Models of the Ocean Biological Carbon Pump, and ocean CO2 exchange with the atmosphere. The existing observations of the OBCP are few and far between, thus advancement of predictive models is limited by lack of observations. There is a consensus that biological dynamics near ocean frontal regions is poorly understood, yet there are many indications that the OBCP is strong in the vicinity of fronts.

Tools: Float based active Acoustics (zooplankton acoustics), GPS of the sea, floats, gliders, and profiling systems that detect particle concentrations, size distributions, and fluxes.

It is important to note that ship operations are dangerous in the vicinity of fronts. My personal example finding out about the loss of key scientific equipment (and my optical sensors) from R/V Revelle due to a rogue wave impact while the ship was operating near the Subantarctic front (55°S, 145°W Dec 25, 2022).

My thinking is that (1b, and 2a and 2b) find a good synergy and high rationale for coordinate autonomous studies. Since biological time scales are of the order of one week, autonomous methods are the only way to advance process understanding. A starting location may be the Subarctic North Pacific front.

Appendix 1A - Invited Experts Responses to Topics and Questions

I. Climate and Ocean Model

<u>Randy Pugh</u>

- We need a thorough understanding of the water column, the seabed, how conditions affect undersea and seabed warfare capabilities, and how the changing conditions (short- and long-term) are leading to uncertainty and risk for the military
- These are risks to force and risk to mission (tactical, operational, and strategic capability to gain and maintain competitive advantage (critically, including stealth and surprise) over potential adversaries / enemies.

<u>Emanuele Di Lorenzo</u>

- Current ocean models face several key inadequacies. Firstly, they often lack proper tidal forcing, which is crucial for accurately representing the internal wave field. This inadequacy can lead to misrepresentations in ocean dynamics. Additionally, there is a scarcity of high-resolution observational data, which limits the ability to monitor and validate Ocean General Circulation Models (OGCMs) at very fine scales.
- Computational and methodological challenges also persist, such as the need for a multiscale approach and advanced parametrizations to accurately simulate processes like double diffusion and air-sea interaction fluxes.
- Furthermore, the resolution of models at basin and global scales is constrained by current computational resources, and ocean-specific challenges like salinity effects, sea ice dynamics, and the accurate representation of fine-scale processes like eddy dynamics remain significant hurdles.
- Fundamental issues such as spurious diapycnal mixing and inaccuracies in Digital Elevation Map (DEM) representation further complicate model accuracy.
- Predictability in ocean weather forecasting is limited by the rapid growth of initial errors, especially in the upper ocean. The error doubling time, which indicates the period after which errors grow significantly, typically ranges from 5 to 7 days in the upper ocean. This rapid error growth is more pronounced at mesoscale or eddy-permitting resolutions. For mid-depth ocean features and large-scale patterns, predictability extends toabout a month due to slower evolution. However, specific regional and seasonal events have shorter predictability horizons, often just a few days. While there is potential for skillful decadal predictions in upwelling systems, the chaotic nature of ocean and atmospheric systems imposes fundamental limits on the accuracy and duration of forecasts.
- The limitations in current ocean models have led to several consequences. A major shift has occurred from process-oriented studies to statistical analyses of multi-model ensembles, prioritizing broad patterns and trends over detailed process-level understanding. This shift may overlook critical nuances of individual processes.
- The development of better ocean models would have a profound impact on multiple fronts. Enhanced models would provide deeper insights into fundamental processes governing the Earth's climate system, such as ocean heat and carbon uptake, which are crucial for understanding the Earth's energy balance and carbon cycle. Improved

accessibility and usability of these models, especially through cloud-based platforms, would democratize research opportunities, allowing a broader range of scientists, including young researchers, to engage with complex simulations. This would foster innovation and exploration in oceanography and climate science.

- Better models would also reduce the spread in climate projections, particularly regarding metrics like the Transient Climate Response to Emissions (TCRE). More accurate representations of oceanic processes would help clarify uncertainties in climate sensitivity and future scenarios, aiding in the assessment of rapid surface warming and coupled atmospheric-oceanic interactions.
- Additionally, improved models would enhance predictions of ocean and weather phenomena, such as El Niño and hurricanes, and support long term planning and adaptation strategies, particularly for coastal communities. The integration of AI with traditional modeling techniques would further bolster the utility of these models in decision-making processes across various domains, including resource management and environmental policy.

Stephen Monismith

- Short time and space scale processes like internal waves (as well as turbulence) are not well represented in most large-scale models. Coastal ocean models are challenged by the presence of remotely generated internal waves as well as by interactions of surface waves with mean and turbulent flows.
- Fundamental problems are model errors failure to include important processes that influence ecological and biogeochemical processes.

Peter de Menocal

- Biases in their equilibrium state means they rapidly 'drift' away from observations, particularly in the deep ocean. Likely source is poorly parameterized mixing and stirring physics, but biased surface forcing can also be a problem. There is also chaos in the system, and a key idea is what space/time scales do we need to constrain and what can we allow to be unconstrained? We presently must make tradeoffs between the size of area being analyzed vs number of ensembles being run vs spatial resolution. Likely related to the point above - lower the resolution, the more things have to be parameterized may lead to higher biases?

- For longer timescales (> 2 weeks), ocean models likely need to be coupled with an atmosphere at high resolution (<=10km). Both heat and momentum coupling are first order in mediating mesoscale energy #ows – e.g. 'eddy killing' by winds etc. The forcing errors include momentum, heat (radiation and LH/SH) and freshwater fluxes

Kristen Davis

- We need the ability to simulate the range of spatiotemporal scales relevant to accurately represent important physical and biogeochemical processes. (e.g. large-scale forcing driving internal waves which propagate across ocean basins and drive episodic mixing at small scales (cm-scale)). On this theme, shelf seas/coastal regions are often not well represented in global ocean models due to limitations in resolution, but they are critically important for biogeochemical fluxes in the ocean due to elevated primary productivity (from terrestrial nutrient inputs and upwelling) and enhanced mixing. We need better strategies for upscaling the biophysical influence of the coastal ocean on the global ocean. These deficiencies cause large errors in prediction.

David Halpern

- Consistent with the vision "to improve ocean models and forecasting capabilities", I suggest that a model is one leg of a 3-legged stool. The other 2 legs are data assimilation and observations. All 3 legs are equally important and discussing one without the other two would make an unstable seat.

- I suggest that ocean currents, u(x,y,z,t) and v(x,y,z,t), be the goal of improving forecasting capabilities. Spatial (i.e., X, Y, and Z) and temporal (i.e., T) domains are to be decided by the application.

Venkatachalam (Ram) Ramaswamy

- Model grid spacing (horizontal resolution) remains limited, and global climate models struggle to represent fine-scale features important to the energy of the ocean (fronts, eddies, dense water formation, etc.) Like other Earth system components, ocean models rely on incomplete or imperfect physical parameterizations at the sub grid-scale. For example, the representation of mesoscale eddies at high latitudes remains a challenge for ocean models even as resolutions increase.
- Representing deep ocean ventilating water masses important to anthropogenic heat uptake remains a challenge. Many models have yet to consider the fate of the Antarctic and Greenland ice sheets which pose the most existential threats of climate change through extreme sea level rise beyond the current century.
- The ocean plays a critical role in the climate system. Biases and inadequacies in ocean models are evident in their projections of future ocean heat uptake. Biases present in the upper ocean also influence SST patterns, and in turn, climate feedback processes. Considerable uncertainty remains regarding future patterns and magnitudes of sea level rise, as sea levels in ocean models represent an integrated effect of many different ocean processes.
- Horizontal resolution limitations also lead to limited/poor representation of physical processes that span the open ocean / coastal transition zone. Better ocean models would lead to reduced uncertainty regarding the Earth's climate sensitivity, projections of future climate change, and sea level rise.

- Improved ocean models would lead to better decision-making for managing coastal resources and living marine resources.

Benjamin Horton

- Including sea-level rise (SLR) projections in planning and implementing coastal adaptation is crucial. Here we analyze the first global survey of the SLR projections for 2050 and 2100. Two-hundred and fifty-three coastal practitioners engaged in adaptation/planning from 49 countries and provided complete answers to the survey which was distributed in nine languages.
- While recognition of the threat of SLR is almost universal, only 72% of respondents currently utilize SLR projections. Generally, developing countries have lower levels of utilization. There is no global standard in the use of SLR projections: for locations using a standard data structure, 53% are planning to use a single projection, while the remainder are using multiple projections, with 13% considering a low-probability high-end scenario.

II. Problems Unique to Ocean vs Atmosphere

Emanuele Di Lorenzo

- The primary distinction between ocean and atmospheric climate lies in their timescales of variability. The ocean has a slower response to changes, with significant variability occurring over months to centuries, whereas the atmosphere exhibits rapid changes from hours to weeks. This slower oceanic response makes it a long-term climate regulator. Additionally, the statistical properties of oceanic and atmospheric #ows differ due to the distinct physical properties and boundary conditions of each system. The ocean tends to have lower frequency variations, while the atmosphere is characterized by higher frequency fluctuations. Understanding these differences is crucial for accurate climate modeling, especially in the context of energy and carbon cycles.

Venkatachalam (Ram) Ramaswamy

- Ocean models require similar improvements to resolution as other Earth system components, but the computational cost is not equivalent; the timescales of ocean processes are longer than the atmosphere and require longer model simulations.

III. Acquisition of Data

Kevin Smith

- Most of the data available to feed models are only from the ocean surface. They help refine input parameters (boundary data for deterministic numerical models) and feeds training data for AI models.
- There is no single answer for every part of the ocean, so we need vastly more sensors.

D. Benjamin Reeder

- The Arctic is data sparse; new sensing systems are required. Potential new sources are cryophone data via onboard processing and satcom.
- Inferred properties of the ice using passive cryophones could be used by USNIC for ice monitoring and by ice modelers for validation and data assimilation. Active cryophones with satcom and GPS could be used for UUV navigation.

Emanuele Di Lorenzo

- More data would significantly improve the verification and calibration of ocean models, ensuring that simulations align with real-world observations. This process helps refine model parameters and enhances the overall reliability of predictions. Additionally, increased data availability supports more robust data assimilation processes, integrating observational data into models to produce more accurate forecasts. Understanding fine-scale processes, such as mesoscale and sub-mesoscale dynamics, would also benefit from enhanced data, leading to more accurate simulations of oceanic phenomena.
- Comprehensive coverage across various depths, large areas, and time scales is essential to capture the full spectrum of oceanic processes. This includes monitoring from the surface to the deep ocean, covering vast oceanic regions, and ensuring temporal resolution that can capture both short-term and long-term variability.
- High precision is required for measurements, particularly for key parameters like temperature, salinity, and currents. Accurate data are essential for reliable modeling and analysis, especially in resolving fine scale features like eddies and fronts.
- Data can be acquired through various means, including satellite observations and in-situ measurements. Expanding satellite capabilities with missions like MODIS, GRACE-FO, and SWOT can provide comprehensive ocean surface coverage. Increasing the density of Argo profiling floats will improve spatial resolution for temperature and salinity profiles. Advanced instruments, such as modern scatterometry and doppler combinations, can provide high-resolution observations of surface currents, SST, and waves. Emerging technologies for remote sensing below the surface are also promising for capturing subsurface processes.
- Acquired data can be used to refine ocean models, enhancing their accuracy and reliability. It can support process studies, providing detailed insights into ocean dynamics and informing the development of new model parameterizations. Data are also crucial for

climate monitoring, tracking long-term trends such as ocean warming and sea level rise. Additionally, advanced data assimilation techniques and data fusion methods, like digital twins, can integrate diverse data streams into a unified framework, improving model accuracy and providing a comprehensive understanding of ocean and climate systems.

Kristen Davis

- More observational data is how we improve (1) our fundamental understanding of physical and biogeochemical processes and (2) from this understanding create more robust parameterizations of those unresolved processes in models.
- One example of a severe lack of data is on global nitrate fields. This macronutrient is critical for oceanic productivity and carbon cycling but has historically been measured by shipboard work only. Recent development of optical sensors is improving data collection, but detection limits and biofouling are still critical challenges.
- We should add more Bio-ARGO floats!

Venkatachalam (Ram) Ramaswamy

- Basic hydrography data remains limited below 2000 m. Programs such as Argo and GO-BGC are critical for this information but have relatively short records.
- Longer records would help establish a climatological record, especially of the deep ocean. Longer records are also needed to study and characterize modes of decadal variability (e.g. NAO, AMV, PDO, etc.)
- Additional observational data would be used to validate and benchmark process-level performance within ocean model recent studies have demonstrated that seasonal prediction models with robust data assimilation systems – especially those that incorporate satellite altimetry data – are needed to forecast coastal inundation and extreme sea levels at seasonal timescales.

IV. Integration & Management of the Data

Ann Kerr

Impact on National Security

- Lack of knowledge of ocean in operational theater
- Looming ice melt poses advantage to adversaries

Inadequate Models and insufficient and/or sparse Data

- Knowledge of ocean in key areas essential
- Arctic key area of strategic importance – ice melt problem

- Ocean Discovery and Exploration is a DARPA Challenge – ala its Founding purpose to match or exceed tech capability of Sputnik - but DARPA can't do alone. It can assess and provide technical expertise and initiate new Programs, involve relevant technical agency expertise. Moving beyond initial stages will involve greater funding from Philanthropic partners. Long term research and measurement programs are essential and require long term stable operational resources. It is imperative to
- Identify and incorporate commercial and market needs as a source of long term operational funds. For example, subleasing portions of cable systems to commercial companies, or providing data on fish migration to the commercial fishing industries.

- Slides show concept for a Global Ocean Monitoring System, integrating data from fixed and floating systems and historical data. (Slides in Meeting Admin File). Implement and test small-scale experiment(s) in a prototype operational testbed.
- Purpose: Collect data from numerous stovepipe systems, integrate with modern sources and sensors and provide to spectrum of users:
    - Navy for strategic and tactical missions
    - Civilian Agencies for (disaster) planning
    - Scientific Community to improve models with more and better data
    - Policymakers for strategic decision making based on science

- Unrealistic that fully within DARPA Mission – but proof of concept/evaluation of if and how models are improved.
- Long term operation of fixed and floating systems is needed but are unrealistic from cost point of view unless:
    - Commercial Value identified to carry operational costs – perhaps cost sharing/leasing bandwidth on fiber cables.
        - Economic value of blue economy – tracking data for fisheries
        - Mineral mining
        - Pharmaceuticals
        - Oil Exploration
        - Environmental monitoring for sea level rise, large events.
- Global Access to provide data and access integrated database.

The purpose of this meeting is to take a broad expert look – but it is no substitute for detailed discussions as suggested by Carl Wunsch – perhaps best achieved through small, targeted workshops to identify critical parameters and precision needed.

Emanuele Di Lorenzo

- Data assimilation involves integrating observational data into numerical models to improve forecast accuracy. This process is vital for reducing uncertainties and enhancing the reliability of model outputs. By continuously updating models with real-time data, the accuracy of predictions can be significantly improved, leading to more reliable forecasts and analyses.
- Machine learning (ML) interpolation processes offer potential improvements in ocean modeling by providing advanced techniques for data analysis and model development. ML can interpolate between sparse data points, offering improved estimates of oceanic variables and helping to fill gaps in observational data. The integration of ML with traditional models can enhance the predictive capabilities and accuracy of ocean forecasts.
- Ocean modeling faces significant challenges in data transmission, computation, and storage. The vast amounts of data generated by high resolution models require efficient transmission systems and substantial computational power. The transition to exascale computing is necessary to handle the increased resolution and complexity of modern ocean models. Additionally, the storage requirements for extensive observational and model data are substantial, necessitating advanced data management systems.
- Barriers to data access hinder broader scientific collaboration, as the limited dissemination of OGCM simulation outputs restricts the ability of researchers and stakeholders to utilize these data effectively. The challenges in optimal estimation and data assimilation further complicate efforts to integrate observational data with model simulations, which is crucial for accurate forecasting. These issues underscore the necessity of democratizing data access and improving data assimilation techniques to enhance model reliability and the broader understanding of ocean systems.

David Halpern

- A consequence of an ocean current forecast or reanalysis capability is the development of an evaluation system. This will require considerable thought for a global ocean system. However, much has been learned in the equatorial Pacific, where monitoring the El Niño and La Niña oscillation began in 1980.

- A perfect ocean current model would reduce emphasis on assimilation of ocean observations, reducing the cost of data acquisition and data assimilation. However, the evaluation cost of the ocean current forecast or reanalysis is unchanged.

Venkatachalam (Ram) Ramaswamy

- Machine learning interpolation would be a viable approach in regions with limited observational data
- From the modeling perspective, NOAA's Modular Ocean Model version6 (MOM6) has a regional spinoff (RegMOM6) which is being applied to study the regions around the US

coasts and Great Lakes regions for both climate and climate - biogeochemical - marine ecosystem interactions. It is also beginning to be applied to the Kuroshio current area.

A.

Comments regarding the NOAA/GFDL current modeling of the oceans and ocean-atmosphere interactions on the seasonal-to-centennial timescales, and predictability:

1. NOAA/GFDL has developed a system for real-time prediction of the state of the ocean for several years up to a decade in advance. This system has verified skill in predicting ENSO a year in advance, as well as other aspects of ocean variations. As an additional example, the system is able to skillfully predict sea level variations along the US East coast up to three years in advance.

2. The prediction system depends critically on ocean and atmosphere observations. Measurements from the ARGO array are critical and are fed into the model. This system provides near-real time observations of ocean temperature and salinity over the upper 2000 meters of the world ocean every ten days or so. Substantially increased measurements in areas of large ocean eddy activity, such as in the Gulf Stream, tropical Eastern Pacific, and Kuroshio Extension could be of significant benefit. There are other important ways that ocean observations could be improved for predictions.

3. The current ocean prediction system uses an ocean model with relatively coarse ocean resolution due to computer resource limitations. Transitioning to a prediction system with a much finer resolution ocean model could improve predictions but would require substantially increased computer resources.

4. A critical issue in predictions is how observations are combined with the models to make the predictions. The combination of data and models often done with data assimilation. efforts to improve such assimilation systems could increase productive skill.

5. The GFDL system is seamless - the same modeling system is used for predictions and projections from a time scale of two months to 100 years. This is an important aspect in dealing with seasonal to interannual variability within the same system as longer tremors climate change. Questions arise such as how our ability to make seasonal to inter annual predictions will change as the over climate system warms.

6. An important issue is what aspects of climate change might be abrupt or irreversible. The GFDL modeling system is probing these issues.

B.

Criteria, needs, and model requirements:

It may be difficult to address the questions posed in the Roundtable document until the question of the requirements for these models is first asked and answered. The stated overall exploratory goal in the DARPA statement is "DARPA DSO is investigating whether changing climate might create strategic or tactical surprises for our national security." Perhaps there already is a list of the "strategic or tactical surprises" for which a prediction system is necessary, but specification of the needs set by these criteria would establish the framework for the model requirements. A few examples of what may be desired and the current gaps:

- Changes in severe storm path and intensity
  - ▶ *Gap:* Requires coupling between climate models capable of representing regional patterns of climate change with high resolution severe storm models incorporating air sea interactions across the ocean and atmospheric boundary layers Increasing vulnerability of coastal structures to "sunny day" flooding under sea level rise
  - ▶ *Gap:* Requires coupling between global model of sea level rise and local/regional model with tides increasing vulnerability of coastal structures to extreme storms under sea level rise
  - ▶ *Gap*: Requires coupling between global model of sea level rise and severe storm model Interior waterway navigation hazards from changing coastal erosion and sediment transport under sea level rise and extreme flooding.
  - ▶ *Gap*: Requires coupling between global model of sea level rise, river and estuarine hydrology model, erosion model, and sediment transport models
- Sea ice and icebergs as navigation hazards
  - ▶ *Gap:* Requires high resolution coupled polar models.
- Risk of heat exposure in marine vessels
  - ▶ *Gap:* Requires coupled modeling of marine heat waves
- Fog and other visibility threats to navigation
  - ▶ *Gap*: Requires coupled Earth system representation of air-sea interactions, aerosols, and clouds

▶ Probability of rogue waves
  - ▶ *Gap*: Requires coupling between severe storm model and wave model

V. Modalities – Sensors and Sensor Platforms

Emanuele Di Lorenzo

- Monitoring the deep ocean presents unique challenges due to the difficulty in accessing and maintaining observational instruments at great depths. The scarcity of high-quality observational data from the deep ocean limits the understanding of deep-sea processes and their role in the global climate system. Advanced technologies and innovative observation strategies are required to improve deep ocean monitoring capabilities.

Jim Bishop

- Biologically mediated particulate organic and inorganic carbon (POC and PIC) concentrations and fluxes from surface waters to kilometer depths are poorly observed in space and time, yet such observations are of fundamental importance to the understanding and prediction of ocean food webs, of the cycling of scores of chemical elements, and of the regulation of atmospheric CO2. To do this the model must be informed by observations.
- To address the gap in observations we have been working to meld the capabilities of the robotic Carbon Explorer (CE, Bishop and Wood, 2008; doi:10.1029/2008GB003206) and Carbon Flux Explorer (CFE, Bourne et al. 2021; doi:10.5194/bg- 18-3053-202172) systems –
- ARGO-style floats – to create the Ocean Carbon Observer (OCO), which is designed to follow variations of POC and PIC concentrations and fluxes from surface to kilometer depths on daily time scales for seasons to years.
- We propose to enhance the ARGO, and BIO-ARGO float deployments through ensemble deployments of Ocean Carbon Observers that will operate to kilometer depths and record particle fluxes and particle concentration profiles on sub 6 hour frequency. Data are relayed in real time (see attached Ocean Sciences Meeting presentation). When we use the term "Ensemble" we mean deploying groups (e.g. 12) of OCOs at key locations. Before separation, OCOs will intercalibrate, and subsequently, physical perturbations of trajectory will lead to a separation of these instruments. Data will reflect temporal perturbations due to winds and air-sea fluxes and will yield a statistically valid result that will inform carbon cycle models.
- Clearly, BIO-ARGO needs to be expanded to Basin scale. In the case of our new OCO's, we wish to sample biologically contrasting open-ocean regimes. For example (subarctic, subarctic front, gyre, equatorial, subtropical waters, subantarctic, Antarctic Circumpolar Current, and Southern Ocean). Approximately 100 OCO's (8 Ensembles) would be deployed in these environments. A basin scale Experiment would certainly suit such operations.
- As primary producers in the surface ocean are consumed every 1-2 weeks, repeat ensemble OCO deployments at 4-6 month intervals for 3 to 4 years would capture how biological carbon fluxes respond on not only storm time scale but also the inter annual time scales.

- Particulate Organic Carbon (0.01 µM), Particulate Inorganic Carbon (0.02 µM), POC flux (0.1 mmol m-2 d-1), PIC flux (0.01 mmol m-2 d-1). We can achieve this precision now.

VI Would a Basin-Scale Experiment Be Valuable? If So, What Would It Look Like?

<u>Emanuele Di Lorenzo</u>

- A basin-scale demonstration would be highly valuable for advancing the understanding of ocean circulation and dynamics. It would involve coordinated synoptic data collection, using multiple ships and instruments across different regions to provide comprehensive mapping of large-scale and eddy-scale circulations. Such an experiment should include both remote sensing and in-situ measurements, focusing on capturing key physical and biogeochemical parameters at high resolution. The experiment would ideally involve repeat observations to capture temporal variability and long-term trends, providing a benchmark for future studies and improving model validation and calibration efforts.

<u>Kevin Smith</u>

Yes, but what would the goal be? That would drive what it would look like?

<u>Kay (Kai) Gemba</u>

- We need a Synaptic Snapshot obtained via fixed, drifting, and moored receivers along a single or multiple-nearby geodesics with a fixed source. One goal is to understand the complex propagation and interactions with seamounts over 1000s of km and its dynamics such as IW, and eddies order 100kms. Acoustic observations and direct measurements are to be digested and contribute to validating/improving HYCOM.
- Extend this single-geodesic example to include a scenario covering the Northeast Pacific (e.g., 3 sources, 500 drifting receivers). As a side-product, this is an enabler for basin-scale robotic research.

Appendix 1B – Di Lorenzo Document

Comments for DARPA/DSO CLIMATE AND OCEAN MODELING ROUNDTABLE

by Emanuele Di Lorenzo, Professor, Brown University, www.ocean.brown.edu

This document provides my personal views on the current state of ocean models followed by a set of answers to specific questions posed by the DARPA Panel. My views have been informed from conversations with **Dr. Baylor Fox-Kemper** (Brown University), **Joseph Zhang** (VIMS), and **Nadia Pinardi** (University of Bologna).

TABLE OF CONTENT

Overall Summary

Inadequacies of Current Ocean Models:
Current ocean models face several challenges, including the lack of proper tidal forcing, insufficient high-resolution observational data, and the need for more advanced parametrizations. The complexities of ocean dynamics, such as salinity effects and sea ice processes, further complicate modeling efforts. Additionally, fundamental issues like spurious diapycnal mixing and inaccuracies in Digital Elevation Maps (DEM) representation highlight the need for continued advancements in model development.

Consequences of Inadequacies:
The limitations in ocean models have led to a shift from process-oriented studies to statistical analyses of multi-model ensembles. Barriers to data access hinder broader scientific collaboration, and the complexities in data assimilation challenge the accuracy of forecasts. These issues underscore the necessity for democratized data and improved data assimilation techniques.

Limits of Predictability in Ocean Weather:
Ocean weather predictions are constrained by the rapid growth of initial errors, particularly in the upper ocean. While longer-term predictions are possible for mid-depth and large-scale features, the accuracy diminishes for specific regional/coastal and seasonal events. The integration of machine learning (ML) and enhanced observational data are essential for advancing forecasting capabilities.

Distinguishing Ocean and Atmospheric Climate:
The primary distinction between ocean and atmospheric climate lies in their timescales of variability. The ocean's slower response acts as a long-term climate regulator, while the atmosphere exhibits rapid changes. Understanding these differences is crucial for accurate climate modeling and projection, especially in the context of energy and carbon cycles.

Importance of Data Acquisition:
More data are crucial for verifying and calibrating models, improving data assimilation, and understanding fine-scale processes. Acquiring data through satellite observations, in-situ measurements, and advanced instruments is essential. The data can be used for model development, process studies, climate monitoring, and innovative data fusion techniques.

Value of Basin-Scale Experiments:
Basin-scale experiments have historically provided valuable insights into ocean circulation. These experiments are essential for capturing large-scale structures and dynamics. The integration of remote sensing technologies and synoptic data collection can enhance the scope and impact of these observations.

Impact of Better Ocean Models:
Improved ocean models will provide deeper insights into Earth's climate system, reduce

uncertainties in climate projections, and enhance decision-making processes. The integration of AI and advanced modeling techniques will be crucial for addressing the challenges of climate change.

Relevant References

- Haine, T. W. N., and Coauthors, 2021: Is Computational Oceanography Coming of Age?. Bull. Amer. Meteor. Soc., 102, E1481–E1493, https://doi.org/10.1175/BAMS-D-20-0258.1.
- Zhang, Y. S., et al. (2024), Debunking common myths in coastal circulation modeling, Ocean Model., 190, 19, doi:10.1016/j.ocemod.2024.102401.
- Jacox, M. G., M. A. Alexander, S. Siedlecki, K. Chen, Y. O. Kwon, S. Brodie, I. Ortiz, D. Tommasi, M. J. Widlansky, D. Barrie, A. Capotondi, W. Cheng, E. Di Lorenzo, C. Edwards, J. Fiechter, P. Fratantoni, E. L. Hazen, A. J. Hermann, A. Kumar, A. J. Miller, D. Pirhalla, M. P. Buil, S. Ray, S. C. Sheridan, A. Subramanian, P. Thompson, L. Thorne, H. Annamalai, K. Aydin, S. J. Bograd, R. B. Griffis, K. Kearney, H. Kim, A. Mariotti, M. Merrifield, and R. Rykaczewski (2020), Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments, Prog. Oceanogr., 183, 23, doi:10.1016/j.pocean.2020.102307.
- Mogen, S. C., N. S. Lovenduski, S. Yeager, L. Keppler, J. Sharp, S. J. Bograd, N. C. Quiros, E. Di Lorenzo, E. L. Hazen, M. G. Jacox, and M. P. Buil (2023), Skillful Multi-Month Predictions of Ecosystem Stressors in the Surface and Subsurface Ocean, Earth Future, 11(11), 15, doi:10.1029/2023ef003605.

Question 1) What are the inadequacies of current ocean models?

Realism and Observational Data

- **Tidal Forcing and Internal Wave Field:** Current models often lack proper tidal forcing, which is crucial for accurately representing the internal wave field. This gap highlights the importance of integrating accurate tidal dynamics, as emphasized by Bryan Arbic's work.
- **Lack of High-Resolution Observations:** There is a scarcity of observational data to monitor and validate the realism of Ocean General Circulation Models (OGCM) at very high resolutions. This limits the models' accuracy and predictive capabilities.

Computational and Methodological Challenges

- **Multi-Scale Approach with AI Downscaling:** The need to advance multi-scale approaches, including AI downscaling techniques, is critical for improving model accuracy across different spatial scales.

- **Parametrizations:** Many ocean processes, such as double diffusion and air-sea interaction fluxes, require more advanced parametrizations. The progress in these areas has been slow, affecting the models' ability to simulate complex ocean dynamics accurately.
- **Resolution and Computing Power:** Increasing the resolution of models at basin and global scales is challenging due to the limitations of current computational resources. The transition to exascale machines, which differ significantly from existing petascale computers, is necessary for future advancements.

<u>Ocean-Specific Challenges</u>

- **Complex Ocean Dynamics:** Unlike atmospheric models, ocean models must account for complex phenomena like salinity effects, sea ice dynamics, and biological processes. These factors add layers of complexity that are not as prevalent in atmospheric modeling.
- **Finer Scale Processes:** Oceanic processes, such as eddy dynamics and thin stratified layers like the pycnocline and mixed layer, require high vertical and horizontal resolution. The horizontal eddy parameterization, particularly at mesoscale and submesoscale levels, remains a significant challenge.

<u>Fundamental Issues and Practical Considerations</u>

- **Spurious Diapycnal Mixing:** This long-standing issue arises from discretization errors, leading to artificial sources of energy and other properties. The use of isopycnal and ALE coordinates has helped mitigate this problem but introduces complexities in model analysis.
- **Digital Elevation Map (DEM) Representation:** The accurate representation of digital elevation maps is fundamental to modeling estuaries and coastal areas. Inaccuracies in DEM can significantly impact the reliability of model outputs. Additionally, uncertainties in boundary conditions, such as tidal and river inputs, pose challenges for defensible modeling.

<u>Summary</u>

Overall, while numerical ocean modeling has made significant progress and is increasingly capable of realistic simulations, several inadequacies remain. These include the need for better tidal forcing representation, improved observational data, advanced parametrizations, increased resolution, and addressing fundamental issues like DEM representation and spurious diapycnal mixing. Future efforts must focus on these areas to enhance the accuracy and reliability of ocean models.

Question 2) What are the consequences?

Shift from Process-Oriented to Statistical Studies

Due to limitations in accurately simulating specific ocean processes, there is a trend towards relying on statistical studies of multi-model ensembles. This shift prioritizes understanding broad patterns and trends over detailed process-oriented research. While this approach provides valuable insights into general ocean behavior, it may overlook critical nuances of individual processes.

Barriers to Data Access and "Democratizing the Data"

The limited dissemination and accessibility of OGCM simulation outputs hinder broader scientific collaboration and application. Lowering these barriers is crucial to democratize the data, enabling a wider range of researchers and stakeholders to utilize high-quality ocean model outputs. This democratization would facilitate more comprehensive analyses, foster innovation, and enhance the overall understanding of ocean systems.

Challenges in Optimal Estimation and Data Assimilation

The complexities associated with high-resolution models make optimal estimation and data assimilation challenging. These challenges impede the accurate integration of observational data with model simulations, which is vital for producing reliable forecasts and reanalyses. The suggestion to use ensembles of reanalyses as a practice reflects the recognition that single-model outputs may not adequately capture the "true ocean." An ensemble approach can provide a more robust representation by accounting for uncertainties and variabilities across different models.

Summary

The consequences of the current inadequacies in ocean models include a reliance on statistical studies over detailed process-oriented analyses, the need for more accessible and democratized data, and the challenges in accurately estimating and assimilating data into high-resolution models. These issues underscore the importance of continued advancements in ocean modeling and data dissemination practices to improve our understanding and predictive capabilities of ocean systems.

Question 3) What are the limits of predictability in ocean weather?

Error Doubling Time

Ocean weather predictions, particularly at mesoscale or eddy-permitting resolutions, exhibit a doubling time of initial errors ranging from 5 to 7 days in the upper ocean. This indicates that the accuracy of predictions deteriorates significantly after this period due to the growth of small errors. In the deep ocean, the error doubling time is longer, but it remains less understood. This concept traces back to Lorenz's theory of error growth in chaotic systems, which remains foundational in evaluating forecasting skill.

Predictability Horizons

- **Upper Ocean and Submesoscale Features**: Predictability for upper ocean fronts, submesoscale processes, and applications like oil spill response and search and rescue operations is typically on the order of days. The short predictability horizon reflects the rapid evolution of these fine-scale features.
- **Mid-Depth and Large Scales**: For mid-depth ocean features and large-scale patterns, predictability extends to about a month. This longer horizon is due to the slower evolution of these features compared to the highly dynamic upper ocean.
- **Regional Variability and Long-Term Forecasts**: Regional features, such as subpolar gyre dynamics and Kuroshio variability, can have predictability on the scale of multiple years. However, predicting specific events within these regions remains challenging. The predictability of large-scale phenomena like ENSO is theoretically around 18 months, but in practice, models struggle to provide reliable forecasts beyond 9 months due to the "spring barrier," a period of reduced predictability.
- **Subsurface Water Masses and Decadal Predictions**: Emerging evidence suggests that subsurface water mass advection can result in skillful decadal predictions in upwelling systems, such as the California Current System and the Gulf of Alaska subpolar gyre. This is particularly relevant for biogeochemical variables like pH and oxygen, providing valuable forecasts for ecosystem services.

Machine Learning and New Observations

The integration of machine learning (ML) techniques into ocean weather forecasting is becoming increasingly feasible and is expected to become more prevalent. ML approaches offer potential improvements in prediction accuracy, especially when combined with traditional models. However, the availability of high-quality observational data is crucial for reducing uncertainties in initial conditions and atmospheric forcing. Enhanced observation networks and asynchronous forecasting methods are needed to improve the accuracy and reliability of predictions.

Seasonal Forecasting Limitations

Despite advances in modeling and ML, seasonal forecasts, such as NOAA's hurricane or ENSO forecasts, remain the most reliable long-term predictions. These forecasts offer reasonable confidence levels due to the inherently stochastic nature of atmospheric and oceanic turbulence, which imposes fundamental limits on predictability. The chaotic nature of these systems constrains the accuracy of forecasts, even with advanced techniques and data assimilation.

Summary

The predictability of ocean weather is constrained by the rapid growth of initial errors, especially in the upper ocean and submesoscale processes. Longer-term predictions are possible for mid-depth and large-scale features, though accuracy diminishes for specific regional and seasonal events. Subsurface water mass advection, particularly in upwelling systems such as the California Current System and the Gulf of Alaska subpolar gyre, shows promising potential for skillful decadal predictions. This capability extends notably to biogeochemical variables like pH and oxygen, offering critical forecasts for ecosystem services. While advances in machine learning and observational data are crucial for enhancing forecasting capabilities, fundamental limitations due to the chaotic nature of ocean and atmospheric systems persist, challenging the precision of predictions.

Question 4) How to distinguish between ocean and atmospheric climate?

Timescales of Variability

The primary distinction between ocean and atmospheric climate lies in their respective timescales of variability. The atmosphere exhibits rapid changes on timescales from hours to weeks, while the ocean's response is generally slower, with significant variability occurring over months to centuries. This difference in timescales is crucial for understanding and predicting climate phenomena, as the ocean's slower response acts as a long-term climate regulator.

Statistical Properties of Flows

To differentiate between oceanic and atmospheric climates, it is essential to analyze the statistical properties of the respective flows. The atmosphere and ocean have distinct flow characteristics due to their different physical properties and boundary conditions. Understanding these statistical differences helps in modeling and predicting climate behavior across the two systems.

Asynchronous Coupling and Downscaling

One approach to better understand and project ocean and atmospheric climates is through asynchronous coupling, where the ocean and atmosphere are simulated at different time steps. This method allows for longer simulations of the ocean, capturing its slower response timescales. Additionally, ocean climate downscaling can be employed to refine projections at regional scales, offering more detailed insights into specific climate impacts.

Stochastic Forcing and Noise Spectrum

Another way to distinguish between ocean and atmospheric climate is by considering the systems as stochastically forced. The noise spectrum, or the range of frequencies of random fluctuations, differs between the atmosphere and ocean. The atmosphere typically experiences higher frequency variations, while the ocean is influenced by lower frequency, longer-term variations. This difference in noise spectrum affects how each system responds to external forcing and contributes to climate variability.

Role in Predictability and Climate Change Projections

The ocean plays a pivotal role in predictability across subseasonal to decadal timescales. It is integral to understanding energy and carbon uptake, which are critical for projecting climate change impacts, such as the Transient Climate Response to Emissions (TCRE) and Zero Emissions Commitment (ZEC). The ocean's ability to store and redistribute heat and carbon makes it a key component in the Earth's climate system, influencing long-term climate stability.

Summary

The distinction between ocean and atmospheric climate is primarily based on their different timescales of variability, statistical properties of flows, and responses to stochastic forcing. While the atmosphere exhibits rapid changes, the ocean acts as a slower, long-term regulator of climate. Understanding these differences is essential for accurate climate modeling and projection, particularly in the context of energy and carbon cycles. Asynchronous coupling and downscaling are valuable methods for exploring these distinctions and enhancing the accuracy of climate forecasts.

Question 5) How would more data help? How would you acquire it? How would you use it?

How More Data Would Help

1. **Model Verification and Calibration**:
   Additional observational data are crucial for verifying and calibrating numerical ocean models. These data allow for continuous assessment of model accuracy, ensuring that simulations align with real-world observations. This process helps refine model parameters and improve the overall reliability of predictions.

2. **Data Assimilation**:
   Enhanced data availability supports more robust data assimilation processes, which integrate observational data into models to produce more accurate forecasts. By continuously updating models with real-time data, the uncertainty in predictions can be significantly reduced, leading to more reliable outputs.
3. **Understanding Fine-Scale Processes**:
   Increased data, particularly from new and advanced observation technologies, can provide insights into fine-scale processes such as mesoscale and submesoscale ocean dynamics. Understanding these small-scale features is vital for accurately simulating oceanic phenomena, including currents, eddies, and air-sea interactions.

How to Acquire More Data

1. **Satellite Observations**:
   Expanding satellite observation capabilities is essential. This includes follow-on missions to existing satellites like MODIS, GRACE-FO, and SWOT, and the deployment of more advanced instruments such as VIIRS for high-frequency monitoring. Satellite data provide comprehensive coverage of the ocean surface, capturing crucial variables like sea surface temperature (SST), surface currents, and wave heights.
2. **In-Situ Observations**:
   Increasing the density of Argo profiling floats is a key strategy. By deploying more floats, the spatial resolution of temperature and salinity profiles can be improved, enabling better resolution of mesoscale features. Additionally, deploying low-cost coastal and deep ocean observational platforms and multi-disciplinary observatories can provide detailed data from the surface to the deep ocean.
3. **Advanced Instruments and Experiments**:
   Utilizing modern scatterometer/doppler combinations can revolutionize our understanding of lateral variations and waves on air-sea fluxes. Instruments capable of providing high-resolution, meter-scale observations of surface currents, SST, and waves are particularly valuable. Experiments like S-MODE demonstrate the potential of such technologies in capturing complex oceanographic processes.
4. **Remote Sensing Below Surface**:
   Emerging remote sensing technologies that can observe below the ocean surface are promising. These technologies can provide crucial data on subsurface processes, which are often challenging to measure. They can aid in understanding vertical structure and mixing in the ocean, essential for comprehensive climate modeling.

How to Use the Data

1. **Model Development and Refinement**:
   The acquired data can be used to refine and develop more accurate ocean models. By incorporating detailed observational data, models can better capture the complexity of ocean systems, leading to more accurate simulations and forecasts.
2. **Process Studies and Analysis**:
   Data from various sources can be used to study specific oceanographic processes, such as ocean circulation, heat transport, and biological productivity. Detailed analysis of these processes can improve our understanding of ocean dynamics and inform the development of new parameterizations in models.
3. **Climate Monitoring and Prediction**:
   Continuous and comprehensive data collection is vital for monitoring climate change and predicting its impacts. High-quality observational records are essential for tracking long-term trends, such as ocean warming, sea level rise, and changes in ocean circulation patterns.
4. **Data Assimilation and Fusion**:
   Advanced data assimilation techniques and fusion methods, like those used in digital twins, can integrate diverse data streams into a unified framework. This approach enhances model accuracy and provides a more comprehensive understanding of ocean and climate systems.

Summary

More data can significantly enhance the verification, calibration, and accuracy of ocean models, improve our understanding of fine-scale processes, and support robust data assimilation. Acquiring this data requires expanding satellite observations, increasing in-situ measurements, and leveraging advanced technologies. The data can be used for model development, process studies, climate monitoring, and innovative data fusion techniques, ultimately leading to more reliable ocean and climate predictions.

Question 6) Would a basin-scale experiment be valuable?

Historical Success and Understanding General Circulation

Basin-scale experiments have previously proven valuable, as demonstrated by efforts in the Mediterranean. Such experiments provided a comprehensive snapshot of the general circulation, allowing researchers to understand the basic structures and dynamics at a large scale. This foundational knowledge marked a new era in oceanography, highlighting the importance of basin-wide observations.

Synoptic Data Collection

To maximize the value of a basin-scale experiment, it's crucial to ensure that data collection is nearly synoptic. This means gathering data within short timeframes (ideally on a monthly basis) to accurately capture the state of the ocean. Achieving this requires the coordinated use of multiple ships and instruments across different regions of the basin, allowing for comprehensive mapping of both large-scale and eddy-scale circulations.

Complementary Observational Strategies

While a short-term basin-scale observational campaign can provide valuable insights, its utility might be limited compared to long-term repeat sections. Repeat sections are essential for capturing temporal variability and understanding long-term changes. However, specific exceptions, such as subsurface carbon measurements (including pH and alkalinity), could greatly benefit from a concentrated effort within a basin-scale experiment.

Global and Multi-Scale Approach

There is a strong argument for extending the scope of basin-scale experiments to a global scale, particularly with advancements in remote sensing technology. Modern techniques allow for high-resolution observations across a wide range of scales, providing detailed information that was previously inaccessible. Emphasizing remote sensing over smaller-scale ship-based surveys could optimize resource allocation and enhance the breadth of data collection.

Recommendations for Implementation

For a basin-scale experiment to be successful, it should:

- Utilize a combination of remote sensing and in-situ measurements.
- Ensure synoptic data collection to provide a coherent snapshot of the ocean.
- Focus on key measurements, including both physical and biogeochemical parameters.
- Consider repeat observations to capture temporal changes and trends.

Summary

A basin-scale experiment is highly valuable for advancing our understanding of ocean circulation and dynamics. Such experiments offer critical insights into large-scale oceanographic structures and can serve as a benchmark for future studies. While focused efforts within a basin can yield significant benefits, extending the approach to a global scale with an emphasis on remote sensing technologies can further enhance the scope and impact of these observations.

Question 7) If better models are accomplished – what difference would it make?

Impact of Better Ocean Models

Enhanced Understanding of the Earth System

Improved numerical models will provide deeper insights into the fundamental processes governing the Earth's climate system. They will be valuable for simulating a range of scenarios, from idealized cases to realistic conditions, including ice-age simulations. These models can elucidate mechanisms such as ocean heat and carbon uptake, which are crucial for understanding the Earth's energy balance and carbon cycle.

Accessibility and Usability for Researchers

With advancements in model accessibility, particularly through cloud-based platforms, better models will be more readily available to young researchers. This ease of access will facilitate their use in a variety of scientific inquiries, allowing for more rapid setup and application. As a result, the next generation of scientists can engage with complex simulations more efficiently, fostering innovation and exploration in oceanography and climate science.

Reducing Uncertainty in Climate Projections

Improved models can reduce the spread in climate projections, particularly in metrics like the Transient Climate Response to Emissions (TCRE). The accurate representation of ocean heat and carbon uptake, which account for a significant portion of model uncertainty, will refine our understanding of climate sensitivity and potential future scenarios. This is crucial for assessing the rapid surface warming observed in recent years and understanding the coupled processes between the atmospheric and oceanic boundary layers.

Improved Predictions and Decision-Making

As climate change progresses, better ocean models will enhance weather and seasonal predictions in maritime climates. This includes more accurate forecasts of phenomena such as El Niño and hurricanes. Additionally, improved decadal predictions will be instrumental in long-term planning and adaptation strategies, particularly for coastal communities and industries reliant on ocean conditions.

Integration with AI and Decision Support

The integration of traditional modeling techniques with artificial intelligence (AI) will further enhance the capability of models. These advanced models will play a critical role in decision-making processes, providing valuable information to policymakers and agencies. This can influence a wide range of areas, from resource management and disaster preparedness to environmental policy and international agreements.

Summary

Better ocean models will significantly impact our understanding of the Earth system, particularly in terms of heat and carbon dynamics. They will also democratize access to advanced modeling tools for researchers, reduce uncertainties in climate projections, improve short- and long-term predictions, and support critical decision-making processes. As a result, these models will be indispensable in addressing the challenges of climate change and advancing ocean science.

Specific Questions from Last Revision

Below are answers to the latest version of the questions. These answers have been rewritten based on the material presented above. Given the time already spent answering the questions earlier, and in the interest of efficiency, I used ChatGPT to summarize the material again within the context of the new questions layout.

Climate & Ocean Models

Question: What are the inadequacies of current models?
Current ocean models face several key inadequacies. Firstly, they often lack proper tidal forcing, which is crucial for accurately representing the internal wave field. This inadequacy can lead to misrepresentations in ocean dynamics. Additionally, there is a scarcity of high-resolution observational data, which limits the ability to monitor and validate Ocean General Circulation Models (OGCMs) at very fine scales. Computational and methodological challenges also persist, such as the need for a multi-scale approach and advanced parametrizations to accurately simulate processes like double diffusion and air-sea interaction fluxes. Furthermore, the resolution of models at basin and global scales is constrained by current computational resources, and ocean-specific challenges like salinity effects, sea ice dynamics, and the accurate representation of fine-scale processes like eddy dynamics remain significant hurdles. Fundamental issues such as spurious diapycnal mixing and inaccuracies in Digital Elevation Map (DEM) representation further complicate model accuracy.

Question: What are the consequences?
The limitations in current ocean models have led to several consequences. A major shift has occurred from process-oriented studies to statistical analyses of multi-model ensembles, prioritizing broad patterns and trends over detailed process-level understanding. This shift may overlook critical nuances of individual processes. Additionally, barriers to data access hinder broader scientific collaboration, as the limited dissemination of OGCM simulation outputs restricts the ability of researchers and stakeholders to utilize these data effectively. The challenges in optimal estimation and data assimilation further complicate efforts to integrate observational data with model simulations, which is crucial for accurate forecasting. These issues underscore the necessity for democratizing data access and improving data assimilation techniques to enhance model reliability and the broader understanding of ocean systems.

Question: If better models are accomplished, what difference would it make?
The development of better ocean models would have a profound impact on multiple fronts. Enhanced models would provide deeper insights into fundamental processes governing the Earth's climate system, such as ocean heat and carbon uptake, which are crucial for understanding the Earth's energy balance and carbon cycle. Improved accessibility and usability of these models, especially through cloud-based platforms, would democratize research opportunities, allowing a

broader range of scientists, including young researchers, to engage with complex simulations. This would foster innovation and exploration in oceanography and climate science. Better models would also reduce the spread in climate projections, particularly regarding metrics like the Transient Climate Response to Emissions (TCRE). More accurate representations of oceanic processes would help clarify uncertainties in climate sensitivity and future scenarios, aiding in the assessment of rapid surface warming and coupled atmospheric-oceanic interactions. Additionally, improved models would enhance predictions of ocean and weather phenomena, such as El Niño and hurricanes, and support long-term planning and adaptation strategies, particularly for coastal communities. The integration of AI with traditional modeling techniques would further bolster the utility of these models in decision-making processes across various domains, including resource management and environmental policy.

Problems Unique to Ocean vs Atmosphere

Question: What are the limits of predictability in ocean weather forecasting?
Predictability in ocean weather forecasting is limited by the rapid growth of initial errors, especially in the upper ocean. The error doubling time, which indicates the period after which errors grow significantly, typically ranges from 5 to 7 days in the upper ocean. This rapid error growth is more pronounced at mesoscale or eddy-permitting resolutions. For mid-depth ocean features and large-scale patterns, predictability extends to about a month due to slower evolution. However, specific regional and seasonal events have shorter predictability horizons, often just a few days. While there is potential for skillful decadal predictions in upwelling systems, the chaotic nature of ocean and atmospheric systems imposes fundamental limits on the accuracy and duration of forecasts.

Question: How to distinguish between ocean and atmospheric climate?
The primary distinction between ocean and atmospheric climate lies in their timescales of variability. The ocean has a slower response to changes, with significant variability occurring over months to centuries, whereas the atmosphere exhibits rapid changes from hours to weeks. This slower oceanic response makes it a long-term climate regulator. Additionally, the statistical properties of oceanic and atmospheric flows differ due to the distinct physical properties and boundary conditions of each system. The ocean tends to have lower frequency variations, while the atmosphere is characterized by higher frequency fluctuations. Understanding these differences is crucial for accurate climate modeling, especially in the context of energy and carbon cycles.

Question: Data transmission, computation and storage challenges
Ocean modeling faces significant challenges in data transmission, computation, and storage. The vast amounts of data generated by high-resolution models require efficient transmission systems and substantial computational power. The transition to exascale computing is necessary to handle the increased resolution and complexity of modern ocean models. Additionally, the storage requirements for extensive observational and model data are substantial, necessitating advanced data management systems.

Question: Monitoring the deep ocean
Monitoring the deep ocean presents unique challenges due to the difficulty in accessing and maintaining observational instruments at great depths. The scarcity of high-quality observational data from the deep ocean limits the understanding of deep-sea processes and their role in the global climate system. Advanced technologies and innovative observation strategies are required to improve deep ocean monitoring capabilities.

Acquisition of Data

Question: How would more data help?
More data would significantly improve the verification and calibration of ocean models, ensuring that simulations align with real-world observations. This process helps refine model parameters and enhances the overall reliability of predictions. Additionally, increased data availability supports more robust data assimilation processes, integrating observational data into models to produce more accurate forecasts. Understanding fine-scale processes, such as mesoscale and submesoscale dynamics, would also benefit from enhanced data, leading to more accurate simulations of oceanic phenomena.

Question: How would you acquire it?
Data can be acquired through various means, including satellite observations and in-situ measurements. Expanding satellite capabilities with missions like MODIS, GRACE-FO, and SWOT can provide comprehensive ocean surface coverage. Increasing the density of Argo profiling floats will improve spatial resolution for temperature and salinity profiles. Advanced instruments, such as modern scatterometers and doppler combinations, can provide high-resolution observations of surface currents, SST, and waves. Emerging technologies for remote sensing below the surface are also promising for capturing subsurface processes.

Question: How would you use it?
Acquired data can be used to refine ocean models, enhancing their accuracy and reliability. It can support process studies, providing detailed insights into ocean dynamics and informing the development of new model parameterizations. Data are also crucial for climate monitoring, tracking long-term trends such as ocean warming and sea level rise. Additionally, advanced data assimilation techniques and data fusion methods, like digital twins, can integrate diverse data streams into a unified framework, improving model accuracy and providing a comprehensive understanding of ocean and climate systems.

Integration and Management of the Data

Question: Data assimilation
Data assimilation involves integrating observational data into numerical models to improve forecast accuracy. This process is vital for reducing uncertainties and enhancing the reliability of model

outputs. By continuously updating models with real-time data, the accuracy of predictions can be significantly improved, leading to more reliable forecasts and analyses.

Question: Machine learning interpolation processes
Machine learning (ML) interpolation processes offer potential improvements in ocean modeling by providing advanced techniques for data analysis and model development. ML can interpolate between sparse data points, offering improved estimates of oceanic variables and helping to fill gaps in observational data. The integration of ML with traditional models can enhance the predictive capabilities and accuracy of ocean forecasts.

<u>Modalities – Sensors, Sensor Platforms</u>

Question: What Coverage is needed? Depth? Area? Time?
Comprehensive coverage across various depths, large areas, and time scales is essential to capture the full spectrum of oceanic processes. This includes monitoring from the surface to the deep ocean, covering vast oceanic regions, and ensuring temporal resolution that can capture both short-term and long-term variability.

Question: What is the required precision of the measurements?
High precision is required for measurements, particularly for key parameters like temperature, salinity, and currents. Accurate data are essential for reliable modeling and analysis, especially in resolving fine-scale features like eddies and fronts.

Question: Would a basin-scale demonstration be valuable? If so, what would it look like?
A basin-scale demonstration would be highly valuable for advancing the understanding of ocean circulation and dynamics. It would involve coordinated synoptic data collection, using multiple ships and instruments across different regions to provide comprehensive mapping of large-scale and eddy-scale circulations. Such an experiment should include both remote sensing and in-situ measurements, focusing on capturing key physical and biogeochemical parameters at high resolution. The experiment would ideally involve repeat observations to capture temporal variability and long-term trends, providing a benchmark for future studies and improving model validation and calibration efforts.

Appendix 2A – Colosi Concept Paper

Sensing of ocean bottom boundary layer turbulence via acoustic scintillation observations

John Colosi, Senior Scientist, Woods Hole Oceanographic Institution

Diapycnal mixing, that is mixing across density surfaces is a fundamental process impacting buoyancy fluxes that not only drive the ocean general circulation showing manifestation is climatic variations of heat and salt but is also a key process in the transport of nutrients and other chemical compounds important to ocean organisms. In the deep ocean bottom boundary layer, there is growing interest in the connection between turbulence driven buoyancy fluxes and the ocean general circulation. In particular, these fluxes have important implications for the upwelling of Antarctic Bottom Water and subsequent diapycnal mixing with the warmer near surface waters at mid latitudes driving the thermohaline circulation and setting the stratification.

To date sensing of ocean mixing has advanced greatly with an array of profiling and moored instrumentation based on either rapid temperature measurements, shear probes, or small high frequency reciprocal acoustic devices. Under proper conditions even ADCPs can sense turbulent mixing in a small test volume. These point measurements have revealed important aspects of mixing from coastal environments to the deep ocean boundary layers (upper and lower) and main thermocline, but are limited because of under sampling of the anisotropic, inhomogeneous, and intermittent nature of ocean mixing processes. This DARPA Advanced Research Concepts (ARC) topic seeks to develop Bottom Boundary Layer Acoustic (BBLA) sensing technology that can provide continuous monitoring of BBLs over an area of order 1-10 km radius. Used with other turbulence sensing technologies BBLA would provide a more complete description of the BBL processes including tidal forcing, internal wave breaking and swash, and the largest turbulent eddies.

The remote sensing system is based on wave propagation through random media weak fluctuation theory (Colosi, 2016; Ostashev and Wilson 1997) and a variant of this approach has been used to quantify mixing in a strongly forced tidal channel (DiOrio and Farmer 1994 and 1998). In the tidal channel, a time series of scintillation was used with the perpendicular channel flow to convert to a wavenumber spectrum identifying the range average turbulence properties according to Kolmogorov and Batchelor's famous models. In the boundary layer case, a vertical acoustic array will be used so that a wavenumber spectrum can be obtained directly without using the Taylor Hypothesis. The acoustic scintillation wavenumber spectrum will give range average information about the time scales of the smallest scale internal waves and the largest turbulent eddies. The challenges in developing such an acoustic system are to achieve accurate array timing and navigation and to build hydrophone arrays capable of quantifying weak scintillation patterns with intensity fluctuations of order a few dB.

References

1. Colosi, J.A., 2016. *Sound propagation through the stochastic ocean*. Cambridge University Press.
2. Ostashev, V.E. and Wilson, D.K., 1997. *Acoustics in moving inhomogeneous media* (p. 259). London: E & FN Spon.
3. Di Iorio, D. and Farmer, D.M., 1994. Path-averaged turbulent dissipation measurements using high-frequency acoustical scintillation analysis. *The Journal of the Acoustical Society of America*, *96*(2), pp.1056-1069.
4. Di Iorio, D. and Farmer, D.M., 1998. Separation of current and sound speed in the effective refractive index for a turbulent environment using reciprocal acoustic transmission. *The Journal of the Acoustical Society of America*, *103*(1), pp.321-329.

Appendix 2B – Edmondson SmallSat Capabilities

Leveraging Small Satellite (SmallSat) Capabilities to conduct Short-to-Long Term Ocean Monitoring
Marquay Edmondson

There is a significant challenge in forecasting Earth's climate change, which requires extensive periodic data that is currently limited on a global scale to measure the current values of and characteristic changes in our oceans accurately. In addition, this includes the importance of integrating innovative technology with science applications to solve our long-term problem in ocean monitoring and health. Measuring, monitoring, and collecting data against Earth's systems consist of a multitude of atmospheric processes and interactions that occur on various, complex modeling systems. These interactions aBect surface temperature, sea level, etc., across land and maritime ecosystems—producing various models, products, and sensory output over a vast range of spatial and temporal scales.[1]

However, there is a long-term and more sustained approach for climate change monitoring and forecasting: the adoption of SmallSat technology. This technology presents new opportunities for extended dwell-time forecasting and provides more mission opportunities to the Department of Defense (DOD), commercial organizations, and most importantly, the science community. This capability dependent on the sensor payload and employment improves spatial and temporal coverages while closing scientific and data-return gaps hindered by larger traditional satellites. Figure 1 depicts spatial coverage of an eight-satellite constellation after twenty-four hours. This shows the capability incorporated with the right communication-data infrastructure on Earth to support a low data latency for real-time delivery of ocean data across large distances.

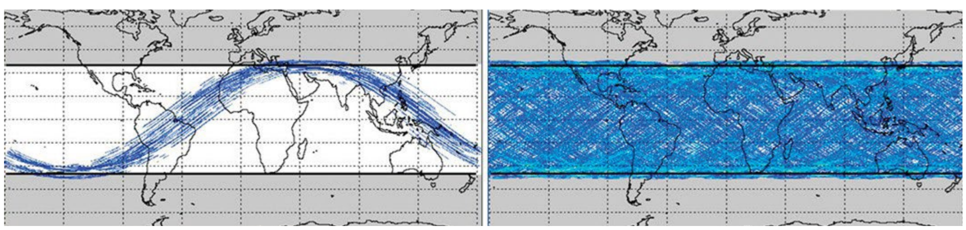


FIGURE 1 Spatial coverage provided by the eight-satellite CYGNSS constellation after ninety-five minutes, or one orbit (left) and after twenty-four hours (right). The mean revisit time of samples within its coverage range of +/– 38 degrees latitude is seven hours.[2]

Currently, oceanographic data is being collected by larger-scale satellites equipped with altimeter sensors such as the Jason series systems. These sensors collect ocean surface data for climate change, ocean circulation, or sea level rise.[3] Moreover, SmallSats can satisfy similar requirements with sensors capable of delivering multiple observations across specified areas. However, for larger areas such as the

---

[1] National Academies of Sciences, Engineering, and Medicine, National Academies of Sciences, Engineering, and Medicine (U.S.), Committee for the Assessment of Partnership Options for a Small Satellite System for Collecting Scientific Quality Oceanic and Coastal Data, National Academies of Sciences, Engineering, and Medicine (U.S.), Intelligence Community Studies Board, and National Academies of Sciences, Engineering, and Medicine (U.S.). Division on Engineering and Physical Sciences, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=7013910.

[2] Ibid.

[3] Margaret Srinivasan and Vardis Tsontos, "Satellite Altimetry for Ocean and Coastal Applications: A Review," *Remote Sensing* 15, no. 16 (2023): 3939. https://doi.org/10.3390/rs15163939.

oceans, SmallSats deployed as a constellation may be more optimal due to continuous global coverage of multi-source remote sensing opportunities and data collection over a period of time.[4] [5] In space, SmallSats can operate in the same orbit and provide temporal resolution coverage at various times in the day over a given area—whereas SmallSats operating in diBerent orbits can acquire data more frequently and cover more area across the ocean surface.[6]

The data integration approach for commercial and legacy space-based capabilities presents a new program by the Defense Innovation Unit (DIU) known as hybrid space architecture (HSA)—information-based architecture and framework that delivers SmallSat sensor data and capabilities on a larger scale with optimal orbital coverage to enhance scientific study for the oceans and coastal regions.[7] Traditional users range from the National Reconnaissance OBice (NRO), DOD, and National Aeronautics and Space Administration (NASA), to the National Oceanic and Atmospheric Administration (NOAA). This opens the space-based ecosystem door for scientific study and data discovery for nontraditional users. The HSA framework, likely in its initial phases, is a multi-layer information-based architecture that can incorporate and disseminate low-latency data and communications from SmallSat sensors across commercial and DOD domains according to DIU reporting.[8] [9]

Last, a limitation to consider in ocean remote sensing technology for SmallSats across multiple orbital regimes is the penetration capability into our Earth's oceans. According to Emery and Camps, certain satellite sensors cannot penetrate very far into the ocean. They stated:

> Satellite altimeters measure the ocean's surface and its variations and therefore reflect a vertical integral, but still the altimetric signal does not penetrate into the interior of the ocean. Ocean color

---

[4] L. Wang, Tianbiao Yang, Xuekuan Li, and Genqin Li. 2020. "Design of Hainan Satellite Constellation and Applications for Ocean Observations." *IOP Conference Series: Earth and Environmental Science* 502 (May): 012002. https://iopscience.iop.org/article/10.1088/1755-1315/502/1/012002.

[5] A. G. C. Guerra, F. Francisco, J. Villate, F. A. Angelet, O. Bertolami, and K. Rajan, "On Small Satellites for Oceanography: A Survey," *Acta Astronautica* 127 (2016): 404–23, https://doi.org/10.1016/j.actaastro.2016.06.007.

[6] National Academies of Sciences, Engineering, and Medicine, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://doi.org/10.17226/26380.

[7] Nicolo Boschetti, Johan Sigholm, Mattias Wallen, and Gregory Falco, "A Hybrid Space Architecture for Robust and Resilient Satellite Services," 2023 IEEE 9th International Conference on Space Mission Challenges for Information Technology (SMC–IT), Space Mission Challenges for Information Technology (SMC–IT), 2023 IEEE 9th International Conference on SMC–IT, July, 14–22. https://doi.org/10.1109/SMC-IT56444.2023.00021.

[8] National Academies of Sciences, Engineering, and Medicine, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://doi.org/10.17226/26380.

[9] Nicolo Boschetti, Johan Sigholm, Mattias Wallen, and Gregory Falco, "A Hybrid Space Architecture for Robust and Resilient Satellite Services," 2023 IEEE 9th International Conference on Space Mission Challenges for Information Technology (SMC–IT), Space Mission Challenges for Information Technology (SMC–IT), 2023 IEEE 9th International Conference on SMC–IT, July, 14–22. https://doi.org/10.1109/SMC-IT56444.2023.00021.

> may penetrate a few tens of meters into the upper layer of the ocean, but that is about the deepest any spaceborne sensor penetrates into the ocean.[10]

Based on this statement, another approach is measuring the ocean's temperature, which may help close the data deficit on the assessing the interior dynamics of the ocean. Measuring the temperature of our oceans with SmallSat capabilities likely provides key estimates for the temperature of the earth, thus helping to improve our analysis of climate change and prediction modeling. Some baseline satellite sensor technology designed to measure ocean temperature produces sea surface temperature (SST) and synthetic aperture radar data.[11] SmallSat constellations equipped with these key multi-source sensors can collect SST data through satellite microwave radiometers and infrared radiometers. Moreover, SST data measured from space can provide key ocean depth measurements based on specified satellite instrumentation, resulting in various application opportunities and products that represent temperatures at diBerent depths.[12]

Additional Information[13]
Information Pipeline (Data):
NASA Commercial SmallSat Data Acquisition (CSDA) Program
European Center for Medium-Range Weather Forecasting (ECMWF)
NOAA Commercial Data Program ODice

Initial Goals of Hybrid Space Architecture (HSA):
Exploitation of overhead imagery
Communications architecture
Beyond line-of-sight situational awareness
Internet-of-things sensors and edge processing

Current Stakeholders:
Defense Innovation Unit (DIU)
National Oceanic and Atmospheric Administration (NOAA)
National Oceanographic Partnership Program (NOPP)

Collaborating Stakeholders w/ Defense Innovation Unit:
United States Space Force (USSF)
USSF Space Systems Command
Space Warfighter Analysis Center (SWAC)
Air Force Research Laboratory (AFRL) Space Vehicles Directorate

---

[10] Emery, William J. 2017. *Introduction to Satellite Remote Sensing: Atmosphere, Ocean, Land and Cryosphere Applications / William Emery, Adriano Camps*. Amsterdam [etc.]: Elsevier. https://www.sciencedirect.com/book/9780128092545/introduction-to-satellite-remote-sensing.

[11] Ibid.

[12] Brasnett, Bruce. "The impact of satellite retrievals in a global sea-surface-temperature analysis." Quarterly Journal of the Royal Meteorological Society 134, no. 636 (2008): 1745-1760. https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/qj.319.

[13] National Academies of Sciences, Engineering, and Medicine, *Leveraging Commercial Space for Earth and Ocean Remote Sensing* (Washington, DC: National Academies Press, 2022), https://doi.org/10.17226/26380.

Appendix 3 – Submitted Materials & Expert Contributions

Appendix 3 provides a comprehensive list of papers and materials submitted both before and after the DARPA Ocean Sensing Roundtable. To view the corresponding files, simply click on the names of the invited experts. This section serves as a valuable resource for accessing all submitted materials related to the roundtable discussions.

Ann Kerr

Benjamin Horton

Carl Wunsch

D. Benjamin Reeder

Emanuele Di Lorenzo

Jim Bishop

John Orcutt

Kay (Kai) Gemba

Matthew Dzieciuch

Meeting Admin

Nancy Hann

Peter de Menocal

Venkatachalam (Ram) Ramaswamy