# Understanding, Modeling and Prediction

**September 6-7, 2017**

**Office of Naval Research**

**Arlington, VA**

**U.S. NAVY TASK FORCE OCEAN**
2017 SUMMER WORKSHOP SERIES

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# Background

Task Force Ocean was established on March 13, 2017, under the direction of the Chief of Naval Operations and led by the Oceanographer of the Navy, Director of Task Force Ocean. The goal of Task Force Ocean is to advance ocean science in the United States and ensure that the U.S. Navy maintains a competitive advantage in its ability to understand and exploit the ocean environment. The Task Force will assess the state of Navy-relevant ocean sciences in the U.S. and the Navy's capacity and capability to exploit new science and technology in this arena.

The Task Force charter, signed July 5, 2017, established five working groups focused on relevant aspects of its mission: 1) Sensing and Observations; 2) Understanding, Modeling and Prediction, 3) Naval Applications and Decision Aids, 4) Human Capital and Technical Workforce, and 5) Strategic Communications. These working groups are tasked with engaging federal interagency stakeholders as well as subject matter experts in government, academia and industry to develop a plan to remain ahead of our competitors in three areas: 1) Navy-relevant ocean science infrastructure, 2) the U.S. Navy's capability and capacity to understand and exploit knowledge of the ocean environment , and 3) the U.S. Navy's capability and capacity to leverage the full range of science and technology development in ocean sciences through successful transitions to operations.

The first four working groups listed above held workshops during August and September of 2017 to identify the key objectives in each focus area, actionable tasks for each objective and identify associated stakeholders and subject matter experts throughout the U.S. ocean science enterprise. This report provides a summary of the Understanding, Modeling and Prediction workshop chaired by Dr. Tom Drake, Director of the Ocean, Atmosphere & Space Research Division, Office of Naval Research.

## Executive Summary

More than 60 Subject Matter Experts from academia, the University Applied Research Centers (UARCs), the Naval Research Laboratory, the Office of Naval Research, the Office of the Chief of Naval Operations (OPNAV) & the Fleet participated in the following briefing, discussions and breakout sessions:

- Introductory Brief: The Navy's Operational Modeling Effort
- Initial Group Discussion: Assessment of current capability and limiting factors for prediction
- Breakout Session I: Forecasting thermohaline structure to understand undersea sound propagation
- Breakout Session II: Forecasting surface and sub-surface currents for ship routing, path planning for unmanned systems, and deployment of drifters, floats and sonobuoy fields
- Breakout Session III: The role of observations and data assimilation in prediction
- Breakout Session IV: Synoptic vs. probabilistic prediction in ocean/acoustic forecasting
- Breakout Session: Grand challenges for the modeling and prediction community
- Final Group Discussion: Re-envisioning the research enterprise

The workshop included scientists that are knowledgeable in observing the ocean, developing model code and data assimilation algorithms, and providing forecast models for both academic and tactical purposes. Participants engaged in interactive, facilitated breakout sessions with the goal of providing expertise on the session topics. The participants did not seek nor were they asked to generate consensus views on session topics; rather, the sessions sought to provide a broad spectrum of ideas, problems and potential solutions that were noted for future consideration by Task Force Ocean sponsors. The Understanding, Modeling and Prediction topic is inextricably connected to the other topics. Environmental models rely on *Sensing and Observations* to provide skillful future predictions, and in turn must provide actionable information for use in *Naval Applications and Decision Aids*. As a result, the following key observations and recommendations should be integrated and considered together with the outcomes of the other TFO groups.

**Key Observations:**

Naval ocean modeling and prediction capabilities fall short of present and future needs. The capability gaps fall into a number of specific areas, listed here in order from higher to lower priority:

- Ocean data
    - Environmental models provide operational utility only with observations.
    - The ocean's interior is inadequately observed to initialize, constrain and validate existing oceanographic and acoustic models.
    - In particular, essentially no local observations are gathered by operational platforms, most notably submarines.
    - Unmanned observational capabilities in areas of interest are very limited due to limited assets and limited means for deployment and recovery
    - Space-based remote sensing observations are inadequate; in particular, the single most useful observation for constraining global ocean models, sea surface height anomaly, has been neglected.

  - The U.S. has no commercial synthetic aperture radar capability to provide useful data on ocean currents, mesoscale structures and air-sea interactions at night or under clouds.

- Ocean-acoustical models
  - Coupled, data-assimilating ocean acoustics models capable of leveraging sophisticated acoustical information have been developed by the S&T community and are available for operations but have not been implemented.
  - Basic research programs have explored extensively the link between ocean processes and acoustics, but such programs have limited lifetimes and do not provide the continuum of observations to support the tactical use of ocean-acoustical models.

- Computational resources
  - Available computational resources ashore and especially afloat are inadequate to resolve ocean and acoustical features at the fidelity needed for tactical utility using existing models, especially when compared to international peers.
  - Needs include high performance computing architectures tailored to support earth system models, modern database structures, data centers, effective cloud and net services all within an information assurance framework. These needs will require significant resources.
  - Ensemble forecasts of the coupled ocean-atmosphere-wave environment are needed
  - Lack of software engineers to work hand-in-hand with ocean/acoustical scientists

In addition to modeling and prediction challenges in the ocean interior, other aspects of the ocean environment impact undersea warfare. Maintaining and advancing the Navy's environmental advantage from seafloor to space requires addressing the following areas, among others:

- Earth system prediction coupling land, ice, ocean and atmosphere phenomena
- Coupled atmosphere-space weather modeling and prediction

**Recommended Actions / Way Forward:**

- Adequately resource fundamental ocean data sources: gliders, floats, profilers, UUVs, satellites
- Request access to on-board data from Navy platforms and develop concomitant data assimilation capabilities
- Improve reach-back computational infrastructure, and
- Push data-assimilative modeling far forward
- Incorporate additional acoustical/physical phenomena into operational models
- Develop reduced order models for use in data-denied environments
- Leverage commercial space-based sensing and ocean databases
- Immerse selected academic scientists into operational oceanographic modeling problems
- Restart Tactical Oceanography Symposia and Ocean Modeling Workshops

**Stakeholders:**

Task Force Ocean modeling and prediction stakeholders include Navy and other DoD services and organizations. Specific Naval stakeholders are OPNAV N2N6E, NAVIFOR, CNMOC, NAVSEA, SPAWAR, the Naval Postgraduate School, the US Naval Academy, the Naval Research Laboratory and the Office of Naval Research. Other US Government stakeholders include the National Ocean and Atmospheric Administration, the Department of Energy, NASA, the Bureau of Ocean Energy Management, the US

Geological Survey and the National Science Foundation, and the other National Oceanographic Partnership Program agencies.

## Group Discussions: An Assessment of Current Capabilities, Limiting Factors for Prediction and Re-envisioning the Research Enterprise

**Summary:** Group Discussions were conducted at the beginning and end of the two day working group session. The initial discussion explored and assessed current capabilities and limiting factors for prediction as a way to establish a capability baseline that spanned early basic research efforts all the way to operational Navy models. These current capabilities were concurrently examined in view of limiting factors for prediction. The final group session provided an opportunity for participants to comment on the overall approach to ocean model and prediction research, and to suggest new approaches to conducting ocean research that would better satisfy Navy requirements in the future. Because many of the suggestions and comments arose in both initial and final discussion sessions, the output of the two discussions is combined below.

The following topic summaries represent the efforts of diligent volunteer note takers to aggregate far-ranging and brisk discussion.

<u>Forward Modeling and Development</u>

Discussion fell into three broad but inter-related areas: high resolution simulation, coupled modeling, and model validation and evaluation.

*High-Resolution Simulation*: A better understanding of how and when to increase model horizontal and vertical resolutions, given the shortage of computational resources, is required. Discussion led to the need to develop accurate down-scaling capabilities (one-way and two-way nesting), as well as investing in high-resolution simulations (realistic forcing) to capture the internal (gravity) wave field, spectra and geo-distribution; this is very important for acoustics and operational oceanography. The recurring theme of improved merging and assimilation of observations emerged in suggestions to develop means of combining adaptive mesh operational modules with high-resolution in-situ sensing. If uncertainty associated with models and used to generate probabilistic predictions is to be quantified, the geographical variations in wave spectra and probability density functions for sub-mesoscale turbulence and internal waves must be characterized and understood. Finally, as part of model development and implementation, documentation is required to support model output reproducibility.

*Coupled Modeling:* The relationship between spatiotemporal scales and predictability were common threads throughout this discussion. Understanding and fully characterizing the impact of the ocean on atmospheric predictability requires more accurate air-sea coupling on mesoscale and sub-mesoscales. Prediction of the complete local environment (i.e., air, undersea, sea surface, land-sea interface, land surface/hydrology) out to 5 days with horizontal resolution of ~ 100 m or less should be a goal. Coupled modeling must also involve more complete modeling systems, including physical and biochemical phenomena. The focus should be on fully-coupled multi-scale (global/mesoscale/local) weather and environmental models that are: (1) physics based and (2) statistical (i.e., ensemble modeling). Coupling of models with differing physics as well as multi-physics "unified" models that consider all aspects of the ocean environment (e.g., acoustic, RF, EO, IR, etc.) should be explored.

*Model Validation and Evaluation:* The concepts of requirements, testing and information technology architectures ran throughout this discussion. Before model evaluation can occur, operationally-relevant metrics must be identified (e.g., ocean circulation, physical and biological phenomena, ocean color, etc.). A mission-driven mapping between model type and information requirements must be established. Additionally, inter-model compatibility must be enforced to simplify and implement a comprehensive model validation approach (e.g., analytics, data comparison, model-to-model comparison, model usage definitions, what model aspects are expected to be correct?). The approach to testing can be summarized as "build-test-build" (e.g., models reconciled with data; identify missing links). To complete the testing picture, instrumenting Navy ranges is recommended to support modeling at, for example, Atlantic Undersea Test and Evaluation Center (AUTEC) or Southern California Offshore Range (SCORE), and to produce range data for assessing the quality of models under development. IT architecture considerations should include improved compression algorithms to enable transmission of large, high-resolution gridded fields and the establishment of a software/model interoperability infrastructure (e.g., standard, efficient and scalable data formats interfaces).

<u>Observations and Sensing</u>

Observations and sensing concerns and suggestions were addressed in the Modeling and Prediction Workshop as well as the workshop dedicated to that topic. The emphasis here was on the use of observations to improve prediction via assimilation into models.

Design and selection of observing systems must be appropriate to the scales of the problem at hand. Spatially extensive subsurface data for assimilation and implementation of high-resolution observing systems is required; this enables evaluation of the highest resolution models, which is very uncommon in today's research environment. For a given spatial scale or process, the sufficient observation density for skillful prediction must be determined.

In-situ sensing capability on Navy platforms to improve ~1-hr modeling capability/skill is sorely needed. Technologies for rapid sub-surface measurements of temperature (T) and salinity (S) for initial model conditions are also required. Complete recording (not decimated) of conductivity, temperature and depth (CTD) and expendable bathythermograph (XBT) systems would provide highly valuable data for model ingestion. Investments in long-term, real-time observing systems (with depth profiling) would be useful; as would the expanded use of undetectable, locally deployable observing systems: drifters, acoustic, surface images. Locally deployable, persistent offboard sensor networks capable of adaptive sampling, along with onboard computers to assimilate local data and make predictions are essential. In-situ sensing must be optimized by computation of modeling/speed/capacity and machine learning. The limits on model improvement from in-situ sensing should be explored. Is a single platform capable of providing all the necessary data? If not, how many platforms and what kinds? Collaboration among USN, USAF, USCG, NATO, allies, NASA, NOAA, academia, industry and others may be one avenue to pursue. Finally, the importance of remotely sensed observations must be recognized. Satellite observations provide sea surface height anomaly for data assimilation, and such satellite observations are becoming more scarce.

Seabed Models and Databases

The oceanography and acoustics community have adopted a far too simplistic model of the seabed to adequately predict related processes and phenomena. The present static description of the seabed must evolve to a dynamic characterization, including processes and biology. Coupling of seabed geologic process models with acoustic models is needed. This is especially important for small-scale structure (roughness, volume heterogeneity and estimation of seabed) in denied areas. Environmental bottom parameter sampling and mapping databases often drive the overall fidelity of models. Acoustic models (especially reverberation models) presently ignore multiple scattering and the resulting errors may be substantial. Global databases must be improved: bathymetry, bottom loss, high-frequency bottom loss, among others. An AUV-based seabed uncertainty quantification (deterministic plus stochastic) survey methodology should be developed. Such a methodology has the potential to substantively improve the speed and accuracy of seabed databases.

Probabilistic Methods

The future of ocean modeling must include multi-model ensembles and multi-model nesting, where nesting and coupling should be two way. Ensemble methods are one approach to quantify uncertainty in models, despite difficult theoretical challenges. For example, can probability-density-function predictions provide useful information beyond predictive time scales? What are the predictability limits for surface layer and topographic wakes, or sub-mesoscale currents? The proper balance of the possible and practical and achievable results is not clear. Efforts should be focused on coupling data assimilations with measurement design, evaluation of accuracy of models and predictions in forward areas, validation of latest models against real data and the quantification of uncertainty related to model error and parameterizations.

Ambient Noise

There is a distinct need to better understand, characterize, survey, model and predict ambient noise in the ocean. Leveraging the most prevalent noise sources in the ocean, e.g., surface waves, shipping, fishing fleets, winds, biologics, etc., will raise existing acoustical prediction capabilities to the next level. Consideration of ambient sound, vice noise, to treat the ocean more realistically as a soundscape would constitute a new paradigm that might provide additional insight.

On-scene Operations

Researchers need a better understanding of how afloat operations are conducted, in terms of observation gathering and use of these observations in on-scene models and tactical decisions aids.

Concepts such as the use of a forward-deployable range, a self-assembling range of unmanned systems, might be productively explored. Fleet personnel can serve as observers of environmental parameters and should be more effectively leveraged. Lessons learned from operational weather observing and forecasting should be applied to ocean forecasting, which is in a relative early stage.

Parameterization and Process Studies

Parameterization reduces the complexity of phenomena and reduces the computational resources required to model ocean processes. Combined high-resolution observational and modeling process studies should be undertaken for poorly understood phenomena to develop parameterizations. Emphasis should be placed on parameterizations not resolved by current models; and a program to systematically replace empirical model parameterizations with mechanistic, understanding -based parameterizations should be initiated. Such parameterizations permit extrapolation into unobserved parts of the parameter space. Process studies are needed to observe new physics not yet included in models. The ability to rapidly incorporate into modeling and prediction systems whatever physical, chemical, biological or geological phenomena are required to respond to an extreme forcing event requires continuation of process studies across the spectrum of ocean phenomena.

Data Assimilation

We must invest in developing efficient data assimilation techniques for operational ocean forecast systems. This is the only means by which we optimally employ sensing, observation, modeling, simulation and prediction. Our approach to Data Assimilation must use all of the information in the observations and should employ hybrid advanced data assimilation (both Variational and Kalman Filter methods). We must perfect the art and science of “inverting” data retrieved from sensors (e.g., through-the-sensor techniques). In this way, we can leverage inversion technology to get accurate subsurface information and we can use models for not only producing climatological data sets, but also to determine surrogate environments.

High Performance Computing

The need for state-of-the-art high performance computing (HPC) cannot be understated - for both ashore production centers and far-forward capabilities. Cloud and clustered computing techniques must be fully employed to maximize computational power ashore and afloat. In general, the Navy lags behind other agencies, countries and the private sector in terms of computational power. Expanded access to HPC resources, better bandwidth and increased security will require software engineering and architecture expertise. We lack a strategy for every aspect of forward-deployed HPC, though it is highly likely to be required in the near future.

Big Data Concepts

Artificial intelligence and machine learning methods for oceanographic research are still in nascent stages. Access to existing data collections, including not only databases but environmental modeling results should be pursued. Such techniques might also be usefully employed for oceanographic and atmospheric remote sensing applications. Collaboration with industry as well as academia is likely needed to maintain the cutting edge.

Approaches to Research

The overall U.S. approach to ocean research deserves close attention. Cross-collaboration between the oceanography and acoustic communities should be emphasized. As it stands, there is little to no true integration between these communities. Academic researchers should work directly with/on planned Navy operational modeling systems to familiarize the widest community with practical issues of modeling and prediction. Dedicated integration and transition teams might be employed to assist in the transition of research to operations. The Navy might consider following the European Center for Medium-Range Weather Forecasts (ECMWF) model of meshing research and development (R&D), operations and infrastructure.

The Navy should sponsor meetings and symposia to bring together physical oceanographers, acousticians, ocean geologists and biological oceanographers, among others, for cross-cutting discussions about modeling and prediction. Scholarships in applied ocean forecasting would be useful to achieve continuity and establish the next generation of ocean prediction scientists. Academic incentives to work on practical or applied research efforts are often lacking and can discourage younger researchers from working on important problems. Finally, research sponsors should be encouraged to fund larger and longer-term efforts with fewer bureaucratic requirements.

## Breakout Session I: Forecasting thermohaline structure to understand undersea sound propagation

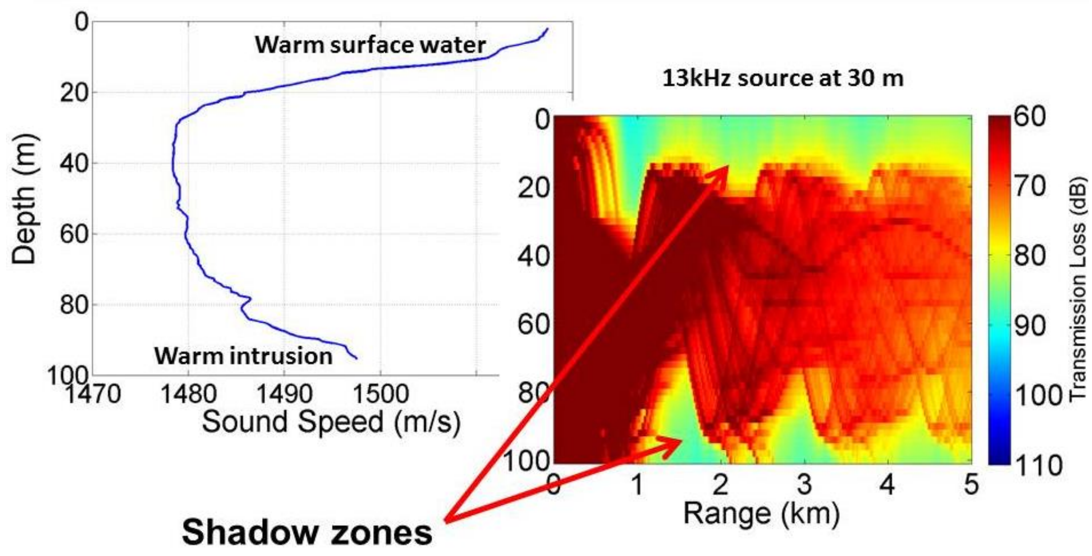


Figure 1. Key to success: Predicting acoustic propagation and the ocean properties that affect acoustics

**Summary:**

The importance of ocean interior observations emerged as a dominant theme. Participants noted that the present methodology using satellite data and sparse ocean state data was insufficient to force, constrain, or support predictive modeling for Naval purposes. Measurement of both physical and acoustic parameters consistently emerged as a theme. A diversity of opinion about the identification of critical parameters is reflected in the takeaways points, but notably included biological populations and bottom type and roughness as these become important tactical acoustic parameters. Methods for increasing observations included more extensive and targeted use of profiling floats, gliders, measurements using wire-walkers or other UxSs as well as new mini-floats that are tracked acoustically to measure vertical velocities to elucidate mixing processes.

Parameterizations that are relevant to the physical processes that affect acoustics are second to observational sparsity in determining model skill. Parameterizations for restratification, bottom-interactions, representation of sub-mesoscale processes, and air-sea interactions that govern the mixed-layer structure are needed. Most subgroups felt the models were adequate if they could be run at appropriate resolution; one subgroup suggested that 1 km spatial resolution was needed to resolve the interior processes and the reproduction of ocean currents at appropriate speed and phase. The group's knowledge of and concurrence on the status of coupled ocean-acoustics modeling was less convergent. There are research level coupled ocean-acoustic models and there was a call for continued development of these codes.

The tasking to address how to provide information to the fleet at sea and in-stride was less fruitful; the essence of the recommendations is to reduce the results to be able to fit over available bandwidth or to create a computational capability on board to provide real-time predictions using on-board sensors to constrain the prediction.

**Takeaways:**

S1 TAKEAWAY 1: In support of a holistic approach to ocean modeling, investigate geophysical processes associated with the continental shelf, to include filaments, internal waves and fronts, in order to fully understand scales associated with and interconnections between deep water and shallow water circulations and phenomena. Explore how existing and emerging capabilities may be leveraged to complete this investigation.

S1 TAKEAWAY 2: In order to fully support operational acoustic modeling and assessment, identify what local oceanographic data are required to sufficiently characterize the ocean. Include optimal data characteristics such as depths, parameterizations, communication/data transfer methods, uncertainty and acceptable errors. Identify variabilities that must be adequately measured and modeled, including seabed properties, water column dynamics, fresh water interactions with the ocean, salinity profiles, wind-driven flows, tidal currents, internal waves, solitary waves, fronts, eddies, thermal changes, temperature profiles, biological distributions, as well as the coupling mechanisms and temporal and spatial scales associated with these variabilities.

S1 TAKEAWAY 3: In order to fully comprehend, measure and predict the thermohaline and sound propagation nature of the ocean, fully describe the temporal and spatial (horizontal and vertical) scales and geophysical phenomena and processes that drive ocean sound propagation processes. Include phenomena like internal waves, internal gravity waves, bio-turbidity, wave heights in the marginal ice zone, low frequency broadband ambient noise, wave interaction with ice floes, ice concentrations, ice stress and moment, ice melt, ice fractures/leads/polynyas, and wind stress. Maximize the use of remote sensing and pattern recognition methods to provide essential geophysical characterizations. Understand phenomena coupling, and consider the use of coupled hydrological and ocean current models to provide a more complete characterization of ocean processes that drive the acoustic environment and sound propagation. Consider the use of statistical/probabilistic/stochastic prediction to better capture variability in phenomena.

S1 TAKEAWAY 4: Carefully consider and account for the military planning and mission execution processes, both strategic and tactical, in determining data, skill levels and temporal/spatial scales necessary to provide actionable output from ocean thermohaline and sound propagation data collections and models.

S1 TAKEAWAY 5: Explore means of transitioning in real-time from statistical to deterministic oceanographic predictions, as they pertain to ocean thermohaline and acoustic properties. Fully understand sensing, data collection and data assimilation methodologies needed to assess and predict ocean sound propagation. Explore the use of surface water, tomographic and temperature data assimilation into models. Understand impacts of surface wave scattering, bottom topography and type. Determine model and data assimilation sensitivities to very fine-scale phenomena (e.g., surface or bottom roughness).

S1 TAKEAWAY 6: Fully understand and employ the appropriate techniques for sub-grid-scale parameterizations of physical phenomena that cannot be practicably modeled explicitly (e.g., bottom layer turbulence, diffusion, dispersion, rain-induced sound). Leverage experts from both the oceanography and acoustics communities to achieve optimal solutions. Develop onboard science teams to support military units in theater, and establish third party Verification and Validation capabilities. Exploit data compression of gridded profiles through analysis of data mean and principal components of variance. Optimize parameterizations by considering strategic and tactical time scales defined by the military planning and mission execution processes.

S1 TAKEAWAY 7: Recognize the need for large gridded fields of high-resolution ocean and acoustic data and model output, as driven by frequency-dependence, geophysical gradients, duct presence/absence, internal tides/waves, double-diffusive mixing near fronts, etc. Develop the ability to resolve small ocean features in order to improve the tactical relevance of ocean and acoustic data collections and models. Recognize the need for a model forecast to include both deterministic and probabilistic (uncertainty) information. Leverage the use of principal components analysis, empirical orthogonal functions, ensemble Kalman filters, and other approaches in order to maximize the use of observations such as XBTs and to maximize the efficiency of data transmission. Achieve the proper balance between practical and theoretical approaches to assessing and modeling the acoustic ocean environment. Leverage observations to improve model employment, and leverage model output to improve observation deployment through scientifically tested feedback loops. Optimize ocean ensemble models and uncertainty products based on acoustic variances.

## Breakout Session II: Forecasting surface and sub-surface currents for ship routing, optimal path planning for unmanned systems, and dispersion of drifters, floats and sonobuoy fields

**Summary:**

Assessment of the state of the science was difficult for this topic because, outside of some key scientific studies, the majority of ocean current model prediction occurs in coastal regions where scientists have the advantage of utilizing Coastal Ocean Dynamics Applications Radar (CODAR) for either assimilation or evaluation of the model prediction. An at-sea Navy would typically not have CODAR for current predictions. The groups noted that the present methodology using satellite data was insufficient to force, constrain, or support predictive modeling for Naval purposes and they were particularly concerned with the stochastic nature of ocean currents, especially in the surface layers. Although this group focused more on model structure and physics, they echoed the theme from the earlier session calling for increased observations.

As in Session I, most groups felt the models were adequate if they could be run at appropriate resolution. There was some debate about the importance of the sub-mesocale processes and model resolution; the debate was resolved by recommending increased development of parameterizations rather than going to extreme resolution. There was concurrence that improved forcing and coupling with the atmosphere was critical.

The groups converged on the use of ensemble predictions to capture the stochastic nature of ocean-acoustic processes, especially in an under-observed ocean. The tasking to address how to provide information to the fleet resulted in a recommendation to reduce model predictions to the parameters that were critical to the Naval operation of interest – such features and processes such as convergent frontal lines, coherent Lagrangian structures, etc. would be small bandwidth and conveyable to a Naval platform.

**Takeaways:**

S2 TAKEAWAY 1: Develop sensing, modeling and uncertainty prediction capability for sonobuoy field trajectories. Establish techniques for minimizing the uncertainty in sonobuoy field trajectories.

S2 TAKEAWAY 2: Establish methods, time scales and spatial (horizontal and depth) scales for observing, assimilating and predicting non-conservative coastal tracers like ocean color. Employ CFD methods, if necessary, to enable unmanned underwater vehicle (UUV) missions like docking. Leverage hydrological modeling in conjunction with ocean modeling.

S2 TAKEAWAY 3: Validate model currents against all possible data sources, not just moorings and altimetry. Include the use of internal tide and internal wave models. Update operational models to include wave-current interaction and Stokes drift. Establish methods to statistically describe currents and achieve vertical turbulence closure.

S2 TAKEAWAY 4: Integrate operational meteorology/oceanography and ship navigation systems to exploit observations and models pertaining to wetting/drying in coastal regions, bottom boundary layer turbulence parameterization, ice edge dynamics. Optimize data delivery via better compression algorithms.

S2 TAKEAWAY 5: Leverage temporal and spatial improvements afforded by enhanced altimetry remote sensing, e.g., Surface Water Ocean Topography (SWOT - https://swot.jpl.nasa.gov/) to better identify features and phenomena that can be observed and predicted at the smallest scales feasible. Utilize this new understanding to gather information on model data assimilation, sensitivities and biases associated with these features.

S2 TAKEAWAY 6: Develop means of capturing 1-km resolution (mesoscale) global ocean characterization and prediction through a combination of observations, data assimilation (e.g., gliders, floats, XBTs, ARGO temperature and salinity large-scale stratification) and modeling. Take full advantage of intensive research being conducted at the sub-mesoscale. Fully characterize air-sea interactions and couplings, to include barotropic and baroclinic effects, wind-driven phenomena, tides, internal tides and surface fluxes. Develop a means of producing local Lagrangian and Eulerian tide predictions that result in a velocity-wavenumber dispersion cone as a function of time to inform operational units at sea.

S2 TAKEAWAY 7: Characterize surface and subsurface currents and their effects on the dispersion of sonobuoy fields, recognizing that gliders may be too slow to gather data needed. Optimize the use of limited observations and recognize that large scale flows drive the mesoscale flows. Use constraint in driving to higher and higher resolutions, and instead develop optimal methods to parameterize dispersion and other fine-scale, high-uncertainty phenomena. Make full use of Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) coupling along with non-hydrostatic modeling and satellite altimetry. Fully characterize both error and uncertainty. Conduct inner shelf studies to better understand fine-scale, high-uncertainty phenomena such as fronts, runoff, rainfall, winds, buoyancy fields, inertial oscillations, non-linear waves, currents and eddies. Work toward producing a daily eddy and dispersion map for operational Fleet application.

S2 TAKEAWAY 8: Optimize a model to inform the placement of floats relative to ocean phenomena of interest to the acoustics problem at hand. Leverage knowledge of subsurface currents to tune vertical resolution of observations. Define waypoints for convergence lines and frontal predictions, recognizing that frontal location is a tremendous challenge. Alleviate communications constraints and limitations by leveraging UxV onboard artificial intelligence.

# Breakout Session III: The role of observations and data assimilation in prediction

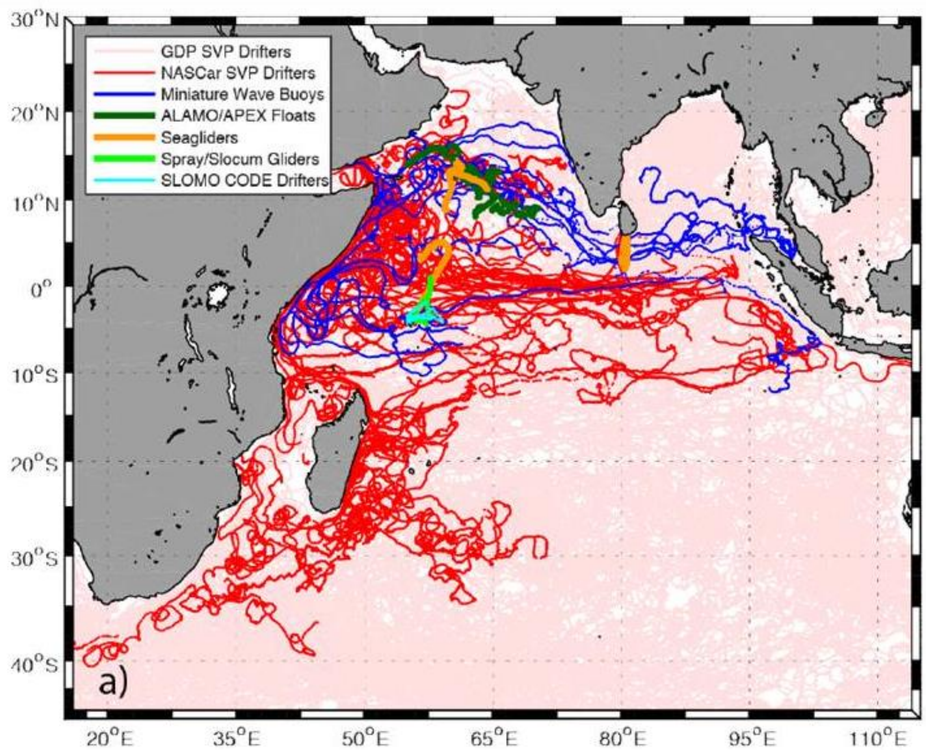


Figure 2. NASCar DRI autonomous observing systems (2014-2017)

**Summary:**

The objective for this session was to better understand the role of observational data in prediction – which observations are most critical, the adequacy of existing observing platforms, the best methodologies for assimilating observations into models, and how the impact of potential future observations might be assessed.

**Takeaways:**

S3 TAKEAWAY 1: To improve predictions, more observations are needed at all space and time scales, particularly in the sub-surface. The most critical observations depend on the intended use of the forecast, and are different for global and regional domains. For the global ocean, sea surface height anomalies, sea surface temperature, and sea surface salinity are available from satellite and are important, but additional data (temperature, salinity, velocity) from the interior ocean that can be provided by profiling floats, moorings, UUVs, and other sources are necessary to constrain the circulation and improve predictions.

S3 TAKEAWAY 2: Other observations besides the standard ocean variables will also help improve forecasts. These include bathymetry and geophysical properties of the seafloor, biological measurements, ambient noise, and optical data. Quantitative relationships between state variables and other variables or parameters in the ocean should be developed to fully characterize the ocean system. Ocean color data in particular may be an underexploited variable, as it can reveal ocean features that may be otherwise not apparent. Observations of the surface forcing must not be forgotten, which includes wind speed, heat and momentum fluxes, clouds, and ocean wave spectra.

S3 TAKEAWAY 3: Development of new observing systems should be encouraged, particularly for tactical predictions. The potential remedies include expanding the use of autonomous mobile sensing systems (gliders, floats, drifters, surface vehicles, drones), incorporating new platforms (microsats, tagged mammals, fleet assets), and developing new technologies (air-deployable systems, micro-floats, interior ocean floats, fixed and drifting tomographic arrays).

S3 TAKEAWAY 4: An observing system simulation experiment (OSSE) capability is needed to enable targeted and adaptive sensing, understand limitations of current observations, and assess new observing systems and methodologies. A clear description of the metrics – what variables need to be predicted - is required.

S3 TAKEAWAY 5: Data assimilation methodologies need to be able to incorporate many heterogeneous observation types, and can be useful for not only improving predictions but also for uncertainty quantification, verification/validation of forecast skill, and to estimate the sensitivity to observations and understand when more observations are needed. Emerging data assimilation techniques (Lagrangian data assimilation, machine learning, neural networks) should be researched or exploited. Data management to ensure operational availability, including real-time assessments of observation quality (QA/QC), remains an important consideration.

## Breakout Session IV: Synoptic vs. Probabilistic Prediction in Ocean/Acoustic forecasting

**Summary:**

The working group conducted an open discussion about the probabilistic nature of ocean state forecasting, including when probabilistic information should be considered, how this forecast uncertainty should be conveyed, and how the nature of probabilistic forecasts changes depending on which variable is being predicted.

**Takeaways:**

S4 TAKEAWAY 1: While there is a need to identify the set of relevant parameters in the ocean models that relate to the accuracy of the acoustic models, a better understanding is needed of the overall uncertainty in acoustic propagation modeling, as the uncertainty associated with non-water column interactions (i.e., bottom loss, forward scattering, ambient noise, reverberation) may out-weigh the ocean model uncertainty.

S4 TAKEAWAY 2: Reduced-order modeling may be a better way forward to predict general behavior of acoustics when the overall uncertainty is high.

S4 TAKEAWAY 3: There is a difference between model bias, model accuracy, and stochastic uncertainty. Ensembles are one way forward for probabilistic prediction, but we need to understand and quantify model errors before ensembles can be appropriately exploited.

S4 TAKEAWAY 4: Conveying uncertainty to users/decision-makers is an important consideration. The uncertainty in tactical decision aids may become so broad that the answer becomes useless, though the operator may have options to make an in-situ measurement if there is significant uncertainty in the forecast. Climatological information about uncertainty, if known in advance, can help set bounds on whether the probabilistic forecast information is useful.

S4 TAKEAWAY 5: Getting a better handle on probabilistic uncertainty in model forecasts is worth exploring particularly for considering the concept of “risk”; if we have reasonable knowledge of the environmental uncertainty, then the ability to estimate manage risk is enabled, which is valuable in operational settings.

## Breakout Session: Grand Challenges for the Modeling and Prediction Community

**Summary:**

The Working Group organizers sought from the modeling and prediction community participants so-called “grand challenges” that would move existing capabilities to a significantly higher level. The request for grand challenges was minimally constrained in order to allow the creativity and expertise of the participants to flow unobstructed. The suggestions listed below represent the thoughts of self-organized groups of participants. At the intersection of the several suggestions is the desire for a fully coupled, data-assimilating atmosphere/ocean/ice/acoustic model capable of producing tactically relevant predictions and concomitant measures of uncertainty. Such a model would rely on bathymetric, bottom type, and biologic data bases, among others, and would intelligently leverage climatological data, perhaps in an expert-system framework. A fully coupled ocean and acoustic model would support assimilation of local acoustic travel time data, as well as in-situ observations from allied gliders, floats, and other data sources. Obviating the necessity for reach back to shore-based computational resources would certainly constitute a grand challenge.

Ocean models impact a wide variety of naval missions. The nuances of the ocean environment, subtle or not, must often be addressed, for example: bubbles, surfactants, chemistry, bottom type, sediment, biology and boundary layers, among a large number of possibilities. The grand challenge involves capturing the required ocean texture to inform mission needs. In many cases parameterizations are required to effectively describe phenomena; new parameterizations and refinements of existing ones are needed. Acoustic models largely focus on improved estimation of sound propagation: sound emitted from sonar systems, echoes, or simply passive emissions. Subtle acoustical signals must be distinguished from noise. A tactically useful ocean noise model does not presently exist. Such a model requires multiple dimensions such as space, time, frequency, arrival angle and statistical nature of the signal to adequately describe the underwater acoustical environment.

**Suggested Grand Challenges (arbitrary order):**

GC 1: Develop locally deployable, dense, inexpensive, persistent (years) acoustic float arrays. Employ tomographic techniques (imaging by sections, via penetrating waves), data assimilation and high-resolution nested modeling to fully exploit data gathered by the acoustic float arrays.

GC 2: Master, leverage and integrate the following concepts to revolutionize ocean geophysical and acoustic measurement and prediction: (1) measured and modeled uncertainty, (2) platform-agnosticism, (3) sensor optimization (unattached, permanent and expendable, smart sensors, adaptive sampling), (4) asset allocation, (5) platform-hosted databases, (6) data assimilation and fusion, (7) flexibility and scalability (operational and tactical scales), (8) stealth, (9) information assurance / cyber security, (10) Smart bandwidth management, (11) model validation and verification.

GC 3: Leverage lessons from the computational fluid dynamics (CFD) community in order to improve ocean predictions: (1) uncertainty quantification, (2) numerics and physics, (3) Quality Control (systematic, reproducible and standardized), (4) model diversity (differing algorithm configurations, parameterizations, software, computational techniques, etc.)

GC 4: Advance our understanding, modeling and forecasting of the coupled ocean-atmosphere-ice environment through fully comprehending the effects of surface wave, bubbles, bottom type, sediment, biology, boundary layers, turbulence, convection, internal waves, sub-mesoscale instabilities, large scales, process/resolution scales. Carefully balance the use of increased model computations with appropriate parameterizations. Leverage the use of observation, data assimilation and numerical testing to adequately validate, verify and address the skill of models. Produce stochastic parameterization ensembles in order to provide seamless prediction and propagate uncertainty using full probability density functions.

GC 5: Improve parameterizations to better capture vertical mixing in the coupled ocean-atmosphere environment and to improve characterization of the mixed layer and upper ocean. Fully characterize the wave-guidance, flare and refractivity of phase-resolved surface waves. Fully integrate our knowledge of weather prediction, acoustics, biologics, currents, optics, and tropical cyclones in order to achieve revolutionary acoustic prediction, models and algorithms. Ensure ultimate ease of use by the Fleet.

GC 6: Produce a forward-deployable, state-of-the-art acoustic model that accounts for multi-dimensional active statistical information (2D direction, 3D position, frequency, clutter, time scales: seasonal-short-diurnal, 3D statistics), active/passive sensing, all sound channels (diffraction-coupling), multiple scattering (sea surface roughness, bottom roughness, etc.), broadband and Doppler effects, data assimilation and self-correction. Enable the model to actively update and verify databases while documenting angle and frequency domains, to include quantification of confidence and uncertainty.

GC 7: Inform acoustic models by leveraging innovative partial coupling and sub-parameterization techniques in order to couple ocean and atmosphere models at mesoscale and sub-mesoscales. Account for the acoustic implications of interior coupling (wave effects, slope effects, surface boundary layer, bottom boundary layer, internal gravity waves). Address the variability in bathymetry (roughness). Leverage innovative dissipation schemes that capture the difference between balanced and internal gravity wave dynamics. Consider coupling spectral models for internal gravity waves with Global Models. Consider development of an ultra-high-resolution large eddy simulation / regional model. Provide a statistical description of ducting associated with potential vorticity anomalies. Leverage data on eddies, winds and nonlinear internal waves in order to accurately characterize the internal wave phase.

GC 8: Develop a coupled ocean/acoustic analysis methodology that goes beyond Gaussian and 4D variational (4DVAR) assimilation. Leverage this to fully exploit tactical data from gliders, floats, hybrids with acoustic communications to afloat units. Leverage autonomous swarming/telescoping methods to optimize data sampling. Consider developing a reduced dynamic model (e.g., based on the Omega equation) and associated ensemble forecast that periodically updates prior predictions through adaptive sampling and feedback control. Enable platform-level prediction, but adhere to information assurance constraints by introducing an optimal computer architecture for environmental prediction. Consider the use of afloat high-performance computing.

# Appendix A: Agenda

**Modeling and Prediction Working Group**
**6-7 Sept 2017 Workshop**
**Office of Naval Research**

**6 September 2017**

**0745 Arrive at ONR**

**0800 Security, Badging, and Continental Breakfast**

**0845 Call to Order Workshop/Administrative Announcements**

**0900 Introductions**

**0915 *Briefing on Task Force Ocean (Objectives/Expectations)*** — **Captain A. J. Reiss**

**1000 Navy Modeling: History and Research to Operations** — **Dr. Scott Harper**

**1015 Break**

**1030 The Navy's Operational Modeling Effort** — **Dr. David McCarren**
*(15min presentation + 15min for questions and discussion)*

**1100 Discussion: Assessment of Current Capability and Limiting Factors for Prediction**

- How good are our current predictive capabilities for the ocean?
- What is limiting our ability to provide more meaningful/skillful forecasts?
- What science should the Navy invest in to improve modeling and prediction?

**1200 Lunch**

**1300 Session I: *Forecasting thermohaline structure to understand undersea sound propagation***

- What is the essence of a good prediction for this purpose? At what spatial scales and lead times are skillful forecasts possible? What critical processes are still poorly understood? What parameterizations must be developed?
- If data transmission to the Fleet is limited, what essential information should be conveyed, at what length and time scales?

**1430 Working Group Brief-Outs and discussion**

**1445 Break**

**1500 Chief of Naval Research**

**1515 Session II: *Forecasting surface and sub-surface currents for ship routing, optimal path planning for unmanned systems, and dispersion of drifters, floats and sonobuoy fields***

- What is the essence of a good prediction for this purpose? At what spatial scales and lead times are skillful forecasts possible? What critical processes are still poorly understood? What parameterizations must be developed?

- If data transmission to the Fleet is limited, what essential information should be conveyed, at what length and time scales?

**1645 Working Group Brief-Outs and discussion**

**1700 Adjourn**

**7 September 2017**

**0745 Arrive at ONR**

**0800 Security, Badging, and Continental Breakfast**

**0845 Workshop Recap/Admin Updates**

**0900 Session III: The role of observations and data assimilation in prediction**

- What observations are the most critical for prediction?
- Are the existing observational platforms and types adequate? What else is needed?
- How can observational data be best exploited to provide useful information? What DA algorithms and approaches are the most promising for operational prediction?
- What tools will be needed to assess the impact of additional observations?

**1030 Working Group Brief-Outs and discussion**

**1045 Break**

**1100 Session IV: Grand Challenges for the Modeling and Prediction Community**

- What are the "grand challenges" for the oceanographic and acoustic modeling communities over the next 15 years? What capability would we want in 2030?

**1200 Working Group Brief-Outs and discussion**

**1215 Break for Lunch**

**1315 Session V: Synoptic vs. Probabilistic Prediction in Ocean/Acoustic forecasting**

- When and how should the probabilistic nature of ocean forecasts be considered?
- How should uncertainty be conveyed?
- Does uncertainty quantification and exploitation differ for the applications discussed in Sessions I and II?
- Are there any additional probabilistic/stochastic issues should we be considering?

**1445 Working Group Brief-Outs and discussion**

**1500 Break**

**1515 Session VI: Re-envisioning the Research Enterprise**

- Given free rein and no cost constraints, in what areas (and in what priority) should investments be made to improve our predictive modeling capabilities?
- What structural or institutional constraints impede improvements in predictive skill?
- What changes would be required to enable these improvements?

**1630 Working Group Brief-Outs and discussion**

**1645 Next Steps and Closing remarks**

**1700 Adjourn**

# Appendix B: Participants

| | |
|---|---|
| Arango, Hernan G. | Rutgers University |
| Arbic, Brian | University of Michigan |
| Badiey, Mohsen | University of Delaware |
| Baker, Frank | Staff of the Oceanographer of the Navy (OPNAV N2N6E) |
| Becker, Kyle | Office of Naval Research |
| Bradley, Paul | National Oceanic and Atmospheric Administration |
| Chassignet, Eric | Florida State University |
| Chu, Peter | Naval Postgraduate School |
| Cornuelle, Bruce | Scripps Institution of Oceanography |
| Curtin, Thomas | Applied Physic Laboratory – University of Washington |
| D'Asaro, Eric | Applied Physic Laboratory – University of Washington |
| Dedrick, Kyle | Office of Naval Research |
| Drake, Tom | Office of Naval Research |
| Duda, Timothy | Woods Hole Oceanographic Institution |
| Eleuterio, Daniel | Office of Naval Research |
| Erickson, Jon | Office of Naval Research |
| Fabre, Josette | Naval Research Laboratory |
| Ferek, Ronald | Office of Naval Research |
| Fox-Kemper, Baylor | Brown University |
| Fringer, Oliver | Stanford University |
| Gardner, Holly | Naval Surface Warfare Center, Pensacola Division |
| Greene, Andrew | Chief of Naval Operations, Director Undersea Warfare (OPNAV N97) |
| Harper, Scott | Office of Naval Research |
| Headrick, Robert | Office of Naval Research |
| Heaney, Kevin | OASIS Inc. |
| Herr, Frank | Office of Naval Research |
| Holland, Charles | Applied Research Laboratory – Pennsylvania State University |
| Jacobs, Gregg | Naval Research Laboratory |
| Jenkins, Brent | Chief of Naval Operations, Director Surface Warfare (OPNAV N96) |
| Jensen, Tommy | Naval Research Laboratory |
| Johnston, Shaun | Scripps Institution of Oceanography |
| Jones, Benjamin | Staff of the Oceanographer of the Navy (OPNAV N2N6E) |
| Keenan, Ruth | Applied Research Laboratory - University of Texas |
| Ko, Dong S. | Naval Research Laboratory |
| Lermusiaux, Pierre | Massachusetts Institute of Technology |
| Mask, Andrea | Naval Oceanographic Office |
| McBride, Marvin | Office of Naval Research |
| McCarren, Dave | Staff of the Oceanographer of the Navy (OPNAV N2N6E) |
| McGovern, Jean | Office of Naval Research |

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|---|---|
| McWilliams, James | University of California, Los Angeles |
| Miles, Travis | Rutgers University |
| Miller, Art | Scripps Institution of Oceanography |
| Miller, Jerry | Science for Decisions |
| Moore, Andrew | University of California, Santa Cruz |
| Murray, James | OASIS Inc. |
| Nichols, Charles | Southeastern Universities Research Association |
| Orris, Gregory | Naval Research Laboratory |
| Paluszkiewicz, Terri | Office of Naval Research |
| Reinhardt, Colin | SPAWAR Systems Center Pacific |
| Rhodes, Robert | Naval Research Laboratory |
| Rice, Edward | National Oceanic and Atmospheric Administration |
| Schurman, Iman | Johns Hopkins University Applied Physics Laboratory |
| Skyllingstad, Eric | Oregon State University |
| Soukup, Raymond | Office of Naval Research |
| Sracic, David | Naval Surface Warfare Center, Carderock Division |
| Tandon, Amit | University of Massachusetts Dartmouth |
| Thomas, Leif | Stanford University |
| Wijesekera, Hemantha | Naval Research Laboratory |
| Winstead, Nathaniel | Johns Hopkins University Applied Physics Laboratory |