Perspectives on Chemical Oceanography in a changing environment: Participants of the COME ABOARD Meeting examine the field in the context of 40 years of DISCO

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Abstract

The questions that Chemical Oceanography prioritizes over the coming decades, and the methods we use to answer these questions, will define our field's contribution to 21st Century science. In recognition of this, the National Science Foundation and the National Oceanic and Atmospheric Administration galvanized a community effort (the Chemical Oceanography MEeting: A BOttom-up Approach to Research Directions, or COME ABOARD) to synthesize bottom-up perspectives on selected areas of future research in Chemical Oceanography. The COME ABOARD Meeting engendered constructive evaluation of the state of our field, what we are striving for, and how we can get there, while developing an actionable pathway toward scientific leadership. Major themes that were discussed include: strengthening our core chemical skillset; expanding our tools through collaboration with chemists, engineers, and computer scientists; enhancing interdisciplinary research at environmental interfaces through collaborative, mid-sized and large programs; and expanding ocean literacy by engaging with the public. A concept unifying many of these themes centered on the unique levels of readiness and stages of knowledge development found throughout our community that may require dissimilar funding structures and metrics of success. In addition to the science, participants of the concurrent Dissertations Symposium in Chemical Oceanography (DISCO) XXV, a meeting of recent and forthcoming Ph.D. graduates in Chemical Oceanography, provided perspectives on how our field could show leadership in addressing long-standing diversity and early-career challenges that are pervasive throughout science. This document provides a synthesis of these discussions, and thus reflects the perspectives of COME ABOARD Meeting participants.

1. Introduction

The Dissertations Symposium in Chemical Oceanography (DISCO) is a United States-based, internationally-inclusive meeting of recent or soon-to-be graduate Ph.D. chemical oceanographers that is funded by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA). Approximately 25 participants are selected from the applicant pool to attend the meeting, which presently occurs every 2 years. Since its inception, over 600 scientists have participated in DISCO. To celebrate the convening of DISCO XXV, and 40 years of Chemical Oceanography graduates (spanning 1977 to 2017), the NSF and NOAA sponsored a three-day meeting entitled COME ABOARD (The Chemical Oceanography MEeting: A BOttom-up Approach to Research Directions) from October 14 to 16, 2016 in Honolulu, Hawaii. The goals of the meeting were to identify future key areas of research in Chemical Oceanography and discuss the efficacy of the DISCO symposium, which is intended to create scientific cohorts. A committee of past DISCO guest speakers chose one individual from each of the prior DISCO classes to represent their cohort at COME ABOARD. Thus, by design, participants represented all career stages in Chemical Oceanography. In addition, the broader Chemical Oceanography community was invited and encouraged to participate, making this an inclusive gathering.

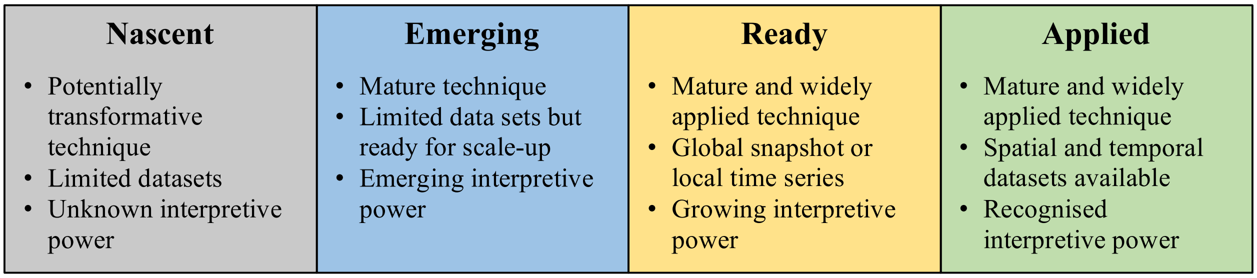
Participants identified six major themes prior to COME ABOARD as topics for discussion: (1) chemical concepts that underpin biogeochemical cycles, (2) geochemical knowledge and interactions across disciplines, (3) technology advancements, (4) boundary fluxes at interfaces, (5) large scale programs, and (6) communication with the public. Not all research topics in Chemical Oceanography were represented during COME ABOARD due to the vast nature of the field. Topics that were covered, therefore, largely reflect the interests of community members in attendance. After plenary presentations on each theme, breakout groups convened to discuss each theme in detail over the subsequent two days. While the specifics were often unique to individual themes, there was significant overlap in conceptual frameworks and actionable recommendations, which emerged from a common recognition that our field is in a rapid state of change. Accelerations in technology advancement have led to major revelations about how undersampled and complex the ocean is. As new tools are developed, our field is acquiring new skillsets and expertise; however, there remains an inherent need to foster traditional chemical training to ensure that Chemical Oceanography is rooted in its core field. How we navigate modern revolutions in technology that enhance as well as generate subfields within Chemical Oceanography (e.g., -omics and sensor development) could significantly influence the future trajectory of our field and its impact on broader society.

It was also acknowledged during COME ABOARD that different subfields of Chemical Oceanography are in dissimilar stages of maturity. For example, some disciplines are still developing the tools necessary to automate sampling that will ultimately allow for large scale mapping of tracers, while other communities with more mature technology have already acquired a remarkable number of observations and are focused on data synthesis. Disparity in the phase of knowledge development and accompanying scale of research questions means that different communities within Chemical Oceanography require different types of funding support and career development opportunities. For example, scientists designing a global observing network or survey program may require time and support to coordinate their research community and draft the framework for a long term project. Alternatively, someone working at the land-sea interface may need to incorporate the expertise of biological oceanographers or hydrologists to make their next advance in understanding local processes. Another scientist may be developing a new, highly-specialized analytical tool that requires sustained funding to achieve commercial viability. Each of these activities contributes to the field as a whole, but requires different timescales and magnitudes of funding, and may experience different levels of validation tied to the commonly used indicator of productivity – peer-reviewed publications. Acknowledging the disparate levels of readiness and phases of knowledge production across the communities within Chemical Oceanography provides an opportunity to reassess the frameworks for funding (e.g., grant duration, amount, and renewal frequency) and career evaluation (e.g., publications and awards). In addition to the six COME ABOARD themes, a compelling presentation by the DISCO XXV participants on the first day of the COME ABOARD Meeting engendered unanimous support for the inclusion of early-career perspectives in this summary document. Complementary themes were merged to develop the four topical sections herein, where we provide actionable recommendations that may allow our community to exemplify scientific leadership as we face 21st century challenges.

2. Producers of geochemical knowledge: our contribution to other fields and society

Chemical oceanographers quantify reactions and mechanisms in seawater in order to conceptualize biogeochemical cycles and understand how they relate to environmental forcing and ecosystem function. Our field develops and applies tools for the determination of stocks, rates, and transformations of dissolved and particulate materials that interact throughout the water column and exchange at interfaces with the atmosphere, seafloor sediments, coasts, and solid earth. The principles of physical, inorganic, and organic chemistry allow us to interpret kinetic processes, define chemical speciation, and characterize molecular structure, while processes occurring in different oceanic environments (pelagic, mesopelagic, bathypelagic, benthic, hydrothermal, coastal) require a mechanistic understanding of temperature, pressure, and salinity effects. The arsenal of tools developed by our field has assisted in quantifying and characterizing processes that occur over a wide spectrum of spatiotemporal scales throughout the Earth system. In particular, chemical oceanographers have played lead roles in describing and understanding past, present, and potential future impacts of human activities on our planetary system. Ultimately, our tools help to drive advances in other fields of oceanography and climate science. Scientific inquiry that arises in those fields, in turn, informs the development of new tools and methods within Chemical Oceanography.

Key advances in Chemical Oceanography result from the interplay of measurements, fundamental kinetic and thermodynamic principles that define relationships and processes, and prognostic models that predict ongoing and potential future trends. These advances require the continuous development of new analytical tools to explore our evolving level of understanding. **Figure 1** characterizes different stages or modes of analytical maturity, spatiotemporal application, and mechanistic interpretation within four categories that are intended to contextualize the development of a geochemical tool as it relates to broad oceanographic understanding.



Nascent	Emerging	Ready	Applied
• Potentially transformative technique • Limited datasets • Unknown interpretive power	• Mature technique • Limited data sets but ready for scale-up • Emerging interpretive power	• Mature and widely applied technique • Global snapshot or local time series • Growing interpretive power	• Mature and widely applied technique • Spatial and temporal datasets available • Recognised interpretive power

Figure 1. Categories for existing geochemical techniques based on their current contribution to broad oceanographic understanding.

In parallel with advancing analytical techniques, chemical oceanographers develop biogeochemical concepts and theories that are used to enhance predictive capabilities. As such, the path by which nascent ideas are developed into mature chemical oceanographic concepts and predictions depends on the rate of analytical progress, the formulation of biogeochemical concepts and theories, and the application of biogeochemical models. Our understanding of the inorganic carbon cycle is a good example of an area of Chemical Oceanography in the *Applied* phase that also has a strong theoretical underpinning [e.g., *Millero*, 2007; *Dickson*, 2010]. Here, extensive datasets coupled with a mature understanding of seawater carbonate chemistry have led to confident estimates of the amount of anthropogenic carbon in the ocean, and application of this knowledge at the societal level [*Ciais et al.*, 2013]. In contrast, the ongoing largescale GEOTRACES program has moved the field of trace-metal chemistry to the *Ready* level and refined our knowledge of important trace element sources [*Anderson et al.*, 2014]. Further evolution in our fundamental knowledge of trace element chemistry is required to achieve fully-representative, global, biogeochemical models that can be used in a prognostic mode [*Gledhill and Buck*, 2012; *Turner et al.*, 2016]. *Emerging* areas of Chemical Oceanography, such as proteomics, metabolomics, and the chemical and structural characterization of organic matter, may have a solid theoretical basis [e.g., *Koch et al.*, 2005; *Slattery et al.*, 2012; *Hansell*, 2013; *Kido Soule et al.*, 2015], but their interpretive power is currently limited by the extent of application. For example, marine proteomics studies have revealed physiological responses of Southern Ocean phytoplankton to changing environmental conditions [*Boyd et al.*, 2016] and been used to track organic nitrogen sources from the water column to sediment burial in the Bering Sea [*Moore et al.*, 2012], demonstrating the field's emerging interpretive power. *Nascent* areas can be high risk for investigators as the scientific benefits of novel method development are not always rapidly realized; nevertheless, techniques such as the interpretation of certain compound-specific isotope ratios [e.g. *Horner et al.*, 2015; *Cao et al.*, 2016] or the determination of specific metal complexes [e.g., *Mawji et al.*, 2008; *Boiteau et al.*, 2016a, 2016b] offer exciting potential for discovery. We are becoming increasingly competent at assessing oceanic stocks, but the changing ocean environment highlights the importance of understanding temporal changes and thus the rates of underlying processes. These temporal changes occur over a range of timescales such that their quantification requires diverse experimental approaches. For example, geochemical tracers have successfully constrained *in situ* processes occurring over seconds to tens of thousands of years. Still, laboratory experiments are required in order to differentiate reaction pathways, assess the significance of reaction rates, and, thus, unravel underlying abiotic and biotic mechanisms [e.g., *Luther*, 2010].

Mature areas of Chemical Oceanography make significant contributions to society. Prominent examples include the Intergovernmental Panel on Climate Change reports (e.g., anthropogenic carbon in the ocean; *Ciais et al.*, 2013), the assessment of risk from disasters and hazards (e.g., Cesium inventory in the Pacific Ocean following Fukishima; *Buesseler et al.*, 2012), and scientific evaluation of proposed geoengineering strategies (e.g., iron fertilization; *Wallace et al.*, 2010). Additionally, Chemical Oceanography supports Physical Oceanography through the determination of water mass properties, with constant improvements and diversification of tracers driven by the chemical oceanographers' desire to know exactly what is in a particular liter of seawater and why. Likewise, Biological Oceanographers use chemistry to assess the magnitude of the biological pump and characterize nutrient limitation of primary productivity. Thus, there is a constant need to develop to maturity new tools in order to reach a better holistic understanding of the ocean and its role as a global resource and mediator of climate change. Optimal application of all analytical approaches, from *Nascent* to *Applied*, demands extensive time and effort for intercalibration, quantification of uncertainties, and innovative data handling and analysis tools. The dynamic nature of the ocean environment means that process studies require a diverse range of interdisciplinary approaches including laboratory studies, shipboard expeditions, ocean observatories, and *in situ* measurements from sensors. As a community, recognizing the fundamental value of developmental efforts such as intercalibration, publication of methods papers, and enhancement of data availability and usability is necessary to ensure that these efforts are appropriately credited during funding and career evaluation exercises. Furthermore, identification of current and future skill gaps (e.g., physical chemistry and oceanographic chemometrics) will be critical to build and maintain the robust chemical oceanographic proficiency and intuition required to address the most pressing ocean science questions.

3. The tools of Chemical Oceanography in a changing field and changing environment

A principle goal driving ocean technology development is the achievement of comprehensive and predictive biogeochemical understanding, not only to address big issues like carbon, nutrient, and trace element cycling, but also to better manage marine resources. Models of the ocean and Earth system are currently data-limited and in need of a more diverse suite of measurements with increased coverage in space and time, as well as improved integration of existing and disparate datasets. The kind of ocean model we envision requires a spatially and temporally rich dataset for development and verification, which can only be obtained through new technologies that enhance our sampling capabilities. Data must be intercomparable with a continued effort to ensure quality control and quality assurance (QA/QC) in an automated, objective, and well-documented manner. Such a dataset will be central in defining questions targeted to understand specific mechanisms and rates of biogeochemical processes. This mechanistic understanding is, in turn, necessary to create the comprehensive, predictive biogeochemical model we are striving for. Mechanistic studies are also driven by new measurement technologies that allow investigation of smaller quantities of material at much smaller temporal and spatial scales, as well as new autonomous platforms to carry these technologies.

Technologies used in the field of Chemical Oceanography span a range of applications that may be grouped into: *Platforms, Sensors/Analyzers, Lab Tools,* and *Data Tools. Platforms* (including vessels, autonomous vehicles, moorings and moored profilers, floats, gliders, and satellites) are, in general, mature technologies ripe to support established and emerging chemical measurement techniques. *Sensors/Analyzers* include common commercial and replicated systems found in many laboratories and, accordingly, may be adaptable to autonomous or automated operation. Examples include both solid-state sensors and wet chemical analyzers used for routine chemical determinations. *Lab Tools* include less-common, high-cost instruments that are typically restricted to a controlled environment. Some approaches, such as automated sediment traps and the use of autonomous underwater vehicles to collect water samples for later analysis, are hybrids between *Sensors/Analyzers* and *Lab Tools,* and represent an exciting forefront of sampling technology development. *Data Tools* include a complex pipeline from measurement to quality-controlled database to model. This subset of tools is heavily reliant on interdisciplinary coordination between chemical oceanographers and computer scientists.

New technologies are enabling great advances in laboratory and *in situ* biogeochemical data production. **Table 1** lists some of the common parameters that chemical oceanographers evaluate and the types of observing platforms presently used to measure them. As future platforms incorporate new measurement technologies, several challenges will emerge for chemical oceanographers:

1) how to automate data quality control for real-time assimilation into models;
2) how to deal with "big data" resulting from multiplying and expanding autonomous observation systems and rapidly growing fields such as "omics" that often use high-output instruments such as high-resolution mass spectrometers;
3) how to accommodate and capitalize on the growing trend toward low-cost, real-time environmental monitoring associated with a do-it-yourself, "maker culture" of young scientists and non-scientists, while encouraging validation and intercalibration of new technologies.

Continued progress in data-analysis and quality-control approaches will be essential to keep pace with the increasing inflow of data. These dense and information-rich datasets will enable new areas of hypothesis-driven research and inform the models needed to manage the contemporary ocean and predict future responses to a changing climate. We must engage the broader chemistry, engineering, and computer science communities in order to expand the revolution in new technologies and data collection and to train the next generation of chemical oceanographers in thinking beyond traditional observational approaches.

Table 1. List of *some* common parameters measured by chemical oceanographers. Columns to the right represent the location where the analytical measurement is made. Research Vessels include volunteer observing ships and Mobile Platforms include floats, gliders, and AUVs. Colors correspond to the geochemical technique readiness levels in **Figure 1**.

Parameter	Laboratory	Research Vessels	Fixed Platform	Mobile Platform	Satellite
Salinity	🟩	🟩	🟩	🟩	🟨
Nutrients					
Nitrate	🟩	🟩	🟩	🟩	
Ammonium	🟩	🟩	🟨	🟦	
Phosphate, Nitrite	🟩	🟩	🟨		
Silicate	🟩	🟩			
CO_2 System					
pH	🟩	🟩	🟩	🟩	
pCO_2	🟩	🟩	🟩	🟨	
DIC	🟩	🟩	🟨	🟦	
TA	🟩	🟩	🟨	⬜	
Gases not CO_2					
O_2	🟩	🟩	🟩	🟩	
N_2O, CH_4	🟩	🟩	🟨	🟨	
N_2	🟩	🟩	🟦	🟦	
DMS, CFCs, SF6	🟩	🟩			
Ne, Ar, Kr, Xe	🟩	🟨			
Trace Elements					
Fe, Al, Zn, Mn, Cd, Cu	🟩	🟩	🟦		
Dissolved Org. Mat.					
DOC	🟩	🟨	🟨	🟨	
DON, DOP	🟩				
Particulate Matter					
Chl-a	🟩	🟩	🟩	🟩	🟩
$CaCO_3$	🟩	🟩	🟨	🟨	🟨
Other Pigments	🟩	🟩			
Org. C, N, P	🟩				
cell properties	🟩				
Stable Isotopes					
^{13}C, ^{15}N, ^{16}O, ^{17}O, ^{18}O	🟩				
^{32}S, ^{33}S, ^{34}S, ^{36}S	🟩				
Fe, Zn, Cd, Cu, Ba	🟨				
Radioactive Isotopes					
^{234}Th	🟩	🟩	🟦	🟦	
^{137}Cs	🟩	🟩	🟦	🟦	
^{223}Ra, ^{224}Ra	🟩	🟩			
^{14}C	🟩				
Radiogenic Isotopes					
Pb, Nd, Sr, Os	🟩				
Omics					
Genomics, Transcriptomics	🟦	⬜			
Proteomics, Metabolomics	🟦				

Key
🟩 Applied
🟨 Ready
🟦 Emerging
⬜ Nascent

4. The scale of 21st Century problems

Chemical oceanographic research is usually conducted at three basic levels: the "traditional" single investigator study, large programs that involve many institutions and investigators, and a hybrid of these end-members that could be termed "mid-sized programs". Each model contributes to a balanced field of research. However, when research questions are multifaceted, cross-disciplinary, or require intensive field- and analytical work to address global-scale problems, large programs can provide a level of integration and efficiency that accelerates discovery. As such, large programs have led to breakthroughs in our understanding of fundamental ocean processes critical to sustaining a habitable planet. As new technologies for data collection, sample analysis, and data processing continue to emerge, it is imperative that we assess the readiness of our community to apply these novel tools to global-scale problems. Below we focus on large programs, defined here as projects that involve either very-large spatial scales (global) or intensive study of a specific area over very-long timescales using multifaceted tools. These programs usually involve many institutions, participation is international, and timescales are longer than the typical three-to-five-year NSF award.

4.1. The role of big programs in Chemical Oceanography

A number of past large programs exemplify the successful application of large-scale science to illuminate ocean processes and enhance our understanding of how the global ocean works. Several programs of this type have aimed to estimate anthropogenic carbon dioxide (CO_2) uptake by the ocean. For example, the Geochemical Ocean Sections program (GEOSECS; *Craig and Turekian*, 1980) was a 1970s-era International Decade of Ocean Exploration (IDOE) project inspired by physical oceanographic theory and coupled chemical-physical models. GEOSECS resulted in a global-scale understanding of ocean circulation through the analysis of chemical tracers, and provided the first estimates of the global ocean distribution of CO_2 and uptake of anthropogenic CO_2 from the atmosphere. This was followed by the Transient Tracers in the Ocean program (TTO; *Brewer et al.*, 1985) in the 1980s, the World Ocean Circulation Experiment (WOCE; *Ganachaud and Wunsch*, 2002) in the 1990's, the Climate and Ocean - Variability, Predictability, and Change (CLIVAR; http://www.clivar.org/) program in the 21st Century, and the closely-related Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP; *Fukasawa et al.*, 2009) which all continued to document the evolution of tracers and CO_2. Also, the Joint Global Ocean Flux (JGOFS) program [*Fasham*, 2003] in the 1990s addressed surface ocean biological processes and geochemistry and the flux of surface-produced material to the deep sea on a global-scale. In the 2010s, the GEOTRACES program [*Anderson et al.*, 2014] set out to map global-scale distributions and characterize sources, sinks, and internal cycling of micronutrients, other trace elements, and isotopes. Future large programs will likely need to address ocean processes that lie at the intersection of disciplines and ocean boundaries. The COME ABOARD community expressed interest in future programs that would integrate the fundamental chemistry and biology of the ocean, including combining emerging "omics" toolsets with established chemical methods as well as integrating into the NASA EXPORTS program [*Siegel et al.*, 2016]. Such programs provide mechanistic insights into the influence of biology on chemistry, and vice versa, at the global scale.

In addition to advancing scientific understanding, existing large oceanography programs (e.g., CLIVAR, GO-SHIP, and GEOTRACES) are particularly good at ensuring and delivering high-quality data to a wide audience, providing excellent networking and field work opportunities for graduate students and early-career scientists, and producing results that inform the general public about consequential oceanographic problems (e.g., acidification, warming, deoxygenation). These same programs face the challenge of remaining focused on their original goals while also engaging early-career investigators in developing and testing their own hypotheses, providing samples or sampling opportunities for complementary science programs, having a clear route for the addition of new investigators, and securing funding from a diverse suite of agencies, including private foundations. One way to address some of these issues is to build synthesis and communication efforts into the structure of big programs such that new methods (e.g., technology and modeling) and new insights (e.g., new investigators) can be incorporated into the overall interpretation of the program's findings along the way.

4.2. Incorporating interfaces into big programs

A broad motivation for ongoing work in Chemical Oceanography is to understand the relationships between, and temporal evolution of, the input, internal cycling, and output of chemical species from the ocean. Interfaces between the ocean and other components of the Earth system are often regions of intense elemental processing, export, and exchange, yet they are particularly understudied with respect to their role in ocean chemistry and climate.

Thanks to careful observing and modeling, supported at least in part by big programs, our understanding of CO_2 fluxes across the ocean-atmosphere interface is well-developed [e.g., *Takahashi et al.*, 2002a; *Gruber et al.*, 2009; *Wanninkhof et al.*, 2013; *Bakker et al.*, 2016]; however, many critical characteristics of this ocean boundary remain poorly constrained (e.g., other climate-relevant gases, dust and aerosol deposition). At the land-ocean boundary, international monitoring programs have succeeded in establishing records of discharge for major world rivers (e.g., GEMS Water (UNEP), Global Rivers Observatory), yet comprehensive gauge coverage of river systems is still lacking in most of the world. Few river systems have active monitoring of material loads required to calculate chemical fluxes as a function of discharge. Submarine groundwater discharge also constitutes a major link between the terrestrial and marine environments; however, relative to surface river fluxes, much less is understood about the fluxes of water and chemical species from groundwater to the ocean and their temporal and spatial variability [*Moore*, 2010]. Estuaries are areas of dynamic biogeochemical processing that alter the magnitude and composition of land-derived chemical fluxes to the ocean [e.g., *Bianchi*, 2006]. Much is known about chemical cycling within a limited number of individual estuaries (e.g., Chesapeake Bay), but an integrated view of the impact of estuaries on ocean chemistry is still lacking. At the interface of the near-shore shelf environment and the open ocean, investigations into the physics and biogeochemistry of plumes, fronts, jets, and eddies are yielding novel, mechanistic insights into the connectivity between these two regions. New technologies (see Section 3 above) provide platforms for a myriad of sensors that have improved our observational ability in the interface regions. However, designing, implementing, and integrating observational and modeling efforts to study these dynamic systems remains a challenge. The sediment-water interface represents the link between short-term land-ocean processes and long-term geological processes. While big programs such as JGOFS and the International Ocean Drilling Program (IODP) have significantly improved our understanding of sedimentation, sedimentary biogeochemical cycling, and past climate (see discussions in *Burdige*, 2006; *Aller*, 2014), studying fluxes across this interface remains complicated by questions of spatial and temporal scales [e.g., *Boudreau and Jørgensen*, 2001]. Finally, hydrothermal systems are the conduit through which the solid Earth and hydrosphere communicate, and their importance to seawater chemical budgets is now increasingly recognized [e.g., *German et al.*, 2016]. However, hydrothermal systems are very difficult to study owing to their overall inaccessibility, large spatial and temporal variability, and the high reactivity of the elements emitted in hydrothermal fluids.

Regardless of the interface, the vast continuum of temporal and spatial scales over which boundary fluxes operate renders them extremely difficult to quantify and characterize. Moreover, interface fluxes are seldom at steady state and are vulnerable to large episodic and stochastic changes that may become less predictable with global change (e.g., sea level rise, ocean acidification, eutrophication) and other anthropogenic pressures (e.g., deep-sea mining). Major discoveries resulting from large programs often emerge from the synthesis of (big) data sets encompassing multiple disciplines, multiple studies, and/or multiple (time and/or space) scales. While a great deal of research is being conducted at ocean interfaces, the associated research communities and scientific outcomes tend to be grouped by flux boundary, creating a need for coordinated scientific activities that cut across these perceived silos. Incorporating ocean interfaces into large programs is one way to advance research at these boundaries far more efficiently than individual investigator-driven science.

4.3. The whole is greater than the sum of the parts

Targeted study of ocean interfaces could be incorporated into existing large-scale programs, although not all big programs will be the appropriate home for all interface research. Mid-scale research programs developed specifically to evaluate the ocean boundaries may be a better approach. Considerable progress can be made in the near term for some ocean interfaces, such as the air-sea boundary, by fostering international collaboration, especially between institutions in the northern and southern hemispheres, and through opportunistic sampling on ships and/or autonomous platforms. Looking ahead, to address the large knowledge gaps that exist at the ocean interfaces, the community recognizes a need for interdisciplinary projects involving multiple investigators with complementary expertise who can work within a supported framework. Community input will be required to identify core groups of researchers invested in ocean interface problems who can determine whether the techniques and methods required to address them are available. Moreover, no single program can fund research into every chemical cycle at every interface, such that priorities need to be determined and evaluated in the context of community readiness.

The COME ABOARD Meeting engendered interest in an umbrella-like initiative to coordinate multidisciplinary, ocean-wide, and ocean-interface research on topics that will impact society over the next century by focusing on the sustainability of ocean services. Existing assets, such as those operated under the Ocean Observatories Initiative (OOI), could be exploited in these efforts by appropriately pairing them with new large and mid-scale programs designed to investigate complex oceanographic problems and systems. Effective coordination of resources and research on ocean sustainability and services would logically fall under an umbrella initiative like that which was implemented during the International Decade of Ocean Exploration. While new knowledge is often generated at disciplinary frontiers, solving big problems requires working across disciplinary and system boundaries. Ocean chemistry plays a central role in these efforts by integrating and recording the products of physical-chemical-biological coupling.

5. Opportunities to exhibit scientific leadership through training and communication

5.1. Training the next generation of chemical oceanographers

In addition to the science itself, the people of Chemical Oceanography are critical to its success. Graduate and postdoctoral training in Chemical Oceanography has traditionally focused on preparing the next generation of academic researchers. While this remains vital, the majority of students who receive graduate degrees in Chemical Oceanography will not pursue academic careers similar to those of their graduate and postdoctoral advisors [*Briscoe et al.*, 2016]. This is due to the broad range of graduates' career interests as well as the realities of the academic job market (**Figure 2**). To support the large number of scientists who will seek non-academic career paths both by choice and by necessity, as well as those who will remain in academia, it would be beneficial to provide opportunities for students to explore a range of career options during their graduate training to ensure that they build the skills necessary for their desired career. Success in this endeavor will require a cultural acceptance in the field that career paths differing from that of one's research advisor – which today may be considered the "more traditional path" [*Briscoe et al.*, 2016] – are equally valid and significant, and that graduate-trained scientists in influential non-academic positions play a key role in enhancing the societal and environmental impact of Chemical Oceanography.

To enhance graduate preparedness for a variety of careers stemming from an education in Chemical Oceanography, graduate and postdoctoral programs could incorporate professional training for a range of careers. This could be accomplished in numerous ways including: the development of mentoring plans based on individual trainee career goals; courses and workshops on skills such as communication, writing, and teaching; and opportunities to engage with those in non-academic environments to gain experience and perspective in those fields. These opportunities could be provided in the form of informational panel discussions and networking events with non-academic scientists, internship programs at non-academic laboratories, as well as fellowships in science policy, outreach, and journalism. Graduate degree-granting institutions, funding agencies, and professional societies can contribute to this effort by providing and promoting such professional development opportunities. Facilitating the acquisition of a broader range of skillsets and tools by chemical oceanographers in graduate school and in postdoctoral positions could both improve the holistic training of those who pursue an academic research-focused career as well as develop a network of trained chemical oceanographers working in industry, government, policy, and science communication who can expand the reach of our field.

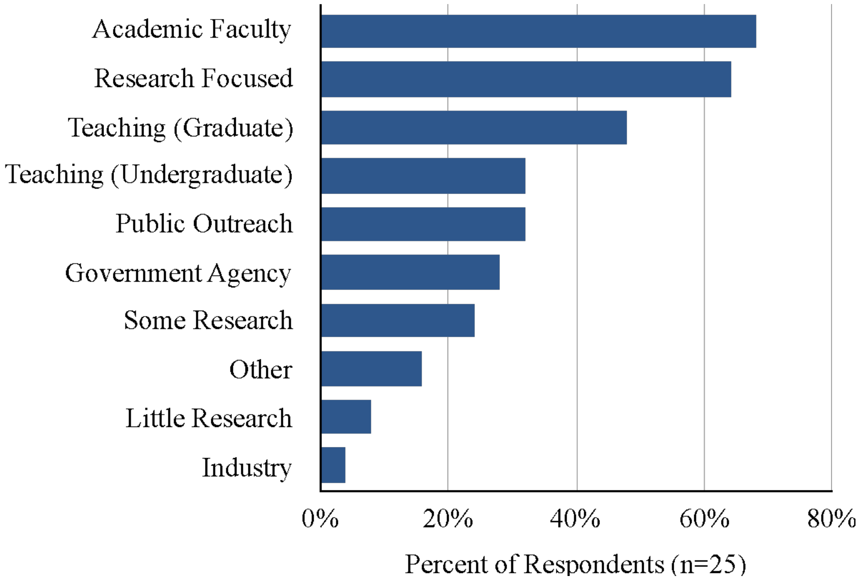


Figure 2. Future career goals of the 25 DISCO XXV participants where participants selected all applicable choices. The group's dominant career preferences are for academic faculty (68%) and research-focused (64%) positions. However, only 44% indicated a combined preference for both an academic faculty and research-focused position (for instance, some respondents preferred a research-focused government position, or an academic faculty position that is not predominantly focused on research). Many indicated interest in multiple potential career paths.

The research trajectories and career paths of early-career scientists are influenced by personal considerations and job availability, as well as their interests and skills. Short-term postdoctoral positions are important career stepping-stones, particularly for a research-focused academic career path, yet are accompanied by financial and geographic instability, and sometimes meager health and personal leave benefits. Early-career scientists who experience more pronounced personal constraints due to their financial situation, geographic limitations, or family and health issues may therefore be at a disadvantage in eventually securing a permanent position. This exacerbates existing underrepresentation of women and minorities in our field (recently documented for Ocean Sciences by *Cook et al.*, 2016). In order to recruit and retain talented scientists who represent a diversity of perspectives within the global community, we need to make Chemical Oceanography more inclusive of researchers from all backgrounds (e.g., race, gender, ethnicity, age, religion, disability status, sexual orientation, gender identity, national origin, socioeconomic background). This requires outreach and training to ensure that we effectively and equitably recruit students who represent our broader national and international community. It also requires policies to improve retention of scientists from groups currently underrepresented in Chemical Oceanography by facilitating equal career-advancement opportunities for people from all backgrounds, including those whose personal circumstances require a hiatus from the academic career path.

Diversity and retention concerns are widespread across all fields in science, and have been considered in detail elsewhere. Here, we highlight two actionable ways in which our community could improve diversity in Chemical Oceanography:

- The requirement of implicit bias training for scientists at all career stages facilitated by our academic and research institutions as well as funding agencies. Implicit bias has been shown to have significant effects on hiring, as well as other critical stages of an academic career [*Smith et al.*, 2015]. This training is particularly relevant for those who serve on admissions or hiring committees, manage or evaluate students or employees, and/or participate in the peer-review process for publications and grant funding. Chemical Oceanography can draw on recent successful models that have been proven to reduce bias when implemented in other fields [e.g., *Carnes et al.*, 2015; *Smith et al.*, 2015].
- Enhanced mentorship of early-career scientists. Mentoring plays an especially important role in the retention of early-career scientists within academia. Many early-career scientists seek mentors with similar personal backgrounds, which can make retention difficult when, for example, there are few women or non-white senior scientists available as mentors. The Mentoring Physical Oceanography Women to Increase Retention (MPOWIR) program [*Coles et al.*, 2011], which creates mentoring groups composed of early-career and senior women from multiple institutions, is one example of how mentorship can be provided through networks that expand beyond a single institution.

5.2. Communicating the science of Chemical Oceanography

Like fostering diversity and providing better mentoring for early-career scientists within Chemical Oceanography, validating and encouraging efforts to develop effective teaching and communication skills is an additional opportunity for progress. The field of Chemical Oceanography has significant relevance to society as it deals with important issues spanning local (e.g., sewage spills) to global (e.g., climate change) scales. Well-informed citizens are essential in building involved communities that are engaged in taking action, and for informing legislators and public officials. Thus, scientists at all experience levels have a duty to engage and inform the public, students, media, legislators, and stakeholders about the importance of the publicly-funded research they conduct. This can be as simple as having a practiced ‘two-minute talk’ [*Kwok*, 2013] about one’s research area, describing field work to a curious member of the public, or explaining to a congressional aide the need for Chemical Oceanography to remain a federally-funded research area. A more involved example of engagement could be the facilitation of a “citizen scientists” program that encourages the public to participate in community science. This type of active participation can foster interest and engagement that persists well beyond any scientific lecture or media story. Commensurate with career stage, knowledge base, and comfort level, scientists in our community can take part in outreach across a variety of media (e.g., social, print, internet), professional (e.g., presentations, science fairs, congressional visits), creative (e.g., poetry or art), and high-profile engagements (e.g., TED talks, Op/Ed pieces, nationwide TV and film appearances). The rapid and ephemeral nature of social media can be daunting, but can also be an effective way to engage an array of communities [*Peters et al.*, 2014]. The use of modern media platforms for scientific exchanges and outreach is one example of an arena where early-career scientists and students could take on leadership roles. Acknowledging the value of communication and outreach activities during career-evaluation exercises may be one way to greatly increasing the participation of chemical oceanographers in the pursuit of a well-informed citizenry.

Effectively communicating science to the public and stakeholders is extremely important; however, it does not come without the risk of backlash. Acknowledging the biases, expectations, and concerns of the audience in advance of communication is critical for positive interactions. Adequate preparation can help lessen the risk of confusing or unintentionally misleading an audience while enhancing the effective exchange of information. This leads to more informed decision-making by the public and stakeholders, and can leave a positive perception of the scientist and their field of study. Support from one's academic institution or funding agency can be key in helping a scientist navigate public communication and avoid becoming overwhelmed in the wake of an unanticipated scientific, political, societal, or economic flurry of activity (for example, studying a disaster such as the Fukushima Tsunami/radiation spill). The Office of Legislative and Public Affairs (OLPA) in the U. S. NSF works to promote science, engineering, and education research coverage in mainstream and targeted media. Scientists funded by the NSF can use this resource for assistance in creating outreach materials for the public or preparing to interact with the news media. Additionally, OLPA requires scientists to contact them about newsworthy research findings. To encourage scientists to communicate their science more broadly, this outreach obligation and the support provided through OLPA could be explicitly stated in NSF award letters.

Enhancing ocean literacy through an active discourse between our field and the public may require improvements to the media savvy of chemical oceanographers. Including media training as part of graduate curricula is one mechanism to grow our skills and comfort in communicating science to the public (*Dudo and Besley*, 2016 and references therein). An alternative to expanding graduate curricula is to increase awareness of and access to regularly offered communication trainings, such as the Alan Alda science communication workshops [*Weiss*, 2011]. In the recent past, communication trainings have been offered during large society meetings (e.g., the American Geophysical Union Fall Meeting and Ocean Sciences Meeting). These opportunities are open to all career stages and serve a secondary purpose of facilitating networking along with the training. Though not all scientists will seek engagement with the public, a goal of our community may be that all early-career scientists have the opportunity for training if desired. Only through participation in a dialogue with the public can we enhance the efficacy of our research and, perhaps, the acknowledgment of its relevance.

6. Concluding remarks

The field of Chemical Oceanography and the climate system are in states of rapid change, which means that our community is shifting, as are the questions we ask and how we go about answering them. Technology advancements in particular have revolutionized the speed, accuracy, and precision of laboratory and field observing capabilities, while evolving computational tools expand our capacity to test theories. With this growth comes the requirement of a broader skillset to keep up with our community's expanding tool kit; however, it is also important that we maintain a firm grounding in chemistry – our foundational tool. Our field is known for its major contributions to the development of geochemical knowledge by using skills and tools rooted in traditional areas of chemistry. Through this knowledge, Chemical Oceanography informs other fields and society about the Earth system and modern human impacts.

A flexible funding structure that supports research at various levels of maturity, rather than focusing too heavily on big programs or on individual research projects, may be required to achieve efficient resource use for studying a global system in transience. Exponential growth in the number of ocean observations made over the past 30 years has made it abundantly clear that *in situ*, global-scale observing is necessary to characterize the modern state of an ocean undergoing rapid changes. Large programs can continue to assist in this effort through global observing as well as process studies that improve the parameterizations used in models; particularly at interfaces where many of the largest and most understudied elemental fluxes occur. Accelerating the technology development required to accomplish ocean state estimates will necessitate enhanced interaction between Chemical Oceanography and the fields of chemistry, engineering, and computer science. This means that funding for cross-disciplinary research and technology development may need expansion. Additionally, some areas of Chemical Oceanography presently require synthesis funding to assist the development of new concepts and theories for incorporation into prognostic models. A flexible funding structure (duration and amount) to accommodate the different stages of readiness (e.g., project planning, technology development, data collection, synthesis, modeling, communication and outreach) and scales (time and space) of research in different subfields of Chemical Oceanography could help steer the course towards the most efficient and effective implementation of our resources and skills. This approach requires careful consideration of how to evaluate all equally important phases of knowledge development (hypothesis development and testing, tool creation and scale up, global mapping, mechanistic interpretation, simulation) and improve validation of time spent on community building efforts such as communication and outreach, synthesis, and mentorship – all of which contribute to the betterment of our field but, often, are not metrics incorporated into career evaluations.

The intersection of COME ABOARD and DISCO XXV provided a unique opportunity to reflect on the field of Chemical Oceanography through the perspectives of established and early-career chemical oceanographers. As representatives of the broader cohort of recent and forthcoming graduates, the specific and well-motivated recommendations from the early-career participants for implicit bias training and enhanced mentoring highlight pervasive issues in science that must be addressed. Our field can exemplify scientific leadership and tackle these seemingly intractable issues head-on by supporting a diversity of early-career scientists who will help lead the next generation from a variety of career paths. As the field of Chemical Oceanography and our major questions evolve, our efforts to facilitate diversity and shape the structure of how we interact with other science, industry, and education communities, as well as the public, will impact the perception and contributions of our field, scientifically and culturally. Acknowledging the dynamic nature of Chemical Oceanography and the myriad paths that early-career scientists may pursue can be an asset as we design modern frameworks for funding, outreach, training, and research in the 21st century.

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Supplemental Information

Table S1. COME ABOARD Meeting coauthors listed in alphabetical order.

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