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Perspectives on Chemical Oceanography in the 21st century: Participants of the COME ABOARD Meeting examine aspects of the field in the context of 40 years of DISCO

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A B S T R A C T

The questions that chemical oceanographers prioritize over the coming decades, and the methods we use to address these questions, will define our field's contribution to 21st century science. In recognition of this, the U.S. National Science Foundation and 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 research in Chemical Oceanography. Representing only a small subset of the community, COME ABOARD participants did not attempt to identify targeted research directions for the field. Instead, we focused on how best to foster diverse research in Chemical Oceanography, placing emphasis on the following themes: strengthening our core chemical skillset; expanding our tools through collaboration with chemists, engineers, and computer scientists; considering new roles for large programs; enhancing interface research through interdisciplinary collaboration; and expanding ocean literacy by engaging with the public. For each theme, COME ABOARD participants reflected on the present state of Chemical Oceanography, where the community hopes to go and why, and actionable pathways to get there. A unifying concept among the discussions was that dissimilar funding structures and metrics of success may be required to accommodate the various levels of readiness and stages of knowledge development found throughout our community. 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. Here we summarize the COME ABOARD Meeting discussions, providing a synthesis of reflections and perspectives on the field.

1. Introduction

The Dissertations Symposium in Chemical Oceanography (DISCO) is a United States-based, internationally-inclusive meeting of recent or soon-to-be Ph.D.s in Chemical Oceanography that is funded by the U.S. National Science Foundation (NSF) and 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

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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 cohorts of scientists who share ideas and knowledge throughout their careers. 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) the role of large 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. Research areas that were covered, therefore, largely reflect the interests of the 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. Advances in technology 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 discipline. 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.

Scientific advancements in Chemical Oceanography occur across a breadth of topics that range in their relevance to basic research and society. Periods of heightened public interest or coordination within the research community can result in rapid maturation of the science or its scale of application through targeted funding and community-initiated programs. Thus, there is some combination of readiness and opportunity that can catalyze scientific progress. One area of research presently being prioritized in Chemical Oceanography is global change, including its impacts on the cycling of elements in the ocean and the interactions between chemical cycles and ocean biology, physics, and geology. Notable scientific advances have been made through this focus; however, the simultaneous proliferation of new and exciting areas of Chemical Oceanography not directly linked to global change research speaks to the importance of maintaining a diverse research portfolio. While an asset to the field, realizing the depth and breadth of Chemical Oceanography caused the COME ABOARD group to abstain from identifying research directions based solely on the expertise of its attendees. Instead, the meeting evolved into discussions of how to enhance the field by fostering diverse research through updated career evaluation metrics, funding agility, community coordination, communicating with the public, and actively addressing retention issues.

It was acknowledged during COME ABOARD that different subfields of Chemical Oceanography are in dissimilar stages of maturity. Some disciplines are developing the tools necessary to automate sampling that will 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 would benefit from different funding models 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 large program. Alternatively, someone working at the land-sea interface may need to incorporate expertise from another discipline to make their next advance in understanding local processes that could benefit the global perspective. 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 collaborations, and may experience different levels of validation from peer-reviewed publications and immediate societal relevance. Acknowledging the varied 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 garnered unanimous support for the inclusion of early-career perspectives in this summary document. COME ABOARD themes 1 and 2 were merged to yield the six topical sections herein where we highlight opportunities for our community to embrace ongoing changes in the field and play an active role in shaping 21st century Chemical Oceanography.

2. Fostering tool and technique development in Chemical Oceanography

Chemical oceanographers develop and apply tools for the determination of standing 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 at equilibrium, and characterize molecular structures, while processes occurring in different oceanic environments (pelagic, mesopelagic, bathypelagic, benthic, hydrothermal, coastal) require a mechanistic understanding of temperature, pressure, and salinity effects. Our arsenal of chemical tools and techniques has assisted in quantifying and characterizing processes that occur over a wide spectrum of spatiotemporal scales throughout the Earth system. It has also helped answer pressing Earth science questions about the response of biogeochemical cycles to environmental forcing and their influence on ecosystem function. In particular, chemical oceanographers have played lead roles in describing and understanding past, present, and potential future planetary states and human impacts on natural systems. Ultimately, our tools and techniques help drive advances in other fields of oceanography and climate science. For example, Chemical Oceanography supports Physical Oceanography through the determination of water mass properties with constant improvements and diversification of tracers. Likewise, Biological Oceanographers use chemistry to assess the magnitude of the biological pump and characterize nutrient limitation of primary productivity. Scientific inquiry that arises in these and other fields, in turn, stimulates tool and method advancements within Chemical Oceanography. Amidst these iterative interdisciplinary interactions, tools and concepts may be discovered not only by deliberate design but also fortuitously, with their full utility only becoming evident over time.

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. Continuous advances require the development of new analytical tools and techniques to explore our evolving level of understanding. Fig. 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. Importantly, while some

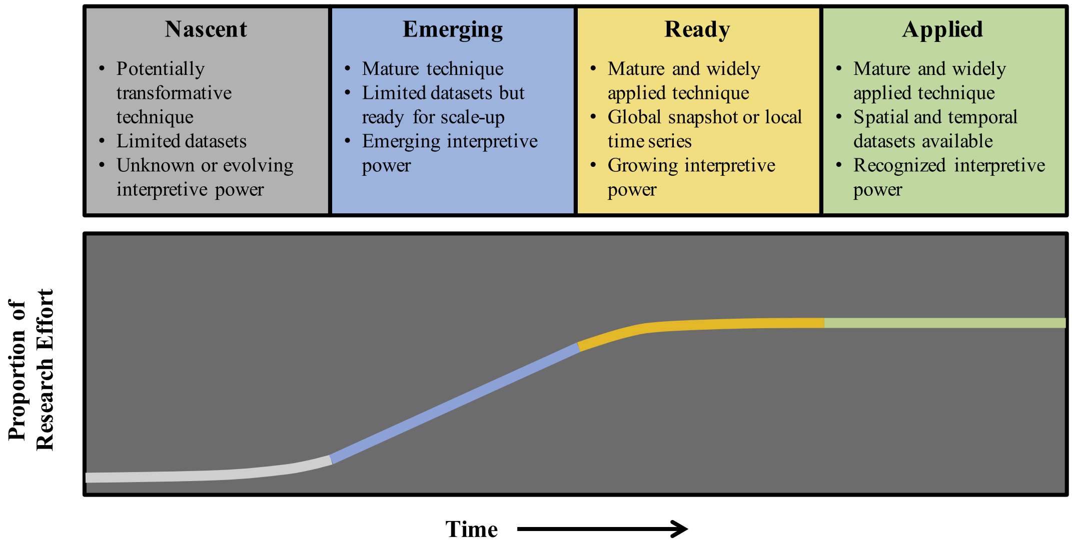

Fig. 1. Categories for existing geochemical techniques based on their current contribution to broad oceanographic understanding. Research effort in Chemical Oceanography is driven by the question(s) being addressed and the tools available to answer them. This determines the rate of transition through stages of readiness. Maximum growth in research effort will mark the turning point from "nascent" to "emerging" as opportunity, ability, and need create the impetus required to drive a particular research area forward. Nascent does not necessarily mean new, as many mature analytical methods remain nascent due to their evolving interpretive power and/or scale of application.

analytical methods may be quite advanced, their interpretation may still be evolving.

In parallel with advancing analytical tools and 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 depends on the rate of analytical progress, the formulation of biogeochemical hypotheses, 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 (Khatiwala et al., 2013; Sabine et al., 2004) and application of this knowledge at the societal level (Ciais et al., 2013). The ongoing large-scale 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). Bulk measurements of organic carbon pools in the ocean are improving our conceptualization of marine carbon cycling (Druffel and Griffin, 2015; Hansell and Carlson, 2013). Research on the cycling of specific organic compounds through proteomics, metabolomics, lipidomics and the chemical and structural characterization of organic matter represent *Emerging* areas of Chemical Oceanography. These types of measurements (e.g., Collins et al., 2016; Heal et al., 2017; Kharbush et al., 2016; Kido Soule et al., 2015; Koch et al., 2005; Pearson, 2014; Slattery et al., 2012) may have a solid theoretical basis 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), identified combined nutrient stressors in the Pacific Ocean (Saito et al., 2014), 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 method development are not always rapidly realized. Nevertheless, techniques such as the interpretation of certain compound-specific isotope ratios (Close et al., 2014; Coppola et al., 2014; Raven et al., 2016; Yamaguchi et al., 2017) or the determination of size-fractionated trace metal concentrations, trace metal isotopes, and organic ligand complexes (Boiteau et al., 2016a, 2016b; Conway and John, 2014; Fitzsimmons et al., 2017; Mawji et al., 2008) offer exciting potential for discovery.

As a field, we are becoming increasingly competent at assessing oceanic stocks, but the changing ocean environment highlights the importance of understanding the underlying processes that occur over a range of timescales and requires diverse experimental approaches to quantify. Geochemical tracers have successfully constrained in situ processes occurring over seconds to tens of thousands of years. Still, laboratory experiments are required to differentiate reaction pathways, assess the significance of reaction rates, and unravel underlying abiotic and biotic mechanisms (e.g., Luther, 2010). Optimal application of all analytical approaches, from *Nascent* to *Applied*, demands extensive time and effort for validation, quantification of uncertainties, and innovative data handling and analysis tools. 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. Harnessing automation and big data in Cheical Oceanography

A principal 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 spatially- and temporally-rich datasets needed for model development and verification can only be obtained through new technologies that enhance our sampling capabilities. Current advances include new measurement technologies that allow investigation of smaller quantities of material at much higher spatial and temporal resolutions, as well as new autonomous platforms to carry these technologies. 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.

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 analyze and archive "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;
4) how to develop and expand the scientifically trained work force

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

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

Key
Applied
Ready
Emerging
Nascent

needed to maintain hands-on scrutiny and utilization of exponentially increasing data streams.

Continued progress in data-analysis and quality-control approaches will be essential to keep pace with the increasing inflow of data. These 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 (academic and industry) in order to expand and harness the revolution in new technologies and data collection and to train the next generation of chemical oceanographers in thinking beyond traditional observational approaches.

4. Then and now: the role of large programs in Chemical Oceanography

Research in Chemical Oceanography 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 balanced research and is essential to the success of Chemical Oceanography as a field. Due to the long lead times and large financial investments associated with large programs, the COME ABOARD participants elected to discuss the role of these programs in our field. Large programs are defined here as projects with large spatial scales (global) or intensive study over a specific area or long timescale using multifaceted tools. These programs usually involve many institutions, international participation, and timescales longer than the typical three-to-five-year grant award. The impetus for this discussion came from a desire to reflect on GEOTRACES, a current large program that is primarily housed within Chemical Oceanography (Anderson et al., 2014; Mawji et al., 2015). Workshop participants generally agreed that large programs have led to breakthroughs in our understanding of fundamental ocean processes. As new technologies for data collection, sample analysis, and data processing continue to emerge, the amount of data generated from large programs will continue to expand. The greater production of publicly available data from these endeavors will in turn stimulate additional lines of scientific inquiry that lie outside the scope of, and investigators involved in, the targeted large program. COME ABOARD participants were mindful that large programs cannot come at the expense of small programs and single or dual investigator research that is critical to advancing our field. However, the group also acknowledged that the application of 21st century tools in large programs may actually facilitate single investigator research through the development of expansive interdisciplinary datasets available for community analysis. Below we provide some historical context and modern perspectives on the role of large 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 such programs have sought 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 (UNESCO, 1974; National Research Council, 1979) 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 (Brewer et al., 1985) in the 1980s, the World Ocean Circulation Experiment (Ganachaud and Wunsch, 2002) in the 1990s, 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; Hood, 2009), which all continued to document the evolution of tracers and CO_2. In addition, 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, which previously represented a weak link in our understanding of ocean carbon cycle drivers. Continuity between these programs and the expansion of observing capabilities over time has produced high-quality data that continues to fuel scientific discovery today.

In addition to advancing scientific understanding, existing large oceanography programs (e.g., CLIVAR, GO-SHIP, and GEOTRACES) are particularly good at providing networking and field work opportunities for graduate students and early-career scientists and at 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 large 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. This approach may be particularly useful for future large programs, which will likely move beyond quantifying ocean stocks toward addressing ocean processes that lie at the intersection of disciplines and ocean boundaries.

Given the technology advances that have occurred over the past decade, further consideration of how large programs can serve the entire Oceanography community is needed. The COME ABOARD group discussed the potential for a new umbrella-like initiative, perhaps similar in spirit to the International Decade of Ocean Exploration, to coordinate multidisciplinary research on topics that will impact society over the next century. These kinds of programs would likely place increased emphasis on synthesis in order to accommodate the generation of significantly more data from modern autonomous sensors and high-output technologies than was feasible in previous ship-based programs. One example of a modern large program is the ongoing Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM; https://soccom.princeton.edu/), which aims to deploy ~200 biogeochemical profiling floats in the Southern Ocean by 2020 with all data being made available in near real time. An embedded component of this project is the use of data assimilating models to make sense of the huge number of observations. Further, the public availability of these data will likely fuel independent physical, chemical, and biological oceanographic research that is not related to SOCCOM's mission or core scientific team, much like Argo has (Riser et al., 2016). Notably, SOCCOM (and Argo) data quality assurance (Johnson et al., 2017) hinges on high-quality ship observations for sensor calibration such that the inclusion of autonomous sensors augments rather than obviates ship-based oceanography. Nevertheless, our expanding abilities to obtain in situ data in real time are transforming Oceanography. This has exciting implications for the future of large programs including broader community inclusiveness through real-time data availability, the growing capacity for interdisciplinary work as instruments and sensors are miniaturized and automated, and enhanced data-model synergies, all of which increase the efficiency of community resources.

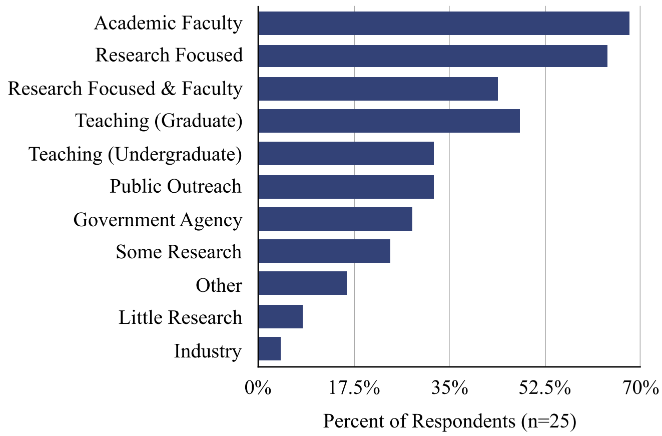

Fig. 2. Future career goals of the 25 DISCO XXV participants where participants selected all applicable choices. The group's dominant career preferences are for academic faculty (68%) and research-focused (64%) positions. However, only 44% indicated a combined preference for a research-focused academic faculty 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.

5. Coordinating interface research in Chemical Oceanography

A perennial motivation in Chemical Oceanography is to describe how chemical species are supplied to, cycled within, and removed from the ocean (Broecker, 1971). As the field becomes more sophisticated, we make new hypotheses and explore how these processes relate to each other and change with time. Interfaces between the ocean and other components of the Earth system are often regions of intense elemental cycling, yet their role in ocean chemistry and climate is particularly understudied. For example, while our understanding of CO_2 fluxes across the air-sea interface is well-developed (Bakker et al., 2016; Gruber et al., 2009; Takahashi et al., 2009, 2002; Wanninkhof et al., 2013), many characteristics of this ocean boundary remain poorly constrained, such as the fluxes of other climate-relevant gases, as well as 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., Global Environment Monitoring System and Global Rivers Observatory), yet few river systems have active monitoring of the material loads required to calculate chemical fluxes as a function of discharge. Even less is understood about submarine groundwater discharge, which constitutes a major link between the terrestrial and marine environments (Moore, 2010). Moving toward the sea, 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). While much is known about chemical cycling within a limited number of individual estuaries (e.g., Chesapeake Bay), an integrated, modern view of estuarine impacts on ocean chemistry is still lacking. At the continental shelf and open ocean interface, investigations into the physics and biogeochemistry of plumes, fronts, jets, and eddies are yielding novel, mechanistic insights into the connectivity between domains. In particular, the sediment-water interface represents the link between short-term land-ocean processes and long-term geological processes. Programs like JGOFS and the International Ocean Drilling Program have significantly improved our understanding of sedimentation, sedimentary biogeochemical cycling, and past climate (see discussions in Burdige, 2006; Aller, 2014), but studying fluxes across this interface is complicated by heterogeneity in space and time (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 stochastic or episodic 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). New technologies provide platforms for a myriad of sensors that have improved our ability to observe ocean interfaces. Still, designing, implementing, and integrating observational and modeling efforts to study these dynamic systems remains a challenge. Often, major discoveries emerge from the synthesis of (big) datasets encompassing multiple disciplines, research foci, and/or spatiotemporal scales. While a great deal of research is being conducted at ocean interfaces, the associated research communities and scientific outcomes tend to be somewhat regionally isolated or grouped by flux boundary, creating a need for coordinated scientific activities that cut across these perceived silos. Thus, the study of ocean interfaces may benefit from an enhancement of collaborative research programs designed to evaluate targeted and complementary ocean boundaries. For example, considerable and rapid progress can be made for some 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. The COME ABOARD participants recognized a need for interdisciplinary projects involving multiple investigators with complementary expertise who can work within a supported framework to address the large knowledge gaps that exist at the ocean interfaces.

6. Training the next generation of Chemical Oceanographers

In addition to the science itself, the people of Chemical Oceanography are critical to its success. The challenges associated with preparing graduate students for a range of future career paths and attracting and retaining chemical oceanographers from a diverse set of backgrounds have long been acknowledged, including in the 1988 retrospective on the first 10 years of DISCO (Green and Sackett, 1988). However, additional effort is still required to address gaps in professional development for early career chemical oceanographers and in recruitment and retention of women and other underrepresented groups.

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 (Fig. 2) as well as the realities of the academic job market. 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, students require opportunities 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.

The career trajectories of early-career scientists are influenced by personal considerations and job availability, as well as their interests and skills. Important career stepping-stones such as postdoctoral positions are often 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, Chemical Oceanography must be 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 the effective and equitable recruitment of students who represent our broader national and international community. It also requires policies to improve the 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 scientific fields, and have been considered in detail elsewhere. Here, we highlight three actionable ways in which our community could improve diversity in Chemical Oceanography:

1) Require implicit bias training for scientists at all career stages facilitated by academic and research institutions as well as funding agencies. Implicit bias has been shown to have significant effects on hiring, and on 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).
2) Enhance mentorship of early-career scientists. Mentoring plays an especially important role in the retention of early-career scientists in 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 to act as mentors. The Mentoring Physical Oceanography Women to Increase Retention (MPOWIR) program (Coles et al., 2011) creates mentoring groups composed of senior and early-career female scientists from multiple institutions and is one example of how mentorship can be provided through networks that expand beyond a single institution.
3) Provide opportunities for students in community colleges and minority-serving undergraduate institutions to gain research experience in Chemical Oceanography (e.g., undergraduate summer research programs that partner these institutions with research-focused institutions). Experience in other science fields (e.g., Hurtado et al., 2009; Schultz et al., 2011) indicates that such programs are important both to recruit underrepresented students to our field and to prepare them to apply for and succeed in Chemical Oceanography graduate programs.

7. Communicating the science of Chemical Oceanography

Much like addressing diversity and retention issues, efforts to enhance the communication skills of chemical oceanographers are essential to the future of the field. Well-informed citizens often build involved communities that engage with legislators and public officials, and people are most interested in information that pertains directly to themselves and their community (e.g., Ostrom et al., 1994). Since it is often publically funded, science can always be made relevant to the public through this lens. Additionally, 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. Some 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). Scientists at all experience levels can contribute to informing the public, students, media, legislators, and stakeholders about the importance of the publicly-funded research they conduct. 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). Acknowledging the value of communication and outreach activities during the funding process and career-evaluations may be one way to greatly increase 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 (e.g., studying a disaster such as the Fukushima tsunami and subsequent 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 public outreach materials or preparing for news media interactions. 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, such as 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 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.

8. Concluding remarks

Earth's climate system is changing rapidly and altering the environment that we, as Chemical Oceanographers, study. Our community is adapting by asking new questions, adjusting the spatial and temporal scales of our research, and developing and applying new tools.

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 tools and techniques 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 large 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. Thus, our field requires funding agility that can accommodate disciplines at varying stages of readiness, which could help steer the course toward the most efficient and effective implementation of our resources and skills. This will require careful consideration of how to evaluate all equally important phases of knowledge development, from hypothesis formulation to global simulations. Finally, community building efforts, such as communication, outreach, synthesis and mentorship, considerably enhance the contribution of our scientific findings. These activities should factor more highly in scientific 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 of 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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Appendix A. Supplementary data

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