Assessment of Future Science Needs in the Context of the Academic Oceanographic Fleet

An NSF-sponsored Workshop

August 9 & 10, 2000
Oregon State University
Corvallis, OR

Co-Chairs:
Tim Cowles, Oregon State University
Larry Atkinson, Old Dominion University

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Executive Summary

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Introduction

The 1999 Academic Fleet Review recommended that the oceanographic research community articulate a vision for the future of ocean science that contributes to the next generation of research vessels required to meet the future scientific needs of the community. In response to this charge, and as a complement to the "futures" documents developed by oceanography disciplines over the past three years, we conducted a two-day workshop in August 2000 that brought together members of the research community to:

- identify potential observational/experimental approaches that may be used to address fundamental questions in ocean science over the next 20 years,
- identify the characteristics of different research platforms that could provide the capabilities for meeting the identified technological requirements, and
- evaluate the role of research vessels and potential trends in vessel utilization within the context of other observational platforms.

Workshop participants addressed these objectives through evaluation of several complementary themes that have emerged from the ocean science community (see 'futures' documents and Brewer/Moore report). Versions of these themes will provide the foundation for major interdisciplinary research initiatives over the next two decades. Workshop participants extracted some of these themes and used them to focus the discussion of future science needs and to attempt to define the path from science needs to vessel capabilities. The following brief outline gives the major headings that guided our discussions.

Examples of themes that will grow in importance over the next decades

Better Observations in Selected Environments
Interdisciplinary Studies
Coupled observation-modeling systems
Perturbation Experiments
Fixed Location Observations/Experiments

The full report expands upon each of these headings and associated sub-headings to draw out future science needs that have some dependency upon research vessels. In this Executive Overview we highlight the major findings and recommendations that emerged from our discussions.

Critical Issues

Some important issues emerged from our discussions that overlapped all the thematic areas. Workshop participants agreed that a failure to confront these issues will hamper the ability of the research community to address the next generation of questions in ocean science.

1. Greater spatial and temporal resolution of ocean processes will permit ocean scientists to detect and respond to events through focused investigations of relevant forcing mechanisms. The need to respond to intermittent events will require more flexibility in our ship scheduling process.
2. The growth of multi-investigator, interdisciplinary studies has fostered the development and increased use of sampling packages that carry multiple sensor systems. Future science needs will require these multi-sensor systems to make coincident and co-located measurements of the same sample volume by all sensors, including acoustic and optical sensors.
3. Complex observational systems will require well-trained technical support staff, on board ships and in the laboratory. It will be critical to develop new strategies to attract and retain the technical personnel required to support these complex systems.
4. The Integrated Ocean Drilling Program will put new demands on our academic fleet. We expect greatly increased demand for sea floor site surveys (high resolution sea floor mapping, coring, imaging of geological sections, etc). This increased demand cannot be met with the existing UNOLS fleet.
5. Improvements in communication/data transfer are a central issue for almost all the new science on the horizon. It is clear that maturation of ocean modeling will contribute to the design and execution of process experiments at sea. The assimilation of experimental results into models, using real-time communication links, will lead to rapid refinements in predictability and adaptive sampling. In addition, improved communication will enhance public outreach and provide a new range of educational opportunities based on real-time ocean science.

Observational Systems to Support Future Science Needs

The workshop participants agreed that use of new observational tools in ocean science will continue to expand our ability to address long-standing science questions, and will provide the means to resolve, on the requisite time and space scales, many of the mechanisms that control ocean processes. The fundamental message from the "futures" documents is the essential need for expanded temporal and spatial coverage of oceanic phenomena. New observational tools and systems (e.g., AUVs, ROVs, observatories) will address this need by ***extending*** the reach of the fleet, but these new systems ***will not replace*** or reduce the fundamental use of vessels to conduct specific observational and experimental research at sea.

We assert that the next two decades of ocean science will witness the maturation of the on-going merger of observational, experimental and modeling work over a much wider range of time and space scales than has been possible to date. To this end, we further assert that the *scientific needs (observational and experimental) of ocean science over the next two decades require the implementation of:*

A. **Remote observational systems with robust sensor suites** (limited to a few variables), such as satellites (color, SST, winds, currents, etc), long-term moorings, drifting platforms (single depth and vertically cycling), and autonomous vehicles.
B. **Vessels with improved capabilities to provide deployment/recovery/service** for moorings, drifters, vehicles, and other tethered and untethered objects.
C. **Vessels with improved capabilities that function as primary observational/experimental platforms** across a wider range of sea states than possible today.
D. **Vessels that can meet the expanded mapping, seismic, and coring needs of the marine geology community** as the Ocean Drilling Program moves into the next decades of research.
E. **Global high-bandwidth communication capability** will fuel real-time interaction and data exchange between remote sensor suites, vessels, and land-based or ship-based laboratories.
F. **Rapid response capability** within the oceanographic fleet, such that vessels/remote systems are available to respond to "events" detected by observational systems.

Each of these sets of capabilities for the existing (and future) version of the academic fleet is derived from a consideration of the science needs that emerged during the workshop (details are listed in the full report).

Recommendations and Conclusions

Our evaluation indicates that demand for shiptime will increase as the fleet supports an expanding range of remote observational tools while continuing to support basic research efforts in all disciplines. We expect a significant increase in the shiptime required to support the anticipated expansion of new observational systems. In addition, we expect no reduction in the shiptime required to conduct experimental work into the mechanisms that drive the ocean processes, particularly as the new observational systems reveal patterns of variability at higher resolution. As we stated earlier, new observational tools will ***extend*** the reach of the fleet, but ***will not replace*** or reduce the fundamental use of vessels to conduct basic observational and experimental research at sea. This "dual use" of the fleet will lead to increased demand for shiptime.

We conclude that the community will require an academic fleet with expanded capabilities beyond those available today. The need for expanded capabilities is driven by the requirements of the pending scientific questions, as well as by the continual technical advances in sensors and observational systems.

We recommend that the scientific users of the research fleet have a role in the decision-making process about types/capabilities of vessels as defined by science needs.

We strongly recommend that the NSF, ONR, and NOAA establish a process for evaluating new models for vessel scheduling as higher temporal and spatial resolution observations of ocean processes will lead to greater pressure for "event-scale" vessel availability.

Assessment of Future Science Needs in the Context of the Academic Oceanographic Fleet

Workshop Report

1. Introduction

As our scientific discipline of oceanography has grown over the past several decades, our fundamental need for dependable observations of the ocean has grown as well. Research vessels have served as the critical platforms for those observations, although oceanographers have expanded the types and extent of observational and experimental approaches to include systems as diverse as satellites, remotely operated vehicles, and molecular probes. As we look into the next ten to twenty years of scientific research into ocean processes, we must consider the wide range of observational and experimental capabilities that scientists will expect from the Academic Fleet. These capabilities and requirements then can guide the design and construction of the next vessels in the fleet.

The 1999 Academic Fleet Review emphasized the need for a defined process for replacing aging vessels in the fleet, and charged the Federal Agencies to develop such a process. A critical complementary recommendation charged the oceanographic research community to articulate a vision for the future of ocean science so that the next research vessels effectively meet the scientific needs of the community for the next two to three decades. Many general aspects of that vision have been addressed in the broad-ranging disciplinary “futures” reports and in the draft GEO2000 report (Brewer and Moore, 2000). In an effort to incorporate those wide-ranging ideas into a discussion of future observational demands of the scientists who use research vessels and other observing platforms, we conducted a two-day workshop in August 2000 that brought together members of the research community and charged them to:

- identify potential observational/experimental approaches that may be used to address fundamental questions in ocean science over the next 20 years,
- identify the characteristics of different research platforms that could provide the capabilities for meeting the identified technological requirements, and
- evaluate the role of research vessels and potential trends in vessel utilization within the context of other observational platforms.

The participants (see Appendix) were asked to consider the three points listed above, and prepare draft vision statements in advance of the workshop, particularly in the context of the disciplinary “futures” documents. These draft documents were read and discussed during the first morning of the workshop, and provided all participants with common ground for elaboration on the workshop objectives.

2. Our Premise

Our understanding of the biological, chemical, geological, and physical processes of the ocean depends upon the scale and scope of our observations. That is, identification and exploration of the mechanisms that control ocean processes must occur within the context of some range of temporal and spatial observations of specific phenomena. Without adequate observational coverage in time and space, we must make assumptions about the mechanisms that create the patterns we observe, and must remain uncertain about the scale on which to focus our experimental approaches. The next two decades of ocean science will bring greater integration of observational and experimental work over a much wider range of time and space scales than has been possible to date.

This premise, in conjunction with the several themes that emerged from the oceanography disciplinary futures reports, provided the context for examination of the workshop objectives. Discussion of the thematic topics (see following section), and the science questions within them, revealed a number of important operating capabilities for future research vessels. In addition, the discussion led to the conclusion that scientific needs over the next two decades will lead to an increase in the size of the research fleet.

3. Common Themes

The following topics represent examples of scientific themes. (The co-chairs and participants all wish to stress that these headings are meant to be representative and were used to provide examples for discussion. These headings are not intended to be all-inclusive).

Better Observations in Selected Environments
Interdisciplinary Studies
Coupled observation-modeling systems
Perturbation Experiments
Fixed Location Observations/Experiments

We now expand upon these headings based on our discussions at the workshop.

3.1 Better Observations in Selected Environments

Coastal Oceans

Understanding the biological, chemical, geological, and physical processes in the coastal ocean is critical, as the processes in this region have a direct impact on society. There are numerous scientific questions that need to be addressed. How is material transported across the shelf between the shore and the open ocean? How does this transport vary geographically and temporally? What is the role of coastal topography and local bathymetry on the rates of cross-shelf transport? These are just a few of the scientific issues that will impact the use of fleet resources in the coastal zone.

In the coastal ocean, the spatial and temporal scales of variability of water properties are much smaller and shorter than found in the open ocean. With these smaller scales, it is necessary to sample the ocean much more quickly and at higher resolution than has been done to date. This sampling approach will place greater demands on the capability of the ships and ancillary observation platforms, such as AUVs. Increased interdisciplinary research will require ships to carry more scientists and deploy more instruments. The ships will be expected to work in harsh conditions but still be able to navigate in shallow waters.

High-Latitude Open Ocean

In the next few decades, a major focus for oceanographic research will be on the physical and biological structure of high latitude portions of the northern and southern hemispheres and the response of these regions to climate variation and climate change. The global warming patterns evident today are predicted to have maximum impact on the northern North Atlantic Ocean. Research efforts will be motivated by the need to understand the driving forces for deep and bottom water formation and changes in the circulation patterns in response to changes in basin-scale air-sea interactions. Research will also be motivated by a need to understand the dynamics of plankton, the impacts of environmental perturbations on their distributions and abundance, their rates of growth and mortality, and their linkages to exploited fish stocks. Major internationally coordinated expeditions to these areas are now in the planning stages and will require research vessels that can withstand the rigors of the high winds and sea states typical of high-latitude regions in winter.

Ice-covered Regions

Ice-covered regions are an example of marine environments for which present ship capabilities are inadequate for future research needs. There are compelling reasons for continued, and increasing, oceanographic research in Antarctic and Arctic systems. Polar regions are of vital importance in terms of ocean circulation, sequestration of atmospheric carbon dioxide, global climate patterns, and marine resources. High latitude systems are predicted to show early and intense responses to global warming. Breakup of ice shelves on the Antarctic Peninsula, and recent decrease in extent and thickness of the Arctic ice sheet, may be indicators of global-scale warming effects.

Logistical difficulties make oceanographic study of polar regions a challenge. This is particularly true for the Arctic Ocean, where more infrastructure in support of Arctic research is needed; currently considerably less infrastructure support is provided for Arctic research compared to support provided for Antarctic research. Research in ice-covered environments will require both large ice-breakers and ice-hardened smaller vessels able to work in regions with partial ice coverage. Considerations for ships working in these regions include the hazard of extreme cold, extended cruises of a month or more, need for easy access to the ice surface from the ship for some programs, constraints on some routine oceanographic procedures when working in dense ice, e.g. towing, and inadequate communication with home laboratories. Land stations, ice camps, moored and drifting instrument packages, observatories such as the recently initiated North Pole observatory, atmospheric sampling with airplanes or balloons, under-ice sampling with submarines or remote vehicles, and satellite remote sensing will also continue to be essential for adequate data collection in polar systems.

In the future, research in polar oceans will increasingly involve multi-investigator, multi-disciplinary, and multiple platform expeditionary programs. Recent examples are the JGOFS Southern Ocean Program, the 1994 Arctic Ocean Section (AOS), and the 1997-1998 Surface Heat Budget of the Arctic Ocean (SHEBA). The SHEBA project, in particular, provided a platform for sampling the central, ice-covered Arctic Ocean for an entire year, including the winter. Lack of data during winter is an ocean-wide problem; this is especially true for polar environments in which ice and weather conditions preclude operation of most existing ships. The addition of the new U.S. Coast Guard research icebreaker *Healy* extends the research capabilities and scientific options for polar investigations.

Ships for near-future research in polar systems thus will need to meet requirements of 1) increase in number of P.I.'s and projects, particularly in the Arctic, 2) increasing infrastructure needs, including servicing of remote moorings, observatories, and ice camps, 3) under-ice sampling and sampling during the polar winter, and 4) large, multi-disciplinary projects. The SHEBA project, in which a Canadian ice-breaker frozen into the permanent Arctic ice pack served as the support hub of ice huts and instrument packages deployed around it, was a resounding success. This could be a model for future ship-ice camp expeditions. U.S. Arctic research in particular could also benefit from international cooperation in major projects, in terms of personnel and platforms, particularly with the Canadians.

Sea Floor – Mapping

The UNOLS fleet of the future will face increasing requirements for seafloor mapping - precise, high-resolution bathymetry and sidescan sonar data to infer seafloor roughness - for a range of scientific purposes. Seafloor surveys of planned ocean drilling sites will be a significant demand. Others will include the need for detailed bathymetric maps as necessary boundary conditions for circulation model runs in a variety of settings: coastal/shallow provinces, continental slopes, deep ocean ridges, and in general any areas in which complex topography is an important influence on local or regional flow patterns.

For the foreseeable future, shipborne multibeam sonar systems will be the method of choice for this work, augmented in some cases by high-frequency multibeam systems carried near-bottom on towed or autonomous vehicles. At the shallowest depths and therefore highest acoustic frequencies, such shipboard systems are relatively compact. They can be added or retrofitted to existing ships and readily designed into new ones, provided the ship acoustic self-noise signatures do not interfere. Some new vessels should be planned with hull-mounted multibeam capability, with careful consideration of the balance between vessel size, required depth range of mapping, and maximum size and type of acoustic array. In the process, attention must be paid early in the design process to the overall acoustic characteristics of the hull and internal machinery, and to the noises imposed by such other ship features as thruster openings or through-hull instrument wells. These openings may require smooth and reliable closures for acoustic success. Careful thought about all acoustic systems on the ship, for science and ship operation, will be required in advance to avoid problems of inter-system interference.

Increased accuracy requirements for seafloor surveys will demand, among other features, the best available attitude (heading, pitch, yaw) information attainable at the sampling frequencies needed by the multibeam systems. This is a rapidly evolving area of technology, and the main point is that, like basic navigation, the best achievable attitude sensing systems will always be wanted by the users and should be upgraded frequently. Since the same attitude information is needed by other systems (ADCPs and related instruments), albeit at different sampling frequencies, it makes sense to consider installation of such a system that can effectively serve all the onboard clients for such information.

Currently, multibeam systems for seafloor mapping generally discard the acoustic signal backscattered from within the water column. However, depending on the acoustic frequency, this signal contains much potentially useful information on organisms of different size categories within the column, from fish to zooplankton. If the acoustic system can be reliably calibrated in absolute terms, something not essential for the mapping function alone, then this biological information could in principle be recorded and utilized to build one aspect of a biogeographic data base or for more focused studies. Since there will be continued effort to collect and archive the seafloor data along ship tracks regardless of the specific onboard program, it makes sense to extend the same data acquisition and archiving approach to the water column signals. This may have significant implications for shipboard data acquisition and mass storage capabilities, even though it may not change the physical sonar design or installation considerations greatly. It requires interaction with multibeam manufacturers to modify the signal processing and data recording of standard systems.

Sea Floor and Earth Processes

Many science questions have emerged from investigations of sea-floor spreading centers and mid-ocean ridges. It is critical to understand the role of hydrothermal fluid circulation through crustal rocks along the ridge axis as a regulation process of ocean chemistry in addition to the impact on the long-term chemical evolution of ocean. The hydrothermal vent fields also play a critical role in deep-ocean ecology and introduce major questions about the evolution and dispersal of deep-ocean flora and fauna. Deep submergence vehicles and their surface support vessels are an essential component of this research field.

The results of the Ocean Drilling Program have established a foundation for the next stages of investigation through the internationally-supported Integrated Ocean Drilling Program. Planning documents for the next decade of the Ocean Drilling focus on the following major scientific topic areas.

- The discovery of extensive and active microbial assemblages in deep sedimentary rocks and basaltic crust raises complex questions about the origin of life on earth, and the role of biological processes in the transformation of geochemical substrates in extreme environments,

- The discovery of fluids flowing along thrust fault zones raises important questions about the role of fluids in the mechanics of faulting, and may provide new insights into earthquake dynamics.

- Recent discoveries of extensive sub-seafloor gas hydrate reservoirs raises important questions about the global carbon budget, about the stability of continental slope sediments, and about the extractions of these deposits as an energy source.

- Fluid circulation through crustal sections has been confirmed by deep ocean drilling. This circulation has important implications for our understanding of deep ocean chemistry, crustal changes, and the deep ocean/deep sediment biosphere.

- Societal impact of rapid climate change coincides with our ability to evaluate the factors associated with ancient climate variability over a range of time scales. It is essential that we possess the ability to extract sediment cores from a wide range of deep ocean environments in order to address these critical questions.

The marine science community will use specialized drill ship technology (riser and non-riser) to address aspects of each of the above topics. However, important components of each topic rely on the use of non-drill ship platforms to meet the scientific requirements. In particular, high-resolution mapping of the sea floor and high-resolution seismic imaging must be done at each site before the drill ship begins work. In addition, high-resolution cores (e.g., large diameter piston cores) must be obtained for examination of short-term and long-term climate variability. These extensive requirements go beyond current capabilities of the UNOLS fleet for coring and seismic work. It is also expected that increased use of ROVs and/or manned submersibles will be required.

Air-Sea Interactions

Surprisingly, the surface of the ocean is currently one of the more difficult regions to conduct research. Many areas of air-sea interaction studies, for example gas exchange, heat and momentum fluxes, and surface circulation, are affected by the presence of the sampling platform. Similarly, boundary layer atmospheric studies and validation of remote sensing platforms like ocean color sensors are affected by the presence of a ship. The bow wake and propeller wash from ships tend to destroy the natural structure in the uppermost 5 m of the water column, while engine exhaust changes the atmospheric chemistry. Even while drifting the presence of the ship hull modifies the flow and structure of the surface layer of the ocean and atmosphere. All of these issues become more complex and less understood as wind speed and sea state increase. New shipboard sampling technologies need to be developed to improve our ability to study the air-sea interface without disturbing the water surface, the upper meter of the water column, and the atmosphere just above the sea surface. It is particularly important to incorporate new air-sea sampling technologies into the new vessel designs that will allow us to work in higher wind and sea state conditions than presently possible. We anticipate that these air-sea interaction questions and sampling technologies will impose constraints on vessel design and construction.

Benthic Boundary Layers

Recent observations and modeling efforts have revealed the importance of the benthic boundary in several areas, including transmission of benthic boundary mixing to the interior of the ocean, recirculation/redistribution of material on continental shelves, determination of the fate of sinking organic matter, and establishment of appropriate boundary conditions for high-resolution circulation models. Several of these scientific issues have direct societal impact, such as how long it might take for toxic waste dumped on the ocean floor to mix into the deep ocean, or be returned to coastal beaches.

Making measurements in the benthic boundary layer is a difficult process. To date, most measurements have been point measurements made by placing instrumentation on the ocean bottom. There is always a question of whether local topographic effects are dominating the observations. Thus, it is necessary to have accurate high-resolution bathymetry in these regions. It is possible that this small-scale bathymetry will change with time. It is also necessary to make high-resolution horizontal resolution measurements within 5m of the bottom. Finally, mixing processes are intermittent and require long time series of measurements.

These issues will require integration of sea floor mapping, precise navigation and station keeping, communication with instrumentation (remote and autonomous vehicles), and new mooring approaches.

3.2 Interdisciplinary

Expeditionary Scale Research

Societal pressure to understand global climate processes and the need to understand the ocean's role in climate change have lead to a distinct trend in oceanographic research towards connecting the physical, chemical and biological responses of the ocean. Over the next two decades this trend is expected to intensify as we seek to understand the coupled responses of specific key regions of the ocean.

The interdisciplinary programs that are needed to achieve these research goals produce significant demands on existing ships through their need to house large numbers of investigators responsible for the determination of a diverse array of parameters. While it can be expected that miniaturization and automation will lead to reduction in shipboard space requirements for instrumentation used for core measurements, ongoing research and the development of techniques for new parameters that are deemed relevant to disentangling coupled responses will be added to the matrix, thus providing a continually increasing pressure for bunk and laboratory space.

An additional constraint on research projects that intend to cover large oceanic regions will be the need to minimize station time by maximizing sampling effort on station through simultaneous deployment of multiple sampling devices.

Acquisition of larger ships will ameliorate laboratory and bunk space pressure although the ability to use larger ships efficiently for smaller scale projects may ultimately limit the size and number of such ships that are incorporated into the fleet. Alternatively space pressures can be mitigated by the use of multiple ships for such cruises. This latter solution has the advantage of maximizing the use of station time by permitting deployment of multiple sampling devices. However, in cases where physical sharing of samples amongst PIs is required (a common requirement for many coupled projects) inter-ship transfer problems will make multi-ship operations logistically complex. In such cases the ability to deploy and to easily recover free-floating sampling devices will significantly improve ship use efficiency.

Mesoscale/FineScale/High Resolution

Vision: A system of AUV’s, buoys, moorings and satellite systems providing near real-time visualization to biogeochemists, on appropriate time and space scales, of the advective and diffusive characteristics of a mesoscale feature.

The complexity of processes in the oceans increases at finer and finer temporal and spatial scales. While traditional technology gave glimpses into these phenomena, recent results from towed, profiling and remote sensing systems have revealed new insights at smaller and smaller scales.

Mesoscale and mixing processes have long been recognized for their importance in many biogeochemical processes but technology has limited observations. All “futures” documents envision that in the coming decades oceanographic missions will address many of the questions related to these processes using emerging technology. The technology will include the merging of assimilative models with real-time observing systems. Models are now or will soon be available that, given the proper data, can provide accurate visualizations of the three dimensional physical environment. Such visualizations will facilitate biogeochemical studies at adequate resolutions.

The key to progress will be merging satellite-based remote sensing (SST, SSA, color, wind, wave) with in situ observations from moorings, drifters, profilers, AUV, ROV's and bottom-mounted systems.

What is the impact on research ships?

> Ships must have the telecommunication bandwidth to acquire data from the sensor systems (both in the water and air) and communicate with satellites and land. Model and observational data must flow seamlessly from ship to sensor systems to land.
>
> Ships must have the ability to launch, retrieve and communicate with multiple underwater vehicles.
>
> Ships must be able to deploy, retrieve and communicate with drifting and fixed sensor systems.
>
> Ships must provide more laboratory facilities for the increased level of sampling by biogeochemists

Biodiversity

There is a growing recognition that for most regions of the oceans, biodiversity has been poorly characterized. Quantification of the numbers of species and relative distributions of individuals among species will likely remain a challenge for biological oceanographers during the next two decades. Such studies increasingly will focus on poorly understood waters including waters in higher latitudes and abyssal regions of the oceans. Sampling will entail oceanographic cruises that utilize available and emerging technologies to sample marine life and the physical-chemical conditions of their habitats. While the tools used to enumerate life in the sea are constantly improving, it is likely that sampling will involve physical collection systems (e.g. nets, dredges, grabs, pumps), optical and acoustical remote sensing, and a suite of manned submersibles, remotely operated and autonomous vehicles. Advanced molecular genetic techniques will be used at sea to extend the range of conventional taxonomy.

Biodiversity studies will, depending upon the sampling location, require multi-purpose ships capable of operating in adverse sea conditions for extended periods. The fleet will have to retain a more specialized capability to support submersibles. A flexible capacity to support the varied suite of sampling systems will be essential and considerations should be given to development of high speed and high capacity winches, as well as addition of motion-compensating winches for work in higher sea states. Multiple vehicles may need to be deployed from one vessel simultaneously. Analysis of data from seafloor mapping systems should be extended to allow their use in water-column surveys.

3.3 Coupled Observation - Modeling Systems

The vision for the real-time coupled observation modeling system is implementing for the ocean what meteorologists provide routinely for the atmosphere. One of the outstanding challenges of observational oceanography is the simple problem of simultaneously characterizing spatial and temporal variability. The vast reaches of the ocean, relative to our ability to sample it synoptically, make it necessary to integrate our observations with models to develop a true sense of ocean structure and dynamics. This is especially relevant for investigations requiring characterization of the physical, chemical, and biological properties of the water column. The problem is that the ocean's interior changes faster than we can measure it. Substantial improvement in sampling approaches is possible as new low cost autonomous platforms come on line, offering the prospect of having coordinated sensing platforms. These systems become even more attractive as new chemical and biological in situ sensors become available.

As the capabilities and cost of at-sea assets increase, there is a growing pressure to use those assets optimally. In part this has to do with placing sampling assets at the right place at the right time, and in part it has to do with assimilating data from a variety of sources into a coherent picture. The two problems are linked, and there is substantial interest in achieving real-time coupled observation-modeling capabilities to address both of these problems.

While creating coupled observation-modeling systems is primarily the province of physical oceanography, such systems would have substantial benefits for scientists studying the biology and chemistry of the ocean. Not only are those scientists greatly handicapped by the difficulty of making measurements, but their measurements must be placed within an accurate hydrographic and dynamic oceanographic context to be interpretable. This requires coincident measurement suites for integration into assimilative modeling systems.

3.4 Perturbation Experiments

Perturbation experiments can be grouped in to three broad categories: natural, deliberate, and anthropogenic. Examples of natural perturbation experiments are the detection and study of seismic events such as undersea volcanoes, earthquakes and ‘land’slides, physical events such as storms, eddies (e.g. warm-core rings), biological events such as red tides. Deliberate experiments can include actual perturbations of systems, for example iron fertilization and suppression experiments, and deliberate introduction and tracking of Lagrangian tracers (floats, dyes, isotopic labels, fish and marine mammal tagging), among others. Anthropogenic perturbations might include oil spills and fisheries actions.

The desire and opportunity for perturbation experiments will only increase in the future. The ability of the oceanic community to observe extreme phenomena that create natural perturbations and to respond to these phenomena has increased-- witness the rapid response to remotely-detected undersea eruptions. The frequency of this sort of experiment will only grow as the number of time-series stations, long-term observatories, and undersea observatories with near real-time data transmission to land-based personnel, and the reliability and diversity of the ocean-observing satellite fleet grows. The ability of the research community to define and then deliberately perturb controlled settings within the ocean has also greatly increased; an example is the success of recent iron fertilization and suppression experiments. Recent developments in the technology allowing oceanographers to tag and track water parcels, chemical constituents, and populations within ecological assemblages will lead to an increase in the number of experiments performed in the Lagrangian frame of reference. The steady development of technologies that allow rapid, near real-time quantification of physical transport fields (e.g. ADCP); physiological status of plankton communities (e.g. Fast Repetition Rate fluorometry); and high-resolution chemical distributions (e.g Pumping SeaSoar) means these deliberate experiments are likely to become the norm in the future of oceanographic research. The anthropogenic impact on the sea will only increase as population and international trade and exploitation of ocean resources grows and fisheries management turns more and more to brief, intense, selective removal of certain species.

3.5 Fixed Location Experiments

Long term time series observations in the ocean

Although ocean scientists have always understood the importance of repeat observations in the ocean to understand temporal variability, most research effort in the past has gone into exploring and describing the ocean as a whole and into process studies designed to understand specific phenomena. There have been few systematic long-term observations. Some of the early time series include the ocean weather ships, which collected oceanographic as well as atmospheric data, the Bermuda time series station, and the CalCOFI program. There is now a very strong interest in continuing the existing time series observations and establishing new ones. The apparent global warming that has occurred during the past few decades and the ice core observations showingdramatic changes in climate on decadal time scales in the past have given a sense of urgency to understanding interannual to decadal variability in the ocean, how this variability affects the oceans' ecology, and how it is coupled to variability in the atmosphere. During the past decade some new time series sites have been established, notably the HOTS station, the LTER study region north of Palmer Peninsula, and several sites in the North Atlantic in regions where North Atlantic Deep Water forms. Many other sites are planned as part of international climate programs such as CLIVAR.

The two primary methods of obtaining repeat observations at particular sites in the ocean are taking oceanographic stations from a ship and collecting data from moored instruments. Both methods are generally used with high frequency observations of a limited number of parameters obtained from moorings and lower frequency observations of a greater number of parameters and with greater spatial coverage, obtained from ships when the moorings are serviced. The mix of these methods varies depending on the type of data being collected. The most ship intensive are long term ecological studies, such as CalCOFI and LTER which require surveys involving on the order of 100 stations and the least ship intensive is the collection temperature and salinity data at a specific site from a mooring.

In the future, new and better in situ sensors will be developed for use on moorings, it will be possible to collect and store water samples from moorings to analyze when the mooring is serviced, and data collected from moorings will be transmitted back to laboratories in close to real time. These advances will increase the amount of data collected dramatically, but ships will still be required to make particular observations and to service the moorings. Typically moorings must be serviced on an annual basis, although technical advances may increase this to two years in the future. The rapid transmittal of data from moorings to the lab will provide the information needed for event sampling. This will be possible from the moorings, but for some studies a ship will also be needed with a short lead-time.

4. Integration of Scientific Themes with Vessel/Technical Issues

Some important vessel/technical issues emerged from our discussions of specific scientific themes. These issues overlapped all the thematic areas. Failure to address these issues over the next several years will hamper the ability of the research community to address the next generation of questions in ocean science. These issues are distinct from specific capabilities suggested for new vessels in the fleet (see Section 5).

4.1 Greater spatial and temporal resolution of ocean processes will permit ocean scientists to detect and respond to events. The resolution of the observational network will define the types of events that could be investigated. We have demonstrated during this past decade, for example, that an equatorial array of moorings can provide a framework for responding to El Niño events. As each discipline has recognized, many processes in the ocean and atmosphere are driven by the variability created by events, and are not driven by the long-term mean conditions. The compelling argument in all "futures" documents for more extensive observational systems is based on the essential need to define variability, and not assume that intermittent snapshots represent the mean condition. Our present approach to ship scheduling limits our ability to respond to intermittent events. This will be an impediment to progress as oceanography broadens the scale and scope of observations.

4.2 The development and increased use of multi-sensor platforms highlights the critical need for coincident and co-located measurements of the same sample volume (water or sediment) by all sensors. For example, optical and acoustic sensors used in plankton ecology may sample water volumes 10s of meters apart if the sensors are carried on the same underwater platform.

4.3 Complex observational systems will require well-trained technical support staff, on board ships and in the laboratory. Most of the academic research community has had difficulty over the past decade competing with industry for talented technical people. It will be important to evaluate the limitations and constraints placed on the research community by this shortage of technical support staff.

4.4 New directions for the ocean drilling program will put new demands on our academic fleet. We expect greatly increased demand for sea floor site surveys (high resolution sea floor mapping, coring, imaging of geological sections, etc). Many of the scientific needs framed within the Integrated Ocean Drilling Program will require ancillary vessels to conduct this work, as the unique capabilities of the specialized riser and non-riser drill ships limit them to specific tasks. It makes sense for these ancillary vessel requirements to be met by UNOLS vessels.

4.5 Improvements in communication/data transfer are a central issue for almost all the new science on the horizon. It is clear that maturation of ocean modeling will contribute to the design and execution of process experiments at sea. The assimilation of the results of those process experiments into models, using real-time communication links, will lead to rapid refinements in predictability and adaptive sampling within the process experiments. Real-time communication of research at-sea will provide greater public outreach and likely will lead to many varieties of "virtual" experiences for students of all ages. While we can assume that most of the communication improvements will occur outside the development environment of marine science, our community must be vocal and clear in its needs, and clear in explaining the dependencies of advances in ocean science on data transfer between observational platforms, whether they are ships, drifters, moorings, AUVs, ROVs, or gliders.

5. Vessel Capabilities Needed to Meet Science Needs

The workshop participants agreed that use of new observational tools in ocean science will continue to expand our ability to address long-standing science questions, and will provide the means to resolve, on the requisite time and space scales, many of the mechanisms that control ocean processes. The most basic message from the "futures" documents is the essential need for expanded temporal and spatial coverage of phenomena. All agreed that today we are hampered in our efforts to uncover the mechanisms that create the patterns we observe, since we cannot be confident that we have resolved the patterns on the appropriate scale and cannot effectively focus our experimental approaches at the proper scale. The next two decades of ocean science will witness the maturation of this merging of observational and experimental work over a much wider range of time and space scales than has been possible to date.

The workshop participants agreed that the *scientific needs (observational and experimental) of ocean science over the next two decades require the implementation of:*

A. **Remote observational systems with robust sensor suites** (limited to a few variables), such as satellites (color, SST, winds, currents, etc), long-term moorings, drifting platforms (single depth and vertically cycling), and autonomous vehicles.

B. **Vessels to provide deployment/recovery/service** for moorings, drifters, vehicles, with improved capabilities for handling untethered objects, that are acoustically quiet for improved subsurface communication with vehicles, that have improved heavy weather capabilities to increase the number of observations obtained under a wide range of forcing conditions, and that have improved functionality in high-latitude, open-ocean regions and ice-covered regions.

C. **Vessels that function as primary observational/experimental platforms** that have more laboratory space and more capacity for experimental work than vessels used to provide deployment, recovery, or service. This category of vessel also will possess improved capabilities for handling untethered objects, will be acoustically quiet, will possess improved heavy weather capabilities, will permit undisturbed sampling in/around air-sea interface, will host AUVs, ROVs and submersibles, and will have improved functionality in high-latitude, open-ocean regions and ice-covered regions.

D. **Vessels that can meet the expanded mapping, seismic, and coring needs of the marine geology community** as the Ocean Drilling Program moves into the next decades of research. New site survey demands alone will expand these needs beyond the capabilities of today's academic fleet.

E. **Global high-bandwidth communication capability** will fuel real-time interaction and data exchange between remote sensor suites, vessels, and land-based or ship-based laboratories. This data communication capability, along with maturation of data assimilation into coupled models, will lead to wide-spread use of adaptive sampling approaches.

F. **Rapid response capability** within the oceanographic fleet, such that vessels/remote systems are available to respond to "events" detected by observational systems. However, this capability implies that additional vessel capacity, held in "ready reserve," will be available (and affordable).

Our discussion of research needs and associated themes pointed to the following specific capabilities for the next vessels in the fleet.

Vessel capabilities identified included:

- Acoustically-quiet vessels for improved communication and tracking of autonomous vehicles;
- Greater stability to work in a wider range of sea states;
- Sheltered, ice-free decks for operations at high-latitudes;
- Undisturbed sampling of ocean surface, air-sea interface, and levels just above and below the interface;
- Improved launch/recovery operations for remote systems, whether towed or untethered (AUVs);
- Ice-hardened ships as climate change drives more research in marginal ice zone areas;
- Clean sampling handling during perturbation experiments (trace elements, etc);
- Improved and expanded shipboard laboratory space;
- Improved sea-floor mapping, coring;
- High-speed data communication to shore, ships, deployed instruments.

6. Conclusions and Recommendations

6.1 We expect demand for shiptime to increase over the next two decades.

Research vessels have been the primary platform in providing scientists access to the oceans. For the foreseeable future, they will provide the primary means of conveying both scientists and their instruments to ocean research areas. Traditionally, the dominant use of ship-time has been for conducting research and much less time devoted to providing service and support for moorings, and other remote sensing instrument systems. The marked increase in the development and use of autonomous systems, and the development of ocean observatories, will result in a shift in the way that the vessels are used and equipped. Thus while the basic research needs for ships are likely to grow, additional pressure for increased access to the sea via research vessels will result from the increased use of remote sensing platforms. The evolving balance between use of ships as the primary, human-occupied laboratories and work sites, and use of unmanned systems to make observations, depends strongly on the variables of interest and therefore to a large extent on nature of the scientific questions posed. Many important physical parameters are amenable to unmanned sensing systems, while observation of many important biological and chemical parameters will continue to require human effort at sea on ships for the foreseeable future. It is critical to note that fundamental advances in biogeochemical methods, for example, will continue to occur through the painstaking collection of discrete samples, followed by more time-consuming sample processing. We expect this sequence of exploratory science to remain one of the central activities of ocean scientists, and one that requires people on ships. For example, we anticipate a continuous development of critical in situ analytical procedures over the next two decades, just as the past decades have witnessed the maturation of in situ conductivity measurements, in situ pCO_2 measurements, etc.

New approaches for ocean observation, therefore, ***extend*** the reach of the traditional oceanographic expedition/cruise, but ***will not replace*** or reduce the role of the research vessel for many aspects of ocean science. This projected increase in the dual use of fleet resources (direct research support and "platform" support) was an important outcome of the workshop.

6.2 Vessel capabilities must be extended to meet the needs of new systems and approaches.

We conclude that future ocean science will require an academic fleet with expanded capabilities beyond those available today. The need for expanded capabilities is driven by the requirements of the major scientific questions posed by the community, as well as by the continual technical advances in sensors and observational systems. Our discussions, and the conclusions of the Fleet Improvement Committee, suggest that the science needs of the next decades first should be incorporated into the planning for intermediate class vessel replacement, as these platforms will soon reach retirement age.

6.3 We recommend a community evaluation of "general-use" versus "specific-use" vessels in the fleet.

The incorporation of specific or specialized capabilities for vessels must be driven by the anticipated technical requirements of the science and the expected balance of those capabilities across the fleet. We recommend that the scientific users of the research fleet have a strong role in the decision-making process about types/capabilities of vessels as defined by science needs. The existing Fleet Improvement Committee of UNOLS provides a framework for this process.

6.4 We recommend a thorough evaluation of the ship scheduling process.

We conclude that science pressure to address "event-scale" processes will create a need to modify the ship scheduling process. We expect that more extensive observational programs, integrated with models/forecasts, will permit detection and close examination of critical events and processes. We expect that the scientific questions that will emerge from the study of intermittent critical events will require access to vessels on relatively short notice (weeks to a few months), depending on the phenomena under study. We therefore recommend that the NSF, ONR, and NOAA establish a process for evaluating new models for vessel scheduling given the expected pressure for more responsive vessel availability.

Appendix

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