SHIP-BASED REPEAT HYDROGRAPHY: U.S. CONTRIBUTIONS TO GO-SHIP

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Abstract

Ship-based hydrography is the only method for obtaining high-quality measurements with high spatial and vertical resolution of a suite of physical, chemical, and biological parameters over the full ocean water column, and in areas of the ocean inaccessible to other platforms. Global hydrographic surveys have been carried out approximately every decade since the 1970s through research programs such as GEOSECS, TTO/SAVE, WOCE/JGOFS, and CLIVAR. This white paper provides scientific justification and guidelines for a coordinated network of sustained ship-based hydrographic sections that are an integral component of the ocean observing system. Without the repeat hydrography observing system, there would be no way to: measure and track ocean carbon inventories, observe the global ocean below 2000 m, measure and track overall ocean heat changes, or provide the highest quality in situ validation data for autonomous sensors.
Key words: global heat and salinity, global carbon cycle, global velocity, operational oceanography, tracer chemistry, biogeochemistry, international coordination

1. INTRODUCTION, BACKGROUND, HISTORY, AND ACCOMPLISHMENTS

Introduction. This CWP is a submission to the IOOC of a condensed version of the OceanObs09 CWP[1], which presented the international vision for the future of repeat global hydrographic surveys. The observing system outlined in the OceanObs09 CWP is overseen by the international GO-SHIP program (http://www.go-ship.org/), which is sponsored by the International Ocean Carbon Coordination Project (IOCCP) (http://www.ioccp.org) and by the Climate Variability and Predictability program (CLIVAR), in collaboration with IMBER, SOLAS, Argo and OceanSITES. Because the OceanObs09 CWP provides the international view of the justification, specifications, and coordination of repeat hydrography, we liberally *reproduce* materials from that previous paper, in order that the material is represented at the IOOS. The authors listed for this IOOS CWP are the co-chairs of the U.S. Repeat Hydrography Oversight Committee, which is currently organized under CLIVAR and the U.S. Carbon Cycle Science Program, and supported by NSF and NOAA (http://ushydro.ucsd.edu). The OceanObs09 CWP includes a substantial reference list, which is not reproduced in this condensed version.

Background. Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 km (52% of global ocean volume not sampled by profiling floats). Hydrographic measurements are needed to

- reduce uncertainties in global freshwater, heat, and sea-level budgets,
- determine the distributions and controls of natural and anthropogenic carbon (both organic and inorganic),
- determine ocean ventilation and circulation pathways and rates using chemical tracers,
- determine the variability and controls in water mass properties and ventilation,
- determine the significance of a wide range of biogeochemically and ecologically important properties in the ocean interior, and
- augment the historical database of full water column observations necessary for the study of long timescale changes.

These results will be critical for evaluating ocean models and providing data constraints for state estimation, assimilation and inverse models. In addition, ship-based hydrographic measurements provide a standard for validating new autonomous sensors and a reference/calibration dataset for other observing system elements (in particular Argo profiling floats, expendable bathythermographs and gliders). Hydrographic cruises also provide cost-effective access to remote ocean areas for the deployment of these instruments.

History. The international conference “Ocean Observing System for Climate” (or OceanObs’99) set the initial scientific and implementation framework for post-WOCE hydrography. Recognizing the need to focus research on climate variability as well as on the documentation of trends from anthropogenic forcing, it was decided to incorporate a program of repeat hydrography in the 15-year international Climate Variability and Predictability Study (CLIVAR). This first global repeat survey of a select subset of WOCE hydrographic sections is being completed in 2012.

The U.S. Repeat Hydrography Program (http://ushydro.ucsd.edu) has made substantial contributions to the global survey, matched by contributions especially from Japan, Australia and the European Union. The first U.S. section was occupied in 2003, shortly after the end of WOCE, and its 23rd cruise was completed in May 2012 (Figure 1); the entire international program has completed 47 cruises. The U.S. cruises in 2012 were the first in the second cycle of U.S. decadal repeats.

Data are rapidly processed and released to the public without restriction, through the CLIVAR and Carbon Hydrographic Data Office (CCHDO) (http://cchdo.ucsd.edu) and the Carbon Dioxide Information Analysis Center (CDIAC) (http://cdiac.ornl.gov/oceans/RepeatSections). The U.S. Repeat Hydrography program has an excellent track record in data collection, data quality, data archiving and dissemination. The GO-SHIP project office is compiling a bibliography of publications using these data. The interagency collaboration between NSF and NOAA has been extremely successful, with integration of NOAA/NSF efforts at all levels on most cruises, and common requirements for data sharing and archiving being routinely met.

Scientific accomplishments. Significant changes in water mass distributions and biogeochemical properties over the last decade have been demonstrated, influenced by both secular changes (e.g., anthropogenic CO_2 invasion) and natural climate mode variability. Some recent research highlights include

- documentation of substantial changes in the oceanic inorganic carbon content, driven by both the uptake of anthropogenic CO_2 and natural variability
- evidence of large-scale changes in oceanic oxygen concentrations
- near global-scale warming of abyssal waters of Antarctic origin, and freshening of these waters in deep basins adjacent to Antarctica
- freshening of the Atlantic waters
- equatorward penetration of CFCs from high-latitude sources filling the deep and abyssal basins on time scales of decades, allowing estimates of water mass formation rates, and
- evidence of reduction in downstream primary productivity brought on by strong convection and mode water formation.

These results illustrate the importance of repeated global surveys for interpreting and attributing changes to physical and dynamical mechanisms operating on a variety of time scales. As this first decade of the repeat hydrography program comes to an end, it is clear that the global repeat survey approach is very effective at quantifying variability and trends of a large suite of physical and biogeochemical parameters. Integration of ship-based repeat hydrography with other observing system elements, such as the Argo profiling float program, Ship of Opportunity Program, Volunteer Observing Ship Program, time-series stations and satellite remote sensing that provide complementary scales of information, is required for the accurate monitoring of ocean change and variability. A comprehensive ocean observing system, in conjunction with synthesis and numerical models, is vital to understand the drivers of global climate change and variability.

2. TECHNICAL AND USER REQUIREMENTS

The international survey that is beginning in 2012 (see map in http://www.go-ship.org) will take into consideration the sampling schedule carried out during the CLIVAR program (2003-2011) in order to ensure decadal repeat frequency for each basin as much as possible. The GO-SHIP priorities[1] suggest that since the Atlantic was sampled most densely between 2003-2005, the Pacific between 2005-2007, and the Indian in 2007-2009, the first post-CLIVAR survey should start with the Atlantic from 2012-2014, the Pacific from 2015-2017, and the Indian from 2017-2019. A separate but useful concept for prioritization is occupation of sections at the same latitude in all ocean basins within a given year, in order to produce a more synoptic view of changes relative to the decadal modes of variability. This was achieved in both 2002-2003 and 2009 at 30°S and in 2004 at about 30°N.

2.1. Spatial sampling resolution

Spatial sampling should follow past surveys, with major efforts carried out in the Atlantic, Pacific, and Indian oceans, with the Southern Ocean integrated as part of the other basins. The Arctic is of increasing importance and should be emphasized, either as a separate effort or a coordinated effort from Atlantic and Pacific basin efforts. Ideally, sections should extend from coast to coast, or coast to ice, follow standard WOCE lines with small modifications as necessary for territorial waters, ice coverage, etc., and maintain the standard WOCE sampling strategy.

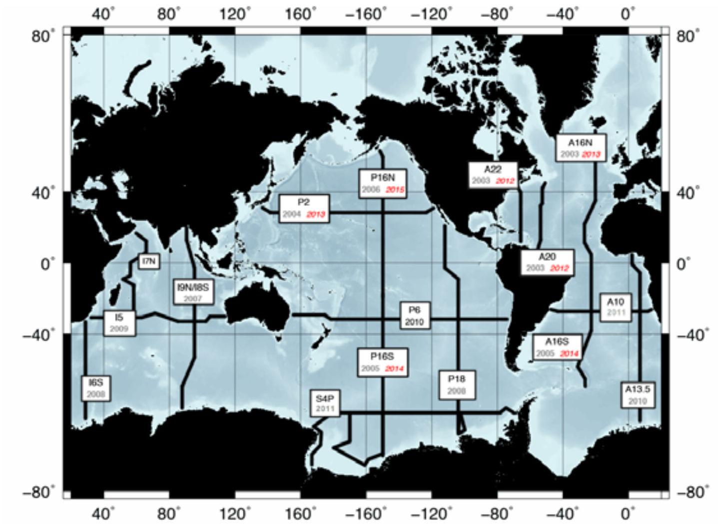

Figure 1: U.S. Global Ocean Carbon and Repeat Hydrography Program, 2003-2015. Red indicates pending cruise; gray indicates completed cruise. (A20 and A22 in the Atlantic were completed in early 2012.) (http://ushydro.ucsd.edu)

Horizontal resolution for physical measurements is nominally 30 nautical miles with higher resolution in regions of steep topography and boundary currents. Carbon and tracers station resolution should be 60 nautical miles or better. Vertical resolution: each station occupies the full water column depth.

2.2. Observed variables

GO-SHIP provides the following guidelines for observed parameters. The U.S. Repeat Hydrography program (http://ushydro.ucsd.edu) has similar lists with more specific prioritizations.

From GO-SHIP, core parameters for each cruise are:
• temperature, salinity, and pressure
•oxygen, phosphate, silicate, and separate measurements of NO_2 and NO_3 if possible; otherwise, $NO_2 + NO_3$ (with clear reporting of what was measured)
• at least 2 carbon parameters (e.g., DIC, Alkalinity, pCO_2, pH), where DIC and Alkalinity are the preferred pair, but spectrophotometric pH is a useful 3rd parameter because of high measurement precision and growing interest in ocean acidification.
• carbon isotopes (^{13}C, ^{14}C), chlorofluorocarbon tracers (CFC-11 and/or 12) and SF_6; tritium and helium-3 should also be measured on key sections, including meridional sections P10, P16, P18, I06S, I08, I10, A16, A22, A20, and zonal sections I05, P06, P04, and A24).
• shipboard and lowered ADCP

Salinity and oxygen should be measured on every bottle. Also recommended are organic carbon parameters (POC, DOC) and underway surface measurements (including pCO_2, pigments, and related biological parameters at the surface). By 2012, microstructure measurements from profilers may also be considered for routine application during the next decade of hydrography. A certain subset of trace elements and isotopes should be included in future high-frequency repeat sections, particularly for parameters to deduce atmospheric mineral dust deposition to the surface ocean in key areas.

For bio-optical measurements, GO-SHIP endorses the recommendations of the International Ocean Color Coordination Group, including the following parameters:
Instruments to be added to a profiling CTD:
• Fluorometer to measure chlorophyll fluorescence
• Transmissometers and/or light-scattering sensors and nephelometers to measure particle beam attenuation coefficient
• PAR sensor (where possible)
Water samples collected for the following measurements:
• Chlorophyll-*a* (Turner Fluorometer)
• HPLC pigments
• Phytoplankton absorption
• CDOM (desirable measurement)
• Flow cytometry
On deck measurements:
• Continuous recording of incoming photosynthetically active radiation (PAR), using a PAR sensor with a data logger (automatic).
• Measurements of spectral reflectance using a hyperspectral hand-held radiometer.
Several ancillary observations should be made whenever possible. The repeat hydrographic ships should make surface meteorological observations, following the guiding principles of the WOCE hydrographic program described in the handbook by

Bradley and Fairall [2]. The observations should include wind speed and direction (relative to the ship and corrected to absolute), air temperature and humidity, sea surface temperature, rainfall, barometric pressure, incoming shortwave radiation, and incoming longwave radiation. Several bio-optical measurements are also highly desirable, including profiling underwater spectral-radiometer measurements and photosynthesis-irradiance experiments.

2.3. Data management

The general strategy proposed for data management is to better support and coordinate the existing data assembly and archive centers, to develop new tools and centers to manage the increasing variety of properties observed on hydrographic lines, to coordinate data management activities with those of the operational programs such as Argo and OceanSITES, and to improve technology and data policies to release data in a more timely manner. It is also proposed to develop a single international information center for repeat ship-based hydrography that will serve as a central communication and coordination forum and include a portal or directory to the data assembly centers.

At present, the GO-SHIP panel recommends the following data-release guidelines:

- Preliminary dataset released within 6 weeks (e.g., all data measured on the ship)
- 6 months for final physical data
- 1 year for final data of all other variables (except for isotopes or tracers with shoreside analysis where 1 year is difficult).

The relatively rapid release of data is motivated by their usefulness for climate studies, which are of increasing societal importance. A system should be developed to appropriately recognize the efforts of data contributors. One solution that should be adopted immediately is to publish the Final Cruise Reports in the journal *Earth System Science Data* (ESSD) with all participating PIs as authors.

3. STATE OF THE OBSERVING SYSTEM AND TECHNOLOGY

The hydrographic observing system has had a successful first ten years, with completion of 47 or more cruises internationally, of which 23 were led by the U.S. Repeat Hydrography Program. Strong collaboration between the NSF and NOAA-led portions of the U.S. program has been critical to this success.

Hydrographic (CTD and rosette sample) data from the international cruises were processed and made available quickly during these ten years. The U.S. repeat hydrography led the way ten years ago in establishing the standards of quick public data release that are listed in Section 2.3, and the other contributing nations have gradually followed. For the last several years, all U.S. cruises have met these data release standards.

The international GO-SHIP program and the U.S. contribution to this program use mature, conservative technology and laboratory methods, with the goal of achieving the highest possible accuracy, against which other elements of the observing system can test and validate their observations. Data processing and calibration protocols are also mature and evolving, with the various technical groups that provide these data for the repeat hydrography program leading the way in improvement of already high accuracies. The U.S. is a full partner in these international activities.

To achieve observations of the highest accuracy, internationally accepted protocols and chemical standards are necessary. This practice was introduced in WOCE, continued through the CLIVAR/CO2 program, and will be continued into the future by GO-SHIP. WOCE produced a set of manuals for each of the core parameters. GO-SHIP has recently completed a revision of these manuals for collection and processing of the core parameters.

Ongoing activities include the introduction of new reference materials for nutrients[3]; all major nutrient analysis groups are participating in testing these standards, including the three laboratories (SIO, NOAA) in the U.S. Repeat Hydrography program. A second completed activity that is now being implemented internationally is a revision of the equation of state of seawater and of the definition of salinity (TEOS-10)[4]. Many scientists involved with the repeat hydrography programs or their oversight were central participants in this development.

4. INTEGRATION WITHIN IOOS, MODELING, AND DMAC

Several data centers currently provide data management services for particular types of hydrographic data. However, to meet the needs of a sustained global program, data assembly centers will need dedicated staff time and new funding, and will need to be increasingly integrated with the data management systems for other sustained programs such as Argo and OceanSITES. The challenges of such integration, both operationally and financially, should not be underestimated, but without this level of support for the data centers, a globally coordinated hydrography program with regular deliverables will not be possible.

5. THE WAY FORWARD FOR THE NEXT TEN YEARS

The U.S. Repeat Hydrography Program will continue its contribution to the decadal survey for at least the next five years, and presumably for at least ten years. Improvements in the next 10 years of the program will result from implementation of ongoing improvements in measurement accuracy (e.g. the nutrient reference materials referred to above, and implementation of TEOS-10), continued interlaboratory calibration facilitated by active collaborations, and a comprehensive data archival system that includes and integrates all of the types of data collected on these cruises. Integration of the related data set across data management systems is strongly recommended.

The committee is fully supportive of emerging technologies and sensors that will replace some of the ship-based measurements. Argo relies on the highly accurate observations made from ships in order to maintain high calibration standards. For pressure, temperature and salinity from profiles, measurements on a global basis to the ocean bottom will only be possible, routine, and highly accurate from the ship-based program, but could ultimately be supplanted by a network such as "deep" Argo. CTD oxygen observations are being supplemented by Argo oxygen profiling, but in situ measurements using the highest standard Winkler titration methods will remain necessary for calibration. pH and nutrient observations using autonomous sensors are at various stages of development; for these, continued availability of ship-based measurements and the platforms for testing and in situ calibration are essential. Many of the chemical tracers measured with Repeat Hydrography cannot be sampled except from a ship.

Satellite observations have partially replaced underway surface observations, but cannot achieve the very high along-track resolution and cannot sample carbon dioxide and other gases. ADCP velocity measurements collected on the ships are not yet being replaced by routine velocity profiling on Argo floats. The underway ADCP provides upper ocean shear information that is unavailable from any other program.

Potential Partners include:

- IOCOS (International Ocean Carbon Observing System)
- Argo
- OceanSITES
- Geotraces

6. CONCLUSIONS

The U.S. Repeat Hydrography program is a critical part of the Integrated Ocean Observing System. It is one of the major contributors to the international GO-SHIP program. Because of the needs for:

- highly accurate carbon and other biogeochemical parameter measurements
- highly accurate deep temperature and salinity
- in situ velocity measurements of the highest accuracy and along-track resolution
- use of these platforms and highly accurate measurements for testing and validating new sensor technology,

the repeat hydrography program is essential to the integrated ocean observing system for at least these next ten years. As sensors for autonomous systems continue to be developed and accuracies of autonomous measurements continue to improve, the priorities for ship-based observations will shift. For the next ten years, this program will be indispensible.

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