THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Schroeder, K., T. Tanhua, H.L. Bryden, M. Álvarez, J. Chiggiato, and S. Aracri. 2015. Mediterranean Sea Ship-based Hydrographic Investigations Program (Med-SHIP). *Oceanography* 28(3):12–15, http://dx.doi.org/10.5670/oceanog.2015.71.

DOI

http://dx.doi.org/10.5670/oceanog.2015.71

Mediterranean Sea Ship-based Hydrographic Investigations Program (Med-SHIP)

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Although the Mediterranean influences the global ocean through its connection to the Atlantic and is clearly important for regional climate, fisheries, and tourism, until now it has been sampled by ship-based research cruises only at irregular intervals, mostly by national expeditions in regional areas. It has largely been neglected by global-scale international programs, such as the one-time survey conducted during the World Ocean Circulation Experiment (WOCE) and the subsequent repetition of key WOCE hydrographic lines promoted and coordinated by the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP). Med-SHIP is a new program that will fill this gap, collecting sustained hydrographic observations in the Mediterranean Sea. Med-SHIP has two primary objectives: (1) to observe and quantify long-term changes in marine physical and biogeochemical properties in the Mediterranean Sea, where the shorter turnover time scale suggests they can be extrapolated to the global ocean, and (2) to observe changes in thermohaline circulation and to determine how often and how much deep water is formed, and whether the currents are changing in position and intensity.

SCIENTIFIC MOTIVATION FOR REPEAT HYDROGRAPHY IN THE MEDITERRANEAN SEA

Dramatic changes in physical and biogeochemical properties observed in the Mediterranean during the last few decades (Malanotte-Rizzoli et al., 2014) provide scientific motivation for Med-SHIP, although trends are partly masked by significant episodic events and regional variability. For instance, both the salinity and temperature of the deep Mediterranean have been increasing for at least the past 40 years at rates of about 0.015° and 0.04°C per decade, respectively (Borghini et al., 2014). Furthermore, both dissolved inorganic and anthropogenic carbon contents are high in the deep Mediterranean compared to the global deep ocean.

Climate and biogeochemical models predict a decline in global ocean oxygen concentrations (Oschlies et al., 2008), with important implications for biology and feedbacks on nutrient and carbon cycling. Although oxygen concentrations in the Mediterranean are relatively high, lower open-ocean background concentrations can potentially affect local oxygen depletion. Careful monitoring of changes in oxygen concentrations in the Mediterranean will help determine whether de-oxygenation is also an issue for regional seas, with consequences for fisheries and ecosystems. Data on nutrients are also essential for understanding and documenting marine biogeochemical cycles. For instance, Kress et al. (2014) report drastic changes in nutrient distribution on a short repeat section in the easternmost Levantine Basin, demonstrating the value of sustained observations in the Mediterranean Sea. Moreover, nutrient values can be used for circulation studies (e.g., Robbins and Toole, 1997) and are also useful for anthropogenic carbon derivations as well as multi-parameter regressions of less-well-sampled properties.

With regard to the carbon cycle, there are only few observations of the carbonate system in the Mediterranean, making it difficult to draw conclusions on the temporal variability of the inorganic carbon at this stage. Because the Mediterranean has very high total alkalinity and pH compared to the ocean, it is peculiar in terms of CO_2 dynamics and possible feedbacks between global change and the carbon cycle. Regular observations of the carbonate system are needed to document climate changes and to build models for high-alkalinity, high-pH systems.

Ventilation of the Mediterranean Sea is known to be intermittent, with pronounced temporal variability in deep water formation rates. For instance, in the early 1990s, the "Eastern Mediterranean Transient" shifted deep water formation from the Adriatic to the Aegean Sea, with a massive increase in deep water production rates (Roether et al., 1996). Since then, deep water formation has been re-established in the Adriatic, although with possibly different rates and properties, leaving the question open as to whether drastic changes in deep water formation could happen again. Recent intense deep water formation events in the western Mediterranean produced a huge amount of new deep water (Schroeder et al., 2008) that has begun to modify the deep stratification of the entire basin and has caused abrupt increases in deep water temperature and salinity. This event (the "Western Mediterranean Transition") strongly enhanced the ventilation of the abyssal part of the western basin and has started to propagate toward the Tyrrhenian Sea and North Atlantic. Temporal variability in ventilation, such as described in Schneider et al. (2014), can only be detected by regular measurements of transient tracers, key variables that Med-SHIP plans to acquire. Ventilation changes can be quantified by comparing modern SF_6 data with historic CFC-12 data. Figure 1 plots the tracer age difference for selected areas, showing that ventilation is slower (age is higher) mainly in the eastern basin, whereas the western basin shows increased deep water ventilation.

Additionally, the export of dissolved organic carbon (DOC) from surface to deep waters represents a significant component of the biological carbon pump, particularly in regions that undergo deep convective mixing. How a change in ocean stratification will affect the role of DOC in the biological pump, compared to that of particulate organic carbon (POC), is of particular interest. These key questions, and others, can only be truly addressed with sustained repeat hydrographic sections.

Despite numerous technological advances over the last 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. For instance, while the global network of Argo profiling floats samples the physical characteristics of the upper 2,000 m of the ocean, more than 20% of the Mediterranean volume lies below this depth, where significant changes have been observed. The latest Intergovernmental Panel on Climate Change report (IPCC, 2013) emphasizes the role the deep ocean plays in taking up excess heat and CO_2, but these changes are subtle and extremely difficult to observe except with the highest quality hydrography.

To document changes throughout the water column, and especially for the deep sea below 2,000 m, it is essential to (1) reduce uncertainties in freshwater, heat, and sea level budgets, (2) determine the distributions of natural and anthropogenic carbon and the factors that control them, (3) define ventilation and circulation pathways, (4) characterize the variability in water mass properties and factors that control it, (5) determine the significance of biogeochemically and ecologically important properties, (6) assess the long-term steric contribution to Mediterranean sea level, and (7) augment the historical database of full water column observations necessary for the study of long-term changes.

Sustained observations are critical for evaluating ocean models and constraining state estimation. In addition, ship-based hydrographic measurements provide a standard for validating new autonomous sensors and a reference data set for other observing systems such as Argo profiling floats, expendable bathythermographs, and gliders. Hydrographic cruises also provide access to remote ocean areas for the deployment of these instruments. Med-SHIP thus provides a full depth, whole basin view of changes in the Mediterranean, a framework that allows regional observations and Argo profiles to be interpreted in a basin-scale perspective.

PROGRAM STATUS AND NEXT STEPS

The Med-SHIP plan, defined by Mediterranean scientists at a 2012 workshop (CIESM, 2012), is to regularly measure physical and biogeochemical properties along two meridional composite transects in each of the eastern and western Mediterranean Sea and one zonal transect from the Strait of Gibraltar to the easternmost Mediterranean (Figure 2). Broadly speaking, the zonal section emphasizes property changes while the north-south sections emphasize circulation changes, though, in fact, all sections contribute to both objectives. Beginning in 2015, the Mediterranean zonal section is considered a component of the global GO-SHIP program (although section MED01, planned for 2017, is still in need of funding; see Figure 3 and http://www.go-ship.org). As for the north-south sections, the scientists committed to the initiative are planning them now and developing needed funding

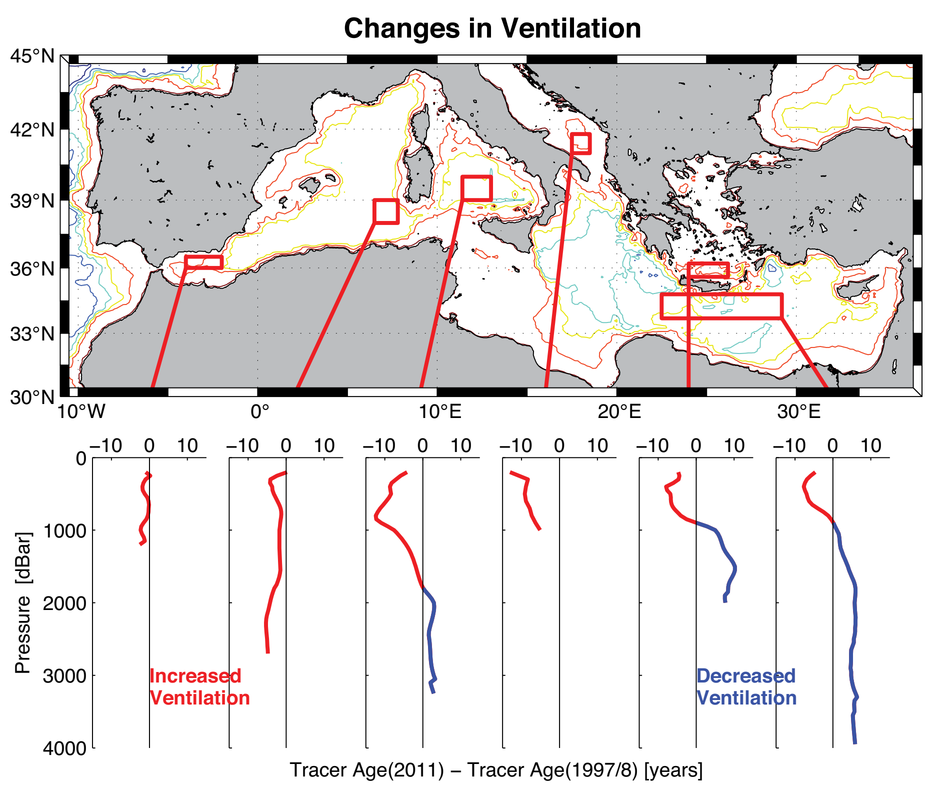

FIGURE 1. Tracer age (years) difference between SF_6 (2011) data and CFC-12 (1997–1998) data in different areas of the Mediterranean Sea. The similar shape, but with a 14-year offset, of the atmospheric concentration history of the two tracers makes direct comparison, with a few assumptions, possible (Tanhua et al., 2013b). Positive (negative) values indicate decreased (increased) ventilation.

within the framework of other projects and national funding and under the coordinating umbrella of CIESM (which will host a dedicated Med-SHIP Web page).

The overall program is for the north-south sections to be done every three years and the zonal section to be done every six years. During these cruises, a suite of relevant physical, chemical, and biological variables would be measured (see Table 1). The repetition frequency proposed for the Mediterranean is somewhat higher than that for GO-SHIP (where low-frequency lines are repeated on a decadal scale), in light of its typical shorter spatial and temporal scales (CIESM, 2012). The zonal transect, repeated on a low-frequency basis and including the full suite of GO-SHIP parameters, would allow assessment of long-term variations in heat and freshwater budgets and calculation of basin-wide inventories of natural and anthropogenic carbon in the Mediterranean, with a focus on deeper layers that are less subject to small-scale variability (Tanhua et al., 2013a; Álvarez et al., 2014). But the Mediterranean is a "coastal ocean" with open-ocean characteristics, where circulation is not driven purely by basin-scale forcings but is also driven by intense, variable, and diverse local forcings. In this respect, the high-frequency repetition of sub-basin meridional transects, including collecting a subset of the GO-SHIP parameters, is essential to capture these degrees of variability.

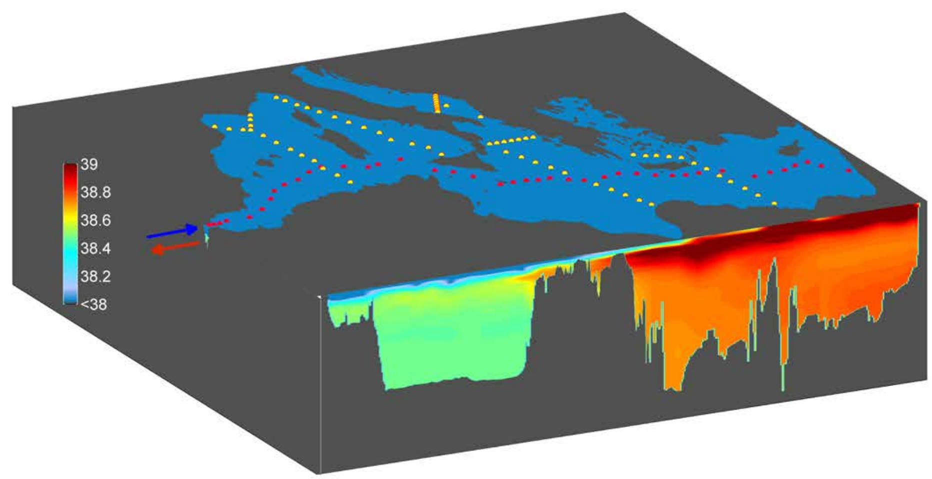

FIGURE 2. Proposed repeat Med-SHIP hydrographic sections. Red dots indicate the low-frequency zonal section, yellow dots the high-frequency meridional sections. The interior salinity along the zonal section is shown in color. Salinity data from a 2011 R/V *Meteor* cruise (Tanhua et al., 2013a).

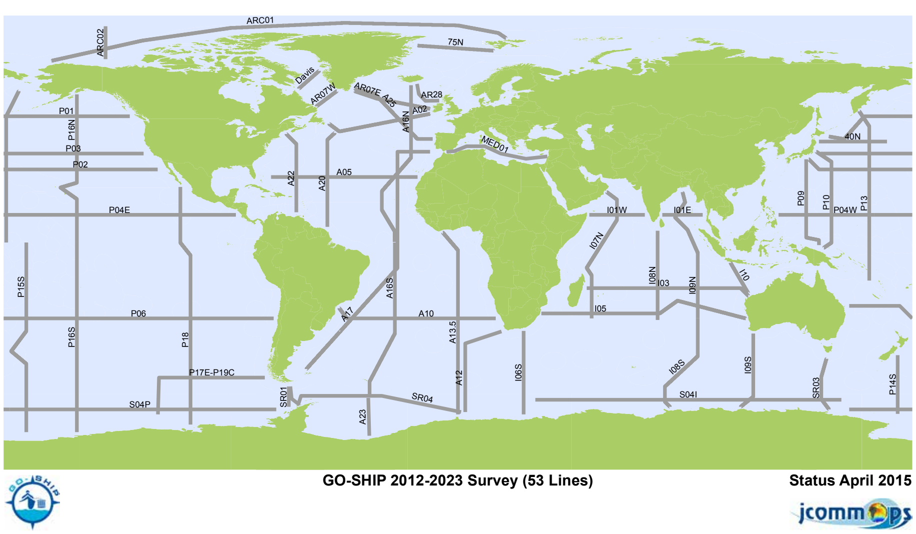

FIGURE 3. GO-SHIP reference sections are repeat hydrographic coast-to-coast or coast-to-ice sections that can be modified as necessary for territorial waters, ice coverage, and other obstacles to gathering data but still maintain the standard GO-SHIP sampling strategy. Updated April 2015 (Source: http://www.go-ship.org).

The Executive Group of GO-SHIP groups measurements in three levels of importance (see Table 1). The same will be adopted for Med-SHIP. Given their usefulness for climate studies, and following GO-SHIP standards, all data shall be openly accessible to the community at large as soon as possible. In the European/Mediterranean region, a network of data centers and specialized marine institutions has already been established (e.g., MyOcean, EMODNet, SeaDataNet). In addition, all data, after quality control by the participating scientists on each cruise, will be sent to the CLIVAR & Carbon Hydrographic Data Office at Scripps Institution of Oceanography for inclusion in the international database.

Coordinated at an international level and with a program that has been vetted in the community, Med-SHIP is now ready to become part of the Mediterranean and global sustained observing systems as a reference component for long-term studies of processes, events, and changes in the Mediterranean Sea. The execution of Med-SHIP relies on national and international (i.e., EU) funding for its science teams, as do most other internationally coordinated programs such as GO-SHIP. We invite the Mediterranean oceanographic community to contribute to the success of Med-SHIP by participating in the execution of the reference sections and their subsequent analysis and interpretation.

Med-SHIP is governed by the Mediterranean Science Commission (CIESM), which supported the Med-SHIP articulation workshop in 2012 (CIESM, 2012). The Med-SHIP program is further supported by the European Marine Board (European Marine Board, 2013), where its implementation is recognized as a priority for identifying climate change effects.

TABLE 1. Core measurements (level 1 data) and data submission timelines as defined by the GO-SHIP Executive Group and adopted for Med-SHIP. Level 1 data are of highest priority for fulfilling scientific objectives and should be collected at least on the low-frequency zonal section. Level 2 data are highly desirable and should be collected when possible. Level 3 data are ancillary measurements that often benefit from being taken in conjunction with core measurements and/or to address a scientific question unique to the region of investigation; only some examples of Level 3 data are given here.

Level 1	Timeline
Dissolved inorganic carbon	6 months
Total Alkalinity	6 months
pH (*Note*: any two of the above)	6 months
CTD pressure, temperature, salinity (calculated)	6 months
CTD oxygen (sensor)	6 months
Bottle salinity	6 months
Nutrients by standard auto analyzer (NO_3/NO_2, PO_4, SiO_3)	6 months
Dissolved oxygen	6 months
Chlorofluorocarbons (CFC-11, -12, -113) and SF_6	6 months
Surface underway system (T, S, pCO_2)	5 weeks
ADCP shipboard	5 weeks
ADCP lowered	6 months
Underway navigation and bathymetry	5 weeks
Meteorological data	5 weeks

Level 2	Timeline
Discrete pCO_2	6 months
^{14}C by AMS	6 months after analysis
CCl_4	6 months
$\delta^{13}C$ of DIC	6 months
Dissolved organic carbon	6 months
Dissolved organic nitrogen	6 months after analysis
Fe/trace metals	6 months
Transmissometer	6 months
Surface underway system (pCO_2, nutrients, O_2, Chl, skin temperature)	5 weeks
N_2O	6 months

Level 3	Timeline
Chlorophyll	2 yrs after analysis
Primary production	2 yrs after analysis
HPLC pigments	2 yrs after analysis
Experimental continuous analyzers (such as pH, DIC, and T_{Alk}, and O_2/Ar)	2 yrs after analysis
$\delta^{15}N$	2 yrs after analysis
^{32}Si	2 yrs after analysis
$\delta^{18}O$ of H_2O	2 yrs after analysis
NH_4	2 yrs after analysis
Low level nutrients	2 yrs after analysis
Total organic phosphorus	2 yrs after analysis
Upper ocean optical	2 yrs after analysis
Isotopes of O_2	2 yrs after analysis
N_2, Ar, O_2	2 yrs after analysis
Methyl halides	2 yrs after analysis
DMS	2 yrs after analysis

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ACKNOWLEDGMENTS

The authors are deeply grateful to the Mediterranean Science Commission (CIESM), its Director F. Briand, and the Chair of the Physics and Climate of the Ocean Committee, M. Gacic, for their continuous support of the Med-SHIP initiative.

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ARTICLE CITATION

Schroeder, K., T. Tanhua, H.L. Bryden, M. Álvarez, J. Chiggiato, and S. Aracri. 2015. Mediterranean Sea Ship-based Hydrographic Investigations Program (Med-SHIP). *Oceanography* 28(3):12–15, http://dx.doi.org/10.5670/oceanog.2015.71.