A New Vision of the MBARI Time-Series Program

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Introduction:

A time series is defined as a sequence of data points, measured at successive increments of time at regular intervals. Current oceanic time-series studies are essential to understand the oceanic ecosystem under changing climatic conditions (Wunsch et al., 2013; Church et al., 2013). To adequately address such change requires sufficient temporal resolution to distinguish monthly, seasonal, inter-annual and decadal variability related to increasing temperature and acidity. Such studies are also critical to address unforeseen threats from volcanic eruptions, tsunamis and unnatural phenomena such as oil spills and other discharges (McNutt, 2014). However, the national public funding for such endeavors is generally shortsighted and lacks the necessary commitment of long term support (Baker et al., 2007).

MBARI currently supports three time-series projects that span the water column from surface ocean processes and midwater communities to benthic community processes in one of the most productive and economically important areas of the world ocean. The common thread connecting these projects is the cycling of food, organic carbon, from its production by phytoplankton in surface waters to its ultimate sequestration on the sea floor. The process of the drawdown of atmospheric CO_2 in conversion to organic carbon through photosynthesis and then remineralization of organic carbon throughout the water column and on the sea floor are critical processes in the carbon cycle. The process of remineralization of carbon can sequester CO_2 for hundreds to thousands of years (Falkowski et al., 1998; Pennington et al., 2010).

The three MBARI studies when combined will provide an unprecedented time-series data-set to track organic carbon production and utilization throughout the oceanic water column allowing us to interpret the impact of global warming on the oceanic carbon cycle. No other time-series program worldwide now provides the requisite measurements with high temporal resolution to conduct such studies throughout the water column and on the seafloor. The MBARI time-series studies also provide an unprecedented historical context of data collected over the last 25 years to put continuing studies in critical temporal perspective, which is of major importance in evaluating the impact of changing climate on ocean ecosystems.

The integration of the MBARI time-series effort into one coordinated program will require timely processing of existing and future data sets to achieve the desired temporal monitoring and to elucidate changing patterns in the oceanic carbon cycle. We propose a major effort to reduce the cost of conducting these time-series studies while increasing the temporal resolution of sampling using state-of-the-art autonomous instrumentation largely developed at MBARI. MBARI is uniquely positioned geographically and technically to make a major contribution to the study of climate change and its impact on oceanic ecosystems and the global carbon budget.

Historical perspective:

Here we present a survey of historic and current time-series studies worldwide to place the existing MBARI time-series in perspective and to indicate how best to proceed with a world-class integrated program that effectively utilizes limited resources and produces exportable technology.

Long time-series studies have become critical to understanding the impact of global warming on oceanic ecosystems that occupy a major portion of the biosphere. Weather ships provided the first oceanic time series data, consisting of routinely measured depth/temperature in the upper water column at ten stations in the North Atlantic and three stations in the North Pacific from 1940 until 1980 (Dinsmore, 1996). These weather ships also used the newly developed Continuous Plankton Recorder (CPR) to conduct sampling in the North Atlantic and to examine basin scale changes in surface ocean zooplankton communities (~10 m depth; Reid et al., 2003; Warner and Hays, 2004). Starting in 1950, a comprehensive ship-based, time-series study was undertaken along the California coast, the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program, to record changes of pelagic communities and the physical, chemical environment in the upper 500 m of the water column (Fig. 1). This CalCOFI program evolved into a more spatially and temporally restricted, quarterly time-series study covering 66 stations off southern and central California (Goericki and Koslow, 2012). There are many other existing oceanic time-series studies that use regular ship-based sampling of upper ocean parameters worldwide (e.g. Mackas et al., 2012). Although these ship-based time-series are extremely important in interpreting the impact of changing climate on oceanic ecosystems, here we have restricted our survey to those sites that include Eulerian and/or Lagrangian platforms as well as monthly to seasonal ship-based observations (Fig. 1). This approach will be necessary in the future as the costs of ship operations increase. The economic reality will drive us to seek more efficient autonomous instrumentation that provides data acquisition with high temporal resolution.

Current time-series stations worldwide:

Global monitoring of surface ocean conditions and phytoplankton chlorophyll began in 1997 using satellite sensors (Cracknell et al., 2010). In the ocean, thousands of Lagrangian Argos profilers, 3560 as of 29 April 2014 (www.argo.ucsd.edu), have been deployed since 2000 in all oceanic areas to measure salinity, temperature, and macro-nutrients to 2000 m depth and fluorescence to 200 m on selected profilers (Roemmich et al., 2009). Eulerian time-series moorings were established in the 1990s across the tropical oceans to monitor atmospheric and upper ocean conditions for prediction of global climate (Tropical Ocean Global Atmosphere; TOGA; McPhaden et al. 2010). Given this global perspective of atmospheric and upper ocean conditions in place, there has been an effort to develop Eulerian time-series stations to study ecosystem processes with high temporal resolution from the surface to the deep ocean on a worldwide basis. In the 1980s there were seven time-series stations located in the North Atlantic, North Pacific and Mediterranean, including three in Monterey Bay and offshore area (Figs. 1 and 2). Studies at these stations extend from the surface ocean to abyssal depths and include physical, chemical, pelagic and benthic community measurements as well as particulate matter fluxes. There are currently a total of 26 time-series stations worldwide that have been operational for > one year, providing data from the surface to the deep seafloor (Fig. 3), sampling over depth ranges to 5500 m from the Arctic to the Antarctic. Most of these time-series stations are located in the North Atlantic and North Pacific Oceans, and the Mediterranean Sea. There are 11 stations associated with abyssal depths and 14 stations over continental margins (bathyal depths). Although the majority of the time-series stations are located in more productive, high-surface-chlorophyll, continental margins, four are positioned in oligotrophic, low-surface-chlorophyll, central gyre regions of the North and South Atlantic and central North Pacific (Fig. 2).

Physical and chemical environmental parameters are routinely measured at almost all of these time-series sites ranging from upper-ocean to full abyssal depth profiling (Fig. 3). Particulate matter fluxes through the water column are measured with moored sediment traps at 14 stations (Fig. 3). Fewer time-series include sampling of the pelagic communities with an emphasis on phytoplankton and zooplankton in the upper ~ 200 m of the water column. Only one station (MBARI's Midwater-1) conducts monthly sampling of mesopelagic communities to 1000 m depth (Fig. 3). Five stations monitor benthic community processes. **There is no existing time-series station where the oceanic ecosystem is monitored from surface waters to the seafloor. Even the most extensively studied time series sites, (Bermuda Atlantic Time Series Study (BATS) and Hawaii Ocean Time-Series (HOT), do not have full ecosystem monitoring that includes surface, midwater, and benthic communities (Fig. 3).**

A new addition to time-series studies is cabled observatories with real-time communication and "unlimited" power supply from a shore-based facility. Cabled observatories are now operational in three areas of the North Pacific, MARS, Neptune/Canada and Aloha (Fig. 2). The MARS (Monterey Accelerated Research System) site became operational in 2008 but has principally served as a test-bed for instrumentation with no serious attempt at serving as a time-series site. Neptune/Canada observatory has four principal nodes extending from shelf to abyssal depths to monitor processes associated with the seafloor since 2009 (Fig. 3). The ALOHA cabled observatory (ACO) has been operational since 2011 and monitors physical and chemical parameters at a depth of 4800 m. All three of these cabled observatories have plug-in ports available to accommodate other time-series measurements.

Most recently in 2013, two time-series moorings were deployed as part of the new U.S. Ocean Observatories Initiative (OOI), one in the Gulf of Alaska at Sta. OSP and the other, Pioneer Array, on the continental shelf and slope off Cape Cod (Fig. 2). In addition, there are three other OOI open ocean stations planned for deployment over the next year in the Irminger Sea, Argentine Basin and Southern Ocean, each consisting of a central and two flanking moorings with glider communication extending to abyssal depths. A companion time-series mooring to the OOI array is being deployed in the central Irminger Sea (CIS) as part of the European Fixed-point open ocean observatories ($FixO^3$) system. In addition to these stand-alone mooring systems, there are two cabled observatories being deployed to furnish power and real-time data transmission from bottom and water column instruments. One of these installations, Antares, is located in the northern Mediterranean Sea at a depth of 2475 m off the southern coast of France (Fig. 2).The second cabled observatory (Regional Scale Nodes, RSN) is part of the OOI program to instrument the Juan de Fuca Plate off the coast of Washington and Oregon extending from slope to abyssal depths. Again none of these most recent time-series installations or those planned in the near future provide full oceanic ecosystem monitoring from surface to the seafloor.

Instrumentation and platforms used in current time-series studies:

Time-series studies employ three general categories of assets, Eulerian and Lagrangian instrumentation, and ships. A composite of these categories of assets are commonly used at each of the existing time-series sites (Fig. 1).

Eulerian instrumentation: The backbone of most time series consists of bottom-anchored moorings and surface buoys. A mooring typically consists of flotation packages, instrument sensors secured along the mooring line at desired depths, ballast weight and a release mechanism (Fig. 4). Common instruments include CTDs, fluorometers, transmissometers, dissolved oxygen and nutrient sensors, acoustic current meters, and sediment traps. Wire-following profilers are also used to provide vertical profiles of physical and chemical parameters along the mooring line. The surface expression of a mooring can be a large buoy equipped with meteorological and surface ocean sensors and the capability for a communication link to shore via satellite. Submersible winches can be used on moorings to profile the upper water column to minimize the mechanical stresses created by surface turbulence and to avoid ship traffic. Cabled observatories are now being used in time-series studies which provide shore-based power and communication to a wide variety of instruments on the sea floor and extending up into the water column.

Lagrangian instrumentation: Autonomous mobile assets that drift with the current or that are self-propelled are routinely used in association with moorings. Gliders are employed to provide greater spatial coverage surrounding a mooring (Fig. 4). They can profile the water column up to 2000 m depth providing many of the same measurements coming from the mooring-based sensor packages. Profiling floats are also used in time-series studies to provide physical and chemical measurements to 2000 m depth. Autonomous underwater vehicles (AUV) with larger payload capacities can support additional instrumentation such as camera systems and sonar devices to insonify extensive portions of the water column and areas of the sea floor. Data transmission from gliders, profiling floats and AUVs is possible through acoustic links with mooring receivers and through direct satellite links when these instruments are on the surface (Fig. 4).

Ship-based instrumentation: Ships are generally required to install and service both Eulerian and Lagrangian instrumentation at time-series stations. In addition, shipboard instruments such as CTD/rosettes, ADCPs, along with net tows and trawls provide seasonal to annual sampling critical to ground-truthing the Eulerian and Lagrangian measurements. Ship-based sampling provides a broader diversity of measurements on larger spatial scales (Fig. 4).

Time-series data acquisition, processing and archiving:

The overwhelming amount of information acquired in time-series studies requires a well-structured system to allow timely access to quality-controlled data. Raw data collected by each instrument in different formats need to be downloaded, quality-controlled, and linked with concurrent measurements and metadata. Processed data can then be archived in relational databases. Several existing time-series networks seek to develop standard practices and processes such that the sampling and analytical protocols used at each site are transparent, consistent and inter-comparable. The ultimate goal is to provide easy, open access to high quality time series data worldwide. Examples of such networks include OceanSITES (http://www.oceansites.org/), FixO3 (http://www.fixo3.eu/) and the TS network (http://www.whoi.edu/website/TS-network/home).

As part of the effort to integrate the three MBARI time series, the data processing is being expanded in a manner similar to the networks cited above. Time series at MBARI traditionally were managed independently and kept in separate databases (Fig. 5). A common relational database is currently being built, based on the open-source Spatial Temporal Oceanographic Query System developed at MBARI (STOQS, https://code.google.com/p/stoqs/). This will enable easy retrieval of data formatted following international standards, and facilitate the time series sharing to outside users and integration into existing international networks.

Financial support to sustain current time-series studies:

One of the major challenges of sustaining long time-series studies in the open ocean is a long-term commitment of financial support (see Baker et al., 2007). Early time series studies such as the weather ship and CalCOFI operations, were conducted using ships supported by national and state government agencies. The increasing costs of using ships has restricted their use and forced the implementation of more cost effective autonomous instrumentation to collect oceanic time-series data. Although the initial cost of infrastructure to support a time-series station is high, the ultimate savings in reduction of ship-time and manpower over years of operation is substantial. It has been almost impossible to obtain accurate estimates of infrastructure installation, maintenance and ship-time costs for the major time-series programs. However, an overview of the cost spectrum is given below. The entire infrastructure cost for the Ocean Observatories Initiative (OOI) when completely installed will be $386 million with an estimated yearly operational cost of $55 million (Witze, 2013). These costs include five mooring arrays and one cabled network (see Fig. 2). The maintenance cost for the HOT program in the central North Pacific is $1.55 million with $1.4 million for shiptime for a total of $2.95 million in 2013 (M. Church, pers. comm). A similar total cost of $2.77 million was required in 2013 to operate the BATS station in the North Atlantic. The cost of operating the CalCOFI program is ~$5 million (Koslow and Couture, 2013). In comparison, the total cost of operating the three existing time-series programs at MBARI, including ship-time is $3.12 million for 2014 (MBARI accounting website).

A unique opportunity at MBARI:

We have a well-established long time-series program at MBARI which is unsurpassed worldwide. Its breadth encompasses all the major components of an oceanic ecosystem in a major eastern boundary current region. The existing MBARI time-series consists of three component parts, upper ocean dynamics, midwater communities, and benthic community processes (Fig. 6). Each component was begun in 1989 and provides one of the very few time-series programs worldwide extending over 25 years (Fig. 1), a period of major climate and oceanic change (Chavez et al., 2011; Robison et al., 2010; Smith et al., 2013). Although each of the three components of the MBARI time-series was begun with different goals in mind, we now realize that when combined, this time-series will serve as an unprecedented program to study the impact of a changing climate on an entire oceanic ecosystem. By combining our efforts at two stations (Fig. 7), we will expand the spatial coverage from Monterey Bay offshore to provide greater resolution of California Current processes and their impact on the ecosystem and carbon cycling, from surface to the deep seafloor. The unique connection between these time-series stations is shown in Fig. 8. Over the 25 year time-series at Stations MB and M the integrated primary production (INTCAR) in surface waters at M-1 and the POC flux (POC) at greater than 3400 m at M are correlated ($r = 0.43$). The abundance of appendicularians, numerically dominant zooplankton that feed on POC in the upper 1000 m of the water column at MidW-1, is positively correlated with POC ($r=0.39$) and INTCAR ($r=0.45$).

The proposed integration of the MBARI time-series into a Monterey Bay and offshore station will require added instrumentation designed for high temporal resolution and autonomous monitoring, while minimizing the costs associated with ship-time. Measurements at both stations would be duplicated and synchronized to facilitate temporal comparisons through the water column and on the seafloor (Fig. 6).

The instrumentation we propose at both sites is shown in Fig. 9 and consists of AUVs and moorings. Two AUVs with different payloads and mission duration will be used for sampling and imaging. The first AUV is a long-range (LRAUV) with a current depth rating of 300 meters. This vehicle can travel long distances and has a payload capable of supporting sensors to measure physical and chemical parameters over its depth range as well as acoustic backscatter from pelagic fauna. In addition, the LRAUV will be equipped with a multi-syringe water sampler to collect water for phytoplankton analyses ashore. When episodic events are sensed during routine monitoring, sampling can be extended between the two sites to better interpret water column phenomena in conjunction with broad-scale satellite monitoring of the same area. A second AUV will be equipped with an optical and acoustic imaging payload. This AUV will conduct video and ultimately acoustic transects in the upper 1000 m of the water column to provide community structure data on zooplankton and nekton. In addition, this AUV will conduct bottom photo-transects and insonify the bottom of the water column for benthopelagic community studies (Fig. 9).

The mooring component will consist of sediment traps to collect sinking particulate matter at 500 m depth and at 50 m above bottom at both sites (Fig. 9). An existing sediment trap at 600 m above bottom at the offshore station (Sta. M) will continue to be maintained. A time-lapse camera to monitor benthic processes will be deployed at the bottom of moorings at both stations. A spray glider will hold station over Sta. MB and provide routine CTD profiling dives from the surface to the sea floor (two spray gliders already exist at MBARI for this purpose, each with a 3-month duration). We are optimistic that the intensive monitoring of water column and benthic processes at the Monterey Bay and offshore time-series stations will stimulate new biogeochemical research to be conducted by both MBARI and external scientists. Collaborations with the CalCOFI/CCE-LTER program to the south will broaden the regional scope of our combined monitoring of the California Current System (e.g. Smith et al., 2014). Our proposed view of the integrated time-series at MBARI will require resources to first upgrade the existing program to ultimately realize overall cost-savings specifically regarding shiptime while maximizing scientific output and exportable technology to other time-series programs worldwide.

MBARI integrated time-series roadmap (ITSR):

We propose the following MBARI integrated time-series roadmap (ITSR) to achieve an economically sustainable, high-profile, unprecedented long time-series program with worldwide importance. To fully implement such a largely autonomous program will take a major effort over the course of 3 to 5 years using AUVS, gliders and long-sustaining moorings.

Infrastructure components:

1. Complete development of midwater and benthic imaging AUV (s) –optical imaging (2015, acoustic imaging (2016)
2. Complete development of 300m -LRAUV water sampling system – Fall 2014
3. Develop existing LRAUV with docking capabilities for both data and power exchange
4. Develop 4000m-LRAUV to conduct full depth optical and acoustic monitoring at both stations
5. Develop 4000m-LRAUV with docking capabilities for both data and power exchanges
6. Install a mooring of two sediment traps and time-lapse camera at Sta. MB
7. Develop mooring based instrumentation to provide continuous monitoring of water column (low-cost cameras, RDI acoustics, SES, Rover) for LRAUV data and power exchanges through docking stations

8. Install a 500 m depth sediment trap w/ extended mooring at Sta. M
9. Establish data management and acquisition system for all MBARI time-series data.
10. Develop VARS routines for processing AUV images from midwater and benthic transects
11. Export time-series instrumentation and data management system

Time-series monitoring implementation:

1. Begin monitoring of upper ocean parameters using LRAUV at Sta. MB and Sta. M and processing data.
2. Begin monitoring of physical and chemical parameters as well as the distribution, abundance and size of pelagic fauna using optical and acoustic imaging at 100m intervals down to 1000 m depth and processing data at both stations.
3. Begin oblique AUV faunal transects of water column between 1000 m and the bottom at both stations.
4. Begin monitoring of the physical and chemical parameters as well as the distribution, abundance and size of benthic boundary layer fauna using optical and acoustic imaging from the sea floor to 50 m above bottom at both stations.
5. Continue annual servicing of moorings and processing of sediment trap and time-lapse images from both stations.

Schedule for development and implementation of integrated time-series program (Table 1):

2014

1. Complete development of 300m-LRAUV water sampling system – Fall
2. Establish data management and acquisition system for MBARI time-series data
3. Continue monthly monitoring of upper ocean parameters at Sta. MB
4. Continue monthly monitoring of midwater community at Sta. MB.
5. Continue annual servicing of moorings and processing sediment trap data from Sta. M

2015

1. Complete development of midwater and benthic imaging for AUVs
2. Install a mooring of two sediment traps and time-lapse camera (existing) at Sta. MB
3. Develop existing 300m-LRAUV with docking capabilities for both data and power exchange
4. Purchase and install a 500m depth sediment trap w/extended mooring at Sta. M
5. Begin monitoring of upper ocean parameters using 300m-LRAUV, profiling and wave gliders, and processing data at station MB
6. Begin monitoring of physical and chemical parameters as well as the distribution, abundance and size of pelagic fauna using optical and imaging at 100m intervals down to 1000 m depth and obliquely to the bottom. Processing data from station MB.
7. Begin monitoring of the physical and chemical parameters as well as the distribution, abundance and size of benthic boundary layer fauna using optical and acoustic imaging from the sea floor to 50 m above bottom and processing data at station MB.
8. Continue annual servicing of moorings and processing of sediment trap and time-lapse images at both stations.

9. Complete development of VARS routines for processing AUV images from midwater and benthic transects.

2016

1. Begin to develop 4000m-LRAUV to conduct full depth optical and acoustic monitoring at both stations
2. Begin to develop 4000m-LRAUV with docking capabilities for both data and power exchanges
3. Develop mooring based instrumentation to provide continuous monitoring of water column (low-cost cameras, RDI acoustics, SES) with LRAUV data and power exchanges through docking stations
4. Monitoring of upper ocean parameters using 300m-LRAUV, profiling and wave gliders, and processing data at both stations
5. Monitoring of physical and chemical parameters as well as the distribution, abundance and size of pelagic fauna using optical and acoustic imaging at 100m intervals down to 1000 m depth and obliquely to the bottom. Processing data from both stations.
6. Begin monitoring of the physical and chemical parameters as well as the distribution, abundance and size of benthic boundary layer fauna using optical and acoustic imaging from the sea floor to 50 m above bottom and processing data from both stations.
7. Continue annual servicing of moorings and processing of sediment trap and time-lapse images at both stations.
8. Export time-series instrumentation and data management system
9. Put time-series data in public domain?

Figures:

Fig. 1– Twenty-six existing oceanic time-series stations representing ship-based, eulerian and lagrangian monitoring in most of the major oceanic areas of the World Ocean with occupations beginning in 1949 and spanning 65 years.

Fig. 2– World map of 26 existing (black) and 7 new (purple) oceanic time-series stations overlain by mean surface chlorophyll concentration. Two rectangular areas are enlarged to show station locations in the Mediterranean Sea and the Eastern North Pacific off the central California coast. Asterisks denote those stations with cabled observatories.

Fig. 3 - Twenty-six existing time-series stations covering a depth range from 350 m in the Bellingshausen Sea along the Antarctic Peninsula to 5500 m depth in the Fram Strait between the Arctic and North Atlantic Oceans. The physical, chemical, pelagic and benthic community monitoring and particulate matter flux are depicted with depth for each station.

Fig. 4 – Illustration of instrumentation with depth for the two MBARI time-series stations (MB and M) for comparison with two stations in the North Pacific (OSP and ALOHA) and two stations in the North Atlantic (BATS and PAP).

Fig. 5 – Flow chart showing data acquisition, processing and archiving from the upper ocean, midwater and benthic components of the MBARI time-series program, adapted from Figure 1 of the OCEANSITES

Data Management Team Meeting Report (http://www.oceansites.org/docs/OceanSITES2013/reports/OceanSITES_2013_DMT_report_v1.pdf). Blue boxes represent the data management currently in place; green boxes represent the new processing being implemented as part of the time-series integration.

Fig. 6 – Surface, pelagic and benthic measurements at the three existing MBARI time-series stations. Surface, pelagic and benthic measurements at the two proposed MBARI time-series stations. Physical measurements (dark blue), chemical measurements (light blue), phytoplankton (green), nekton (red), benthos (purple) and particulate matter flux (yellow).

Fig. 7 – Map of existing MBARI time-series stations along with MARS site. The Monterey Bay stations, (M1, Midwater 1) are considered MB. Station M offshore is considered M. The CalCOFI station grid is shown along with two recently established California Current LTER moorings (CCE1 and CCE2).

Fig. 8 – The relationship between particulate organic carbon flux (POC- mgC $m^{-2}d^{-1}$- blue), integrated primary production(INTCAR – mgC $m^{-2}d^{-1}$-green) and mesopelagic appendicularian abundance (total counts d-1 over 1000 m depth range - orange) over 24 years from 1989 to 2014. In this Integrated Time Series that spans more than 10 years, POC and integrated carbon are closely coupled (r=0.43). The abundance of appendicularians - animals that feed on POC - is positively correlated with POC (r=0.39) and INTCAR (r=0.45) after a lag of 2 months, Appendicularians are among the most abundant animals annotated in the Midwater Time Series.

Fig. 9 – Proposed instrumentation to monitor physical and chemical parameters as well as pelagic and benthic community processes and particulate matter fluxes at stations MB and M.

Tables:

Table 1 – Integrated Time-series roadmap (ITSR) components and proposed schedule for implementation over the next 3 years (2014-2016).

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