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Sea change: Charting the course for biogeochemical ocean time-series research in a new millennium

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ABSTRACT

Ocean time-series provide vital information needed for assessing ecosystem change. This paper summarizes the historical context, major program objectives, and future research priorities for three contemporary ocean time-series programs: The Hawaii Ocean Time-series (HOT), the Bermuda Atlantic Time-series Study (BATS), and the CARIACO Ocean Time-Series. These three programs operate in physically and biogeochemically distinct regions of the world's oceans, with HOT and BATS located in the open-ocean waters of the subtropical North Pacific and North Atlantic, respectively, and CARIACO situated in the anoxic Cariaco Basin of the tropical Atlantic. All three programs sustain near-monthly shipboard occupations of their field sampling sites, with HOT and BATS beginning in 1988, and CARIACO initiated in 1996. The resulting data provide some of the only multi-disciplinary, decadal-scale determinations of time-varying ecosystem change in the global ocean. Facilitated by a scoping workshop (September 2010) sponsored by the Ocean Carbon Biogeochemistry (OCB) program, leaders of these time-series programs sought community input on existing program strengths and for future research directions. Themes that emerged from these discussions included:

1. Shipboard time-series programs are key to informing our understanding of the connectivity between changes in ocean-climate and biogeochemistry.
2. The scientific and logistical support provided by shipboard time-series programs forms the backbone for numerous research and education programs. Future studies should be encouraged that seek mechanistic understanding of ecological interactions underlying the biogeochemical dynamics at these sites.
3. Detecting time-varying trends in ocean properties and processes requires consistent, high-quality measurements. Time-series must carefully document analytical procedures and, where possible, trace the accuracy of analyses to certified standards and internal reference materials.
4. Leveraged implementation, testing, and validation of autonomous and remote observing technologies at time-series sites provide new insights into spatiotemporal variability underlying ecosystem changes.
5. The value of existing time-series data for formulating and validating ecosystem models should be promoted.

In summary, the scientific underpinnings of ocean time-series programs remain as strong and important today as when these programs were initiated. The emerging data inform our knowledge of the ocean's biogeochemistry and ecology, and improve our predictive capacity about planetary change.

1. Preface

1.1. Time, water, and change

Oceans are vital to Earth's habitability and are important socio-economic resources. The massive and diverse oceanic ecosystems play interactive roles in shaping climate, serve as reactive pools of bioelements, and comprise vast reservoirs of biodiversity. Despite their importance to humans and planetary health, we currently lack confident predictive understanding of how oceanic ecosystems may respond to global change. In part this derives from chronic under-sampling of these remote and spatiotemporally complex habitats. There are currently only a few regions in the sea where we have sustained, decadal-scale observations on the interactions between ocean biogeochemistry, hydrography, and ecology. These few time-series, built largely around shipboard sampling programs, provide

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evidence that ocean–climate–human interactions can have cascading impacts on ecosystem processes across a wide range of time and space scales. Moreover, these time-series records provide the critical data needed to better understand the ocean's and our planet's sensitivity to change.

A major challenge facing ocean scientists is how to advance interdisciplinary, multi-decadal time-series programs that provide high quality data at sufficient spatiotemporal resolution to inform our understanding of marine ecosystem change. Despite the successes of ship-based time-series in documenting ocean change, sampling from research vessels is relatively restrictive in its spatio-temporal resolution. Rising costs associated with operating and maintaining ships require continual reassessment and justification of the cost–benefit scenarios to science and society behind sustaining ship-based oceanographic programs. Moreover, technology advances in the past decade now allow for high-resolution autonomous sampling of various oceanographic properties. Such factors have partly motivated the current expansion of ocean observational systems designed to rely on remote and autonomous sensing platforms, promising higher frequency spatio-temporal sampling of ecosystem dynamics difficult to adequately sample from ships alone, at a potential cost savings. Satellites, floats, gliders, moorings, and remotely operated vehicles have all become increasingly central to such observing strategies. However, to date, we lack the capabilities to detect many of the key climate-sensitive biogeochemical properties and processes we know are fundamental to ecosystem function from these autonomous sensing platforms. Balancing investments required to maintain comprehensive ocean carbon and biogeochemistry time-series and more autonomous observatory systems is central to the evolving vision of the ocean sciences.

Facilitated by the Ocean Carbon Biogeochemistry (OCB) program, three contemporary ocean time-series programs convened a "scoping workshop" in September 2010 to gather community input on the future direction and scope of ship-based time-series programs. The workshop largely focused on three on-going programs whose research aligns with the OCB program objectives: the Hawaii Ocean Time-series (HOT), Bermuda Atlantic Time-series Study (BATS), and the CARIACO Ocean Time-Series. All these programs maintain near-monthly ship-based sampling programs in hydrographically and biogeochemically distinct regions: the North Pacific Subtropical Gyre (NPSG), the subtropical North Atlantic, and the Cariaco Basin in the tropical North Atlantic, respectively (Table 1). These sites are complemented by systematic observations collected from other observing platforms including moorings, satellites, floats, and gliders. The data from these time-series programs provide some of the only decadal-scale records available for assessing seasonal- to interannual-scale changes in ocean hydrographic structure, biogeochemistry, and biology.

Ocean biogeochemistry time-series programs remain vital community resources, providing invaluable cross-disciplinary information on ocean ecosystem change. Discussions as part of this workshop provided an opportunity for community input on science priorities for the next decade of research at these sites, including exploring the strengths and limitations of existing shipboard time-series programs. In this paper, we summarize some of these discussions within the framework of the research done at the three on-going time-series, define opportunities for new science built around these programs, and provide several recommendations for improving the state of global ocean observing that includes a long-term role for shipboard time-series research.

2. Background

2.1. If you build it, they will come

The vision to establish shipboard time-series sprung from recognition that detecting how anthropogenic and natural-climate changes influence the biosphere is impossible without time-resolving measurements collected over long periods of time (Keeling et al., 1995; Likens et al., 1996; Schindler, 1988). Historical roots for contemporary ocean time-series can be traced in part to use of weather ships,

Table 1
Ocean Carbon Biogeochemistry time-series programs and study site characteristics.

Program and study site	Period and frequency of shipboard observations	General site characteristics	Annual mean (and range) primary productivity and carbon export (mol C m^{-2} yr^{-1})	Sampling infrastructure	Program leadership
BATS (31.75°N, 64.16°W)	1988–present (monthly)	Subtropical North Atlantic (Sargasso Sea), seasonally oligotrophic, moderate seasonality (largely attributable to winter mixing)	14 (9.7–16), 0.87 (0.67–1.1)	Shipboard observations (1988–present), bottom-moored sediment traps (1978–present), profiling floats (2009–present), moored platform (1994–2007)	Anthony Knap (1988–2012), Anthony Michaels (1989–1996), Rob Johnson (1988–present), Nick Bates (1995–present), Debbie Steinberg (1997–2001), Craig Carlson (1992–2001), Michael Lomas (2001–present)
HOT—Station ALOHA (22.75°N, 158°W)	1988–present (monthly)	Subtropical North Pacific, persistently oligotrophic, low seasonality in hydrography and biogeochemistry	14 (9.4–18), 0.84 (0.64–1.2)	Shipboard observations (1988–present), bottom-moored sediment traps (1992–present), profiling floats (2005–present), moored platforms (1997–present), cabled observatory (2010–present)	David Karl, Roger Lukas, Ricardo Letelier, John Dore, Robert Bidigare (all 1988–present), Eric Firing (1988–1998), Stephen Chiswell (1988–1993), Christopher Winn (1988–1997), Michael Landry (1992–present), Luis Tupas (1991–2000), Dale Hebel (1988–2005), Matthew Church (2009–present)
CARIACO (10.5°N, 64.67°W)	1995–present (monthly)	Tropical Caribbean Sea (Cariaco Basin), mesotrophic, highly seasonal hydrography and biogeochemistry (attributable to changes in upwelling)	40 (29–53), 2.1 (1.4–2.8)	Shipboard observations (1995–present), bottom-moored sediment traps (1995–present)	Frank Muller-Karger, Mary Scranton, Gordon Taylor, Robert Thunell, Ramon Varela, Yrene Astor (all 1995–present), Kent Fanning, Luis Troccoli (2000–present), Baumar Marín (2000–present), Robert Weisberg (1996–2006), John J. Walsh (1995–2000)

deployed in remote regions of the world's oceans to gather meteorological data necessary to improve weather forecast models. The value of such repeated occupations to otherwise inaccessible regions of the oceans attracted the interests of a diverse group of scientists. The "ancillary" observations collected by process-oriented scientific programs, conducted alongside the weather-ship hydrographic and meteorological sampling, led to important discoveries. For example, ocean productivity and irradiance measurements at Weathership "M" in the North Sea laid the framework for the formulation of the critical depth theory explaining the prerequisite interactions between light, mixing, and photosynthesis in controlling formation of phytoplankton blooms (Sverdrup, 1953). The legacy of these programs continues today. For example, measurements conducted at Station P (50°N, 145°W) continue the observations started in the 1940s from a weather-ship outpost in the subarctic North Pacific (Freeland, 2007; Whitney and Tortell, 2006). The resulting data highlight complex, climate-forced biogeochemical interactions, including long-term changes in dissolved oxygen concentrations within the main thermocline of the North Pacific Ocean (Whitney et al., 2007).

In addition to ocean weather ships, economic interests in commercially important fisheries motivated the establishment of time-series monitoring programs. The collapse of the Pacific sardine fishery in the mid 1940s resulted in the creation of the California Cooperative Fisheries Investigations Program (CalCoFI) program in 1949. This program has maintained a near-continuous record of climatic influences on ecosystem variability in the California Current ecosystem (Field et al., 2006; Rebstock, 2002; Rykaczewski and Checkley, 2008) with a focus on fisheries stocks and management.

The establishment of Hydrostation S (32°10′N, 64°30′E) off Bermuda in 1954 marks a major historical entry point for modern ocean time-series research (Fig. 1). Motivated by the desire to better understand seasonal to interannual variability in meteorological forcing of ocean physics, and with the support from the Office of Naval Research, Henry Stommel (Woods Hole Oceanography Institution) and William Sutcliffe (Bermuda Biological Station) initiated a biweekly sampling campaign to physically characterize the ~2600 m water column at Hydrostation *S* in the northwestern Sargasso Sea (Jenkins, 1982; Schroeder et al., 1959). Providing physical context and regular access to the open sea, facilitated in large part by suitably equipped research vessels and infrastructure support from the Bermuda Biological Station, Hydrostation S rapidly attracted new and diversified science programs. Among the first to capitalize on the Hydrostation *S* time-series were Woods Hole scientists David Menzel and John Ryther. By placing measurements of productivity and nutrient cycling into the time-resolved hydrographic context afforded by Hydrostation *S*, their work helped define factors shaping biogeochemistry in the subtropical ocean gyres (Menzel and Ryther, 1960, 1961). By the 1970s and 1980s several important biogeochemical studies had coalesced around the Hydrostation S, including a study that continues today aimed at quantifying temporal relationships between upper-ocean productivity and the downward flux of material to the deep sea (Conte et al., 2001; Deuser and Ross, 1980; Deuser et al., 1983, 1990), and geochemical approaches to estimate net community productivity (Jenkins, 1982; Jenkins and Goldman, 1985). These studies revealed that the vast subtropical ocean gyres serve as globally important carbon reactors, where productivity was greater than historically recognized and whose carbon storage potential depended on complex biological–physical couplings. By embedding such measurements into the time-resolving hydrographic framework, Hydrostation S became one of the few places in the world where quantitative information on seasonal to interannual scale interactions between plankton ecology, hydrographic forcing, and biogeochemical cycles in the open sea was available.

These early efforts solidified a recurrent theme among contemporary ocean time-series: regular access to the open sea

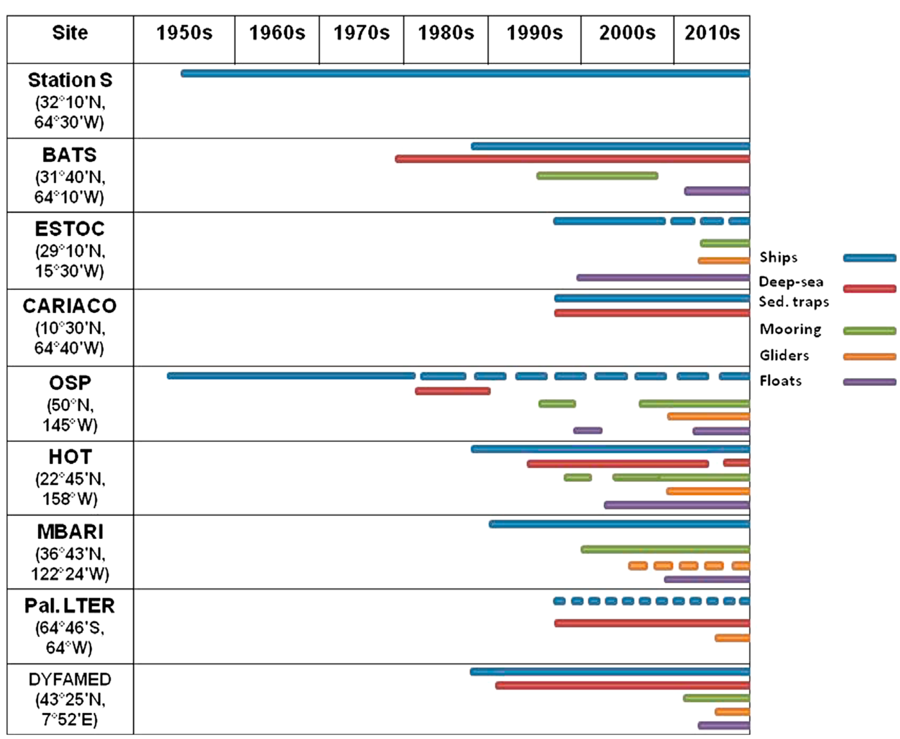

Fig. 1. Timeline of research conducted at various ocean time-series sites around the globe. Colored lines indicate types of sampling and measurement activities (ships, moorings, gliders, floats, and sediment traps). Solid lines reflect sustained measurement program on at least monthly time scales; dashed lines indicate measurements have continued but at lower than monthly frequency; and gaps in time-series records are shown by broken lines. Site abbreviations are: Station *S*, Hydrostation *S*; OSP, Ocean Station Papa; Pal. LTER, Palmer Long Term Ecological Research program in Antarctica. Figure adapted from Karl et al. (2003). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

afforded by a ship provides unique opportunities for studying ocean processes, developing new methods, training students and technicians, and testing hypotheses. Encapsulating these attributes in a rich historical context of physical and biogeochemical measurements further strengthens the allure of such programs. These efforts inspired questions that remain at the core of contemporary oceanography, including identifying processes controlling rates of primary production; examining how plankton community structure influences productivity and material export; quantifying nutrient supply to the upper ocean; and defining seasonal to interannual scale variability in stocks of oxygen, carbon, and nutrients essential for life on Earth. The time-series sampling approach allows studying ecosystem behavior that would be otherwise obscured by higher frequency "noise" or time lags between perturbations and responses (Magnuson, 1990).

The scientific and logistical successes of these early studies stimulated recognition that ocean ecosystems previously considered to be relatively static exhibit significant temporal variability over a variety of scales. Moreover, these programs highlighted that efforts to document changes to the sea require a well-formulated plan for sustained, long-term ocean time-series research. By 1984, ocean scientists working under the umbrella of the Scientific Committee of Oceanic Research (SCOR) formulated plans for a new oceanographic program to document anthropogenically induced changes to the sea. The Global Ocean Flux Study (GOFS) sought better understanding of the processes controlling ocean biogeochemistry at regional to global scales (Global Ocean Flux Study, 1984). With international partnerships in place, the Joint Global Ocean Flux Study (JGOFS) emerged as one of the first core projects of the International Geosphere-Biosphere Program (IGBP). Central to the objectives of JGOFS was the need to determine the interactions among elemental cycles in the sea and understand the processes controlling time-varying fluxes of carbon and associated bioelements. Ocean time-series were included as an essential component of this interdisciplinary program (Brewer, 2003). At the same time that JGOFS was formulating its science agenda, the World Climate Research Program (WCRP) was developing plans for the World Ocean Circulation Experiment (WOCE), a program centered on observations and models of ocean-climate change. The programs collectively recognized the need for an integrated, interdisciplinary approach to ocean observing that included relying on time-series sampling. In 1987, three separate proposals (two to JGOFS and one to WOCE) were submitted to the US National Science Foundation (NSF) for the establishment of HOT and BATS. Starting in October 1988 both HOT and BATS were in the water, undertaking near-monthly shipboard time-series sampling in the NPSG and Sargasso Sea, respectively (Karl and Michaels, 1996; Michaels and Knap, 1996).

HOT and BATS were born from the idea that time-series are essential to understand time-varying fluxes of carbon and associated vital elements in the oceans. The core elements of both HOT and BATS fell under the auspices of JGOFS and WOCE throughout the lifetimes of these larger programs. The time-resolved physical and biogeochemical context and regular access to the open sea stimulated numerous "ancillary" research projects that continue to collect a wide range of observations at both locations. Within 5 years it became apparent that one of the major strengths of these programs was the interdisciplinary, multi-investigator approach to studying ecosystem dynamics. The resulting high-quality measurements, together with the scientific and ship-based infrastructure fueled numerous collaborative scientific interactions. Between the late 1980s and the mid-1990s, many time-series programs were initiated in various marine ecosystems around the globe (Fig. 1) including Monterey Bay (MBARI, 36° 43′N, 122° 24′W; 1989–present), in the Mediterranean (DYFAMED, 43°25′N, 7° 52′E; 1991–present), in the northeast Atlantic (ESTOC, 29°10′N, 15°30′W; 1994–present), and in the semi-enclosed Cariaco Basin (CARIACO; 1995–present). CARIACO was initiated with support from the Venezuelan government, NSF, and NASA. The project seeks to examine linkages between upper ocean productivity, terrigenous material input to the enclosed basin, material fluxes from the shelf into deep water, and the preservation of climate signals in the sediment accumulating at the bottom of this anoxic tropical ecosystem (Muller-Karger et al., 2010; Taylor et al., 2012). The region has a rich history of paleo-oceanographic research (Black et al., 1999; Hughen et al., 2004) that provides additional motivation for contemporary time-series studies linking upper ocean biogeochemical processes to climate signals stored in seafloor sediments.

The successes of the time-series programs made them among the most transformative accomplishments of JGOFS. By the end of the JGOFS program in the early 2000s, HOT, BATS, and CARIACO found themselves lacking a unified programmatic base to facilitate exchange of ideas on science priorities pursued by these programs. The initiation of the OCB program in 2007 provided a scientific support framework whose research interests aligned well with these on-going time-series efforts. HOT, BATS, and CARIACO remain focused on studying processes that control the distributions and cycling of elements in the sea, with specific focus on carbon, in sufficient detail to provide predictive understanding on how global scale perturbations to ocean-climate might influence biogeochemical transformations and feedbacks. To achieve this broad objective, the programs seek understanding of the following:

1) The linkages between seasonal, interannual, and long-term (multi-decadal) variability and trends in ocean physics, chemistry, and biology.
2) Processes underlying physical and biogeochemical temporal variability.
3) The role of physical forcing on carbon fluxes, including rates of biologically mediated carbon transformations, air–sea CO_2 exchange, and carbon export.
4) The response of ocean ecosystems and biogeochemistry to planetary change.

The scientific and logistical support afforded by these programs continues to generate activities that serve as focal points for new science, education, and public outreach. The times-series sites have proven fertile grounds for improving existing methodologies and implementing novel sea sensing technologies (Fig. 1). The short duration (<1 week) cruises in globally significant but remote habitats continues to attract the interests of diverse science projects that benefit from a time-resolved sampling approach. The core time-series benefit from the knowledge of ecosystem dynamics provided by such ancillary research projects, while the ancillary projects benefit from time-resolved scientific context and logistical, infrastructural, and technical support provided by the core programs. As a result, HOT, BATS, and CARIACO have attracted numerous scientists, students, teachers, and volunteers from all over the world seeking opportunities to participate in time-series research or just to experience science from aboard a research vessel. Between 1988 and 2009, more than 320 scientists and their staff have been involved in process studies that build on the "core" time-series programs, and an additional >140 "core" time-series scientists and staff have participated in HOT, BATS, and CARIACO cruises. Over 420 undergraduate and graduate students and ~ 50 teachers (elementary to university level) from around the globe have and continue to participate in these cruises for education and training opportunities. These programs have become models by which other nations are developing their own time-series programs to assist in understanding local ecosystems and responses to impacts and change, and which will ultimately help us to understand global-scale ocean change.

3. Program highlights

3.1. From the predictable to the unexpected

All three time-series programs measure a core set of physical and biogeochemical properties on each cruise (http://hahana.soest.hawaii.edu/hot/; http://bats.bios.edu/; http://www.imars.usf.edu/CAR/index.html); these measurements were selected to provide a comprehensive and interdisciplinary framework from which to view time-varying changes in these oceanic ecosystems. The long list of highlights emerging from the time-series data records include documentation of progressive changes in oceanic carbon inventories and fluxes (Astor et al., 2005, 2013; Bates, 2001, 2007; Dore et al., 2003, 2009; Keeling et al., 2004); unexpected variability in the elemental stoichiometry of seawater nutrient pools (Karl, 2002; Michaels et al., 1994, 1996; Thunell et al., 2008); complex climate-linked interactions between plankton ecology and biogeochemistry (Corno et al., 2007; Karl, 1999; Lomas et al., 2010; Taylor et al., 2012); elucidation of variability associated with pools and fluxes of organic matter (Carlson et al., 1994; Emerson et al., 1997); and the importance of plankton community structure in controlling time-variability in carbon sequestration (Dore et al., 2002; Lomas et al., 2009; Thunell et al., 2007).

On the surface, HOT and BATS sample similar ocean habitats: both sites are located in relatively warm and isolated subtropical gyres where Ekman downwelling associated with the anticyclonic rotation of the gyres results in deep permanent pycnoclines and near-surface ocean chlorophyll concentrations are persistently low (Fig. 2). Despite these broad similarities, there are fundamental differences in hydrographic, biogeochemical, and ecological characteristics at HOT and BATS, and both sites experience variability in upper-ocean dynamics that alter biogeochemical dynamics and plankton community structure across a range of time scales. BATS features higher-salinity waters from the surface to the ocean bottom, compared to those found at HOT (Fig. 2). Moreover, the mid- and deep waters at HOT (>1000 m) have depleted concentrations of dissolved oxygen and enriched concentrations of nutrients compared to BATS, both signatures consistent with greater time-integrated organic matter remineralization characteristic of older deep waters in the North Pacific (Fig. 2).

The physical and biogeochemical characteristics of CARIACO contrast those observed at HOT and BATS (Fig. 2). While HOT and BATS both sample deep-ocean locations (>4700 m), CARIACO lies on a geological fracture on the continental shelf (bottom depth ~1400 m) off the coast of Venezuela in an permanently anoxic basin. The physical and biogeochemical conditions at this site are defined by factors influencing oceanography of the tropical and subtropical Atlantic, the Caribbean Sea, and the continental margin. High near-surface biological productivity and settling particulate organic matter flux leads to anoxic subsurface waters in the Cariaco Basin. CARIACO is a mesotrophic tropical ecosystem that experiences seasonally dynamic trade-wind forced upwelling (January through May), and episodic delivery of terrestrially derived organic matter in the autumn (Ho et al., 2004). Anoxia below approximately 250 m is caused by physical isolation of the deep waters in the basin and the relatively high biological activity. The lack of oxygen in this region of the water column (>250 m) promotes finely structured vertical redox gradients (Scranton et al., 2001; Taylor et al., 2001), including complete removal of nitrate by denitrification.

HOT, BATS, and CARIACO all rely on near-monthly shipboard sampling. The resulting time-series data capture seasonally

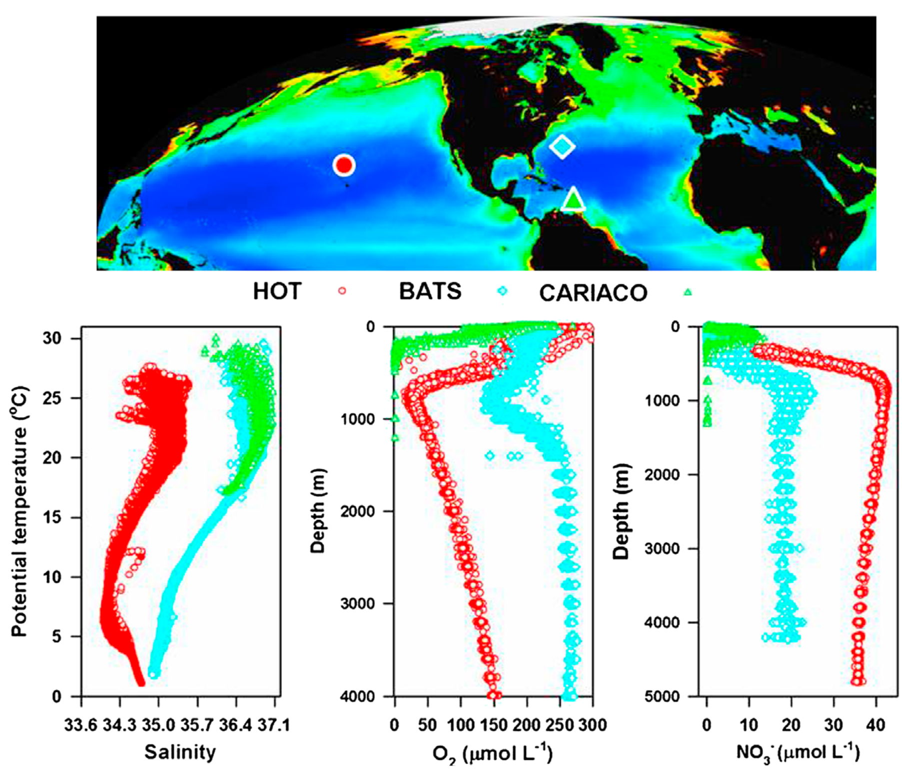

Fig. 2. Study locations of HOT (red circle), BATS (blue diamond), and CARIACO (green triangle) superimposed over 6-year composite of satellite-derived near-surface ocean chlorophyll concentrations. Bottom panels depict temperature–salinity relationships, and vertical profiles of dissolved oxygen and nitrate+nitrite from the three time-series sites. Satellite data courtesy of the Ocean Biology Program (NASA Goddard Space Flight Center). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

recurring patterns in both hydrographic forcing and biogeochemical dynamics, with both higher- and lower-frequency variability superimposed on that seasonal dynamic. Although all three sites undergo relatively weak seasonal variability in sea surface temperatures (SST), the amplitude and timing of SST variations at BATS are notably different than observed at HOT or CARIACO. Near-surface ocean temperatures at HOT generally vary $<5\,^{\circ}C$ over the course of the year, while SST at CARIACO varies about 5–8 °C, and at BATS SST can vary by $>9\,^{\circ}C$ (Fig. 3). All three regions also demonstrate seasonality in the depth of upper ocean mixing. The mixed layer at HOT and CARIACO displays relatively weak seasonality (Fig. 3); at HOT the mixed layer is almost always restricted to the upper 120 m (and hence within the euphotic zone ~125 m; Letelier et al., 2004) and at CARIACO the perennially warm and saline upper ocean waters restricts mixing to <50 m, which is of the order of the euphotic zone depth (Lorenzoni et al., 2011). In contrast, mixed-layer depths at BATS can exceed 400 m in the late winter (and thus can seasonally exceed the depth of the euphotic zone ~100 m; Siegel et al., 2001), then shoal rapidly to <30 m by the late spring and summer (Fig. 3).

These seasonal differences in hydrographic forcing imprint unique biogeochemical signatures on each region. The relatively weak seasonal mixing combined with rapid plankton growth results in an upper ocean at HOT that is consistently starved of nutrients. Depth-integrated (0–100 m) inventories of $NO_3^- + NO_2^-$ at HOT are low throughout the year (Fig. 3), but become more variable during the winter periods when mixed-layer depths increase and incident irradiance reaches its annual minima (Karl et al., 2008; Letelier et al., 2004). In contrast, nutrient inventories at BATS show more prominent seasonality (Steinberg et al., 2001); upper ocean (0–100 m) $NO_3^- + NO_2^-$ concentrations increase sharply during periods of late winter mixing, and then rapidly decrease to levels similar to those measured at HOT during the warm, stratified summer months (Fig. 3). Nutrient concentrations in the near-surface waters at CARIACO are typically relatively low, with $NO_3^- + NO_2^-$ generally $<1\ \mu M$ (Astor et al., 2003); however, the strong vertical gradient in nutrient concentrations, together with seasonal upwelling, yields upper ocean (0–100 m) nutrient inventories that are several hundred times greater than those observed at HOT or BATS (Fig. 3).

Rates of primary production (as estimated from ^{14}C-bicarbonate assimilation) and particulate matter export at all three sites demonstrate variability on seasonal to interannual scales (Figs. 4 and 5). Both production and export (and hence rates of new production) are sensitive to changes in plankton community structure and to interannual variations in hydrographic forcing (Chavez et al., 2011; Corno et al., 2007; Letelier et al., 1996; Muller-Karger et al., 2001; Saba et al., 2010). Moreover, the emerging seasonal climatologies in production and particulate carbon export at these sites highlights several patterns reflective of the unique biological responses to annually recurring ecosystem dynamics (Fig. 4). Consistent with the relatively quiescent physical nature of the NPSG, primary production (0–100 m) at HOT typically varies ~2-fold over the year (~30 and 50 mmol C $m^{-2}\ d^{-1}$) (Fig. 5). A weak but predictable seasonal dynamic is observed where rates increase during the summer when irradiance is maximal and the upper ocean is well stratified. Particulate matter flux (150 m) increases <2-fold during the more productive spring and summer months (Fig. 5), resulting in a weak seasonal-scale coupling between productivity and export. In contrast, upper-ocean productivity (0–100 m) and export (150 m) at BATS increase in the early spring when nutrient inventories are at their annual maximum. The amplitude of the seasonal cycle in productivity at BATS is larger than observed at HOT, with primary production during the

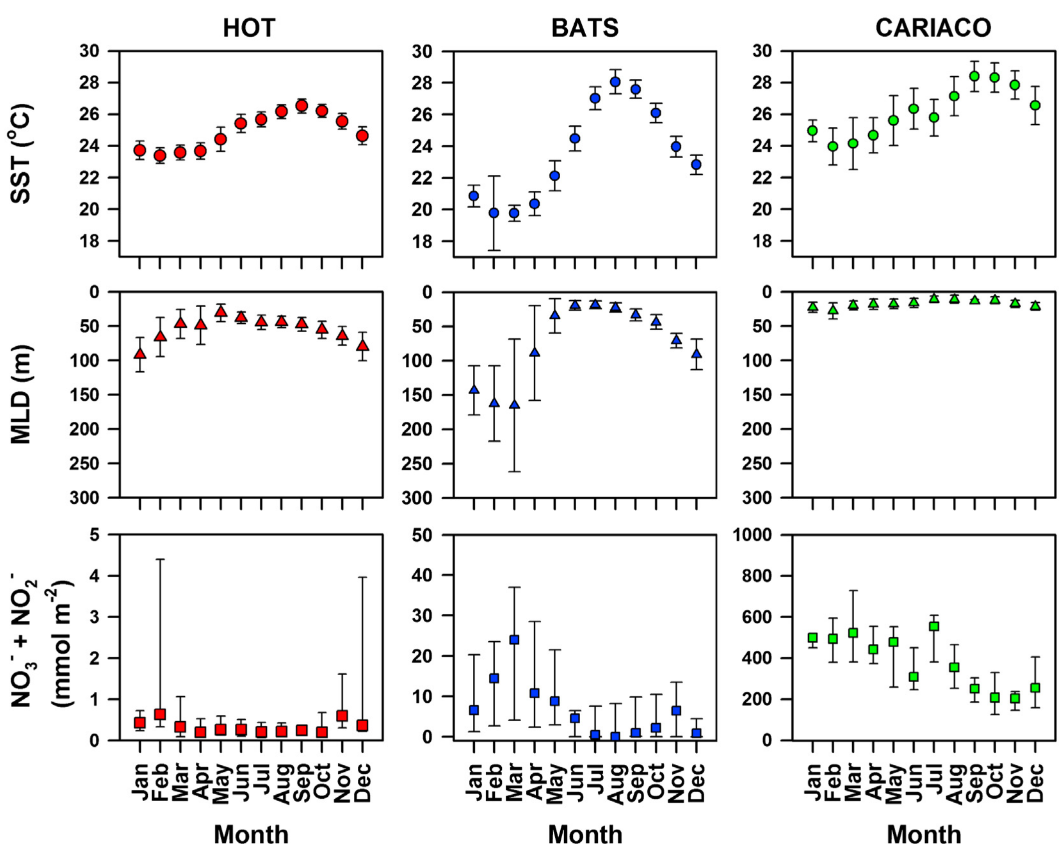

Fig. 3. Mean monthly sea surface temperatures, mixed-layer depths, and depth-integrated, upper ocean (0–100 m) inventories of nitrate+nitrite at HOT, BATS, and CARIACO. Symbols represent monthly means, error bars are standard deviations of the monthly means.

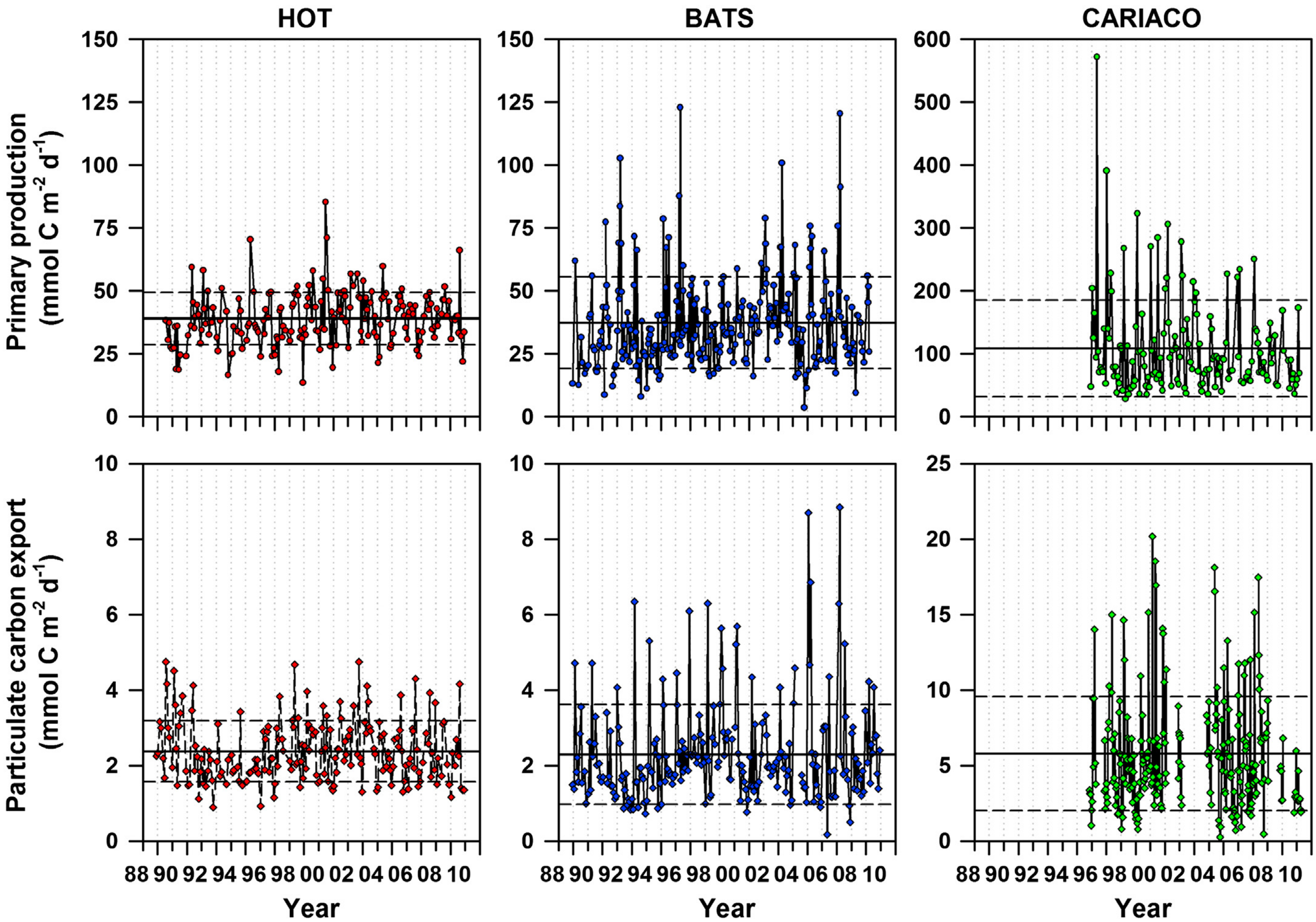

Fig. 4. Time-series determinations of net primary production (0–100 m depth-integrated rates) and particulate carbon export at HOT (red), BATS (blue), and CARIACO (green). Note that carbon export at HOT and BATS were measured by particle interceptor traps at 150 m; fluxes at CARIACO were determined using bottom moored sediment trap collections at 225 m. Solid lines depict mean productivity or export for the time-series; dashed lines represent $\pm$ one standard deviation of the mean fluxes. Note *Y*-axes scales differ for CARIACO data. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

spring bloom periods sometimes >80 mmol C m^{-2} d^{-1}. By late spring and early summer production decreases sharply, often remaining <30 mmol C m^{-2} d^{-1} throughout the summer and fall (Fig. 5). Despite notable seasonal differences in upper-ocean nutrient availability and greater variability in primary production and export, on an annual basis rates of production and particulate matter export at HOT and BATS are comparable, with net primary production averaging $\sim$14 mol C m^{-2} yr^{-1} and particulate carbon export (150 m) averaging $\sim$0.8 mol C m^{-2} yr^{-1}, respectively (Table 1).

Upper-ocean primary production (0–100 m) at CARIACO is considerably greater than that observed at either HOT or BATS, with rates typically ranging between $\sim$80–145 mmol C m^{-2} d^{-1} but punctuated by periods of very high productivity (>200 mmol C m^{-2} d^{-1}) in the late winter and early spring (Figs. 4 and 5). The observed seasonal cycle of primary production at CARIACO reinforces the importance of seasonal-scale changes in trade-wind driven upwelling as a major control on ecosystem variability in this region (Muller-Karger et al., 2004; Thunell et al., 2000). The origin of material sustaining particulate material export at CARIACO derives from both autochthonous productivity and terrestrial material introduced through riverine discharge (Lorenzoni et al., 2011; Montes et al., 2012; Muller-Karger et al., 2004). Both these processes dominate export at different times of the year, with productivity peaking in the late winter and spring during periods of strong upwelling, and riverine input generally increasing in the summer (Thunell et al., 2007). As a result, despite relatively strong seasonality in upper ocean productivity seasonality in particle export is less well defined than at either HOT or BATS (Fig. 5).

Some of the most important contributions to emerge from the ocean time-series programs are reconstructions of biogeochemical rate processes based on annual mass balances of properties such as dissolved oxygen, dissolved inorganic carbon, nitrate, and nitrogen and carbon isotopes. Among other processes, such approaches have provided insight into variability associated with annual rates of net organic matter production (or net community production – NCP). Accurate determinations of NCP require time-resolved measurements, and hence there are few places in the world's oceans where such measurements exist. Over the history of HOT and BATS a variety of sampling and analytical approaches have been used to determine NCP, yielding some of the most comprehensive estimations of NCP anywhere in the world's oceans (Table 2). Such efforts have been strengthened by use of instrumented remote and autonomous sampling platforms (moorings, floats, gliders), providing information on the coupling between high-frequency physical dynamics and variability in net organic matter production and export. Together these time-resolved sampling approaches have helped transform our view of temporal variability associated with organic matter production and carbon sequestration in this open-ocean habitat. The emerging data suggest annual NCP at BATS and HOT may be similar, ranging 2.3–4.7 mol C m^{-2} yr^{-1} and 1.1–4.1 mol C m^{-2}

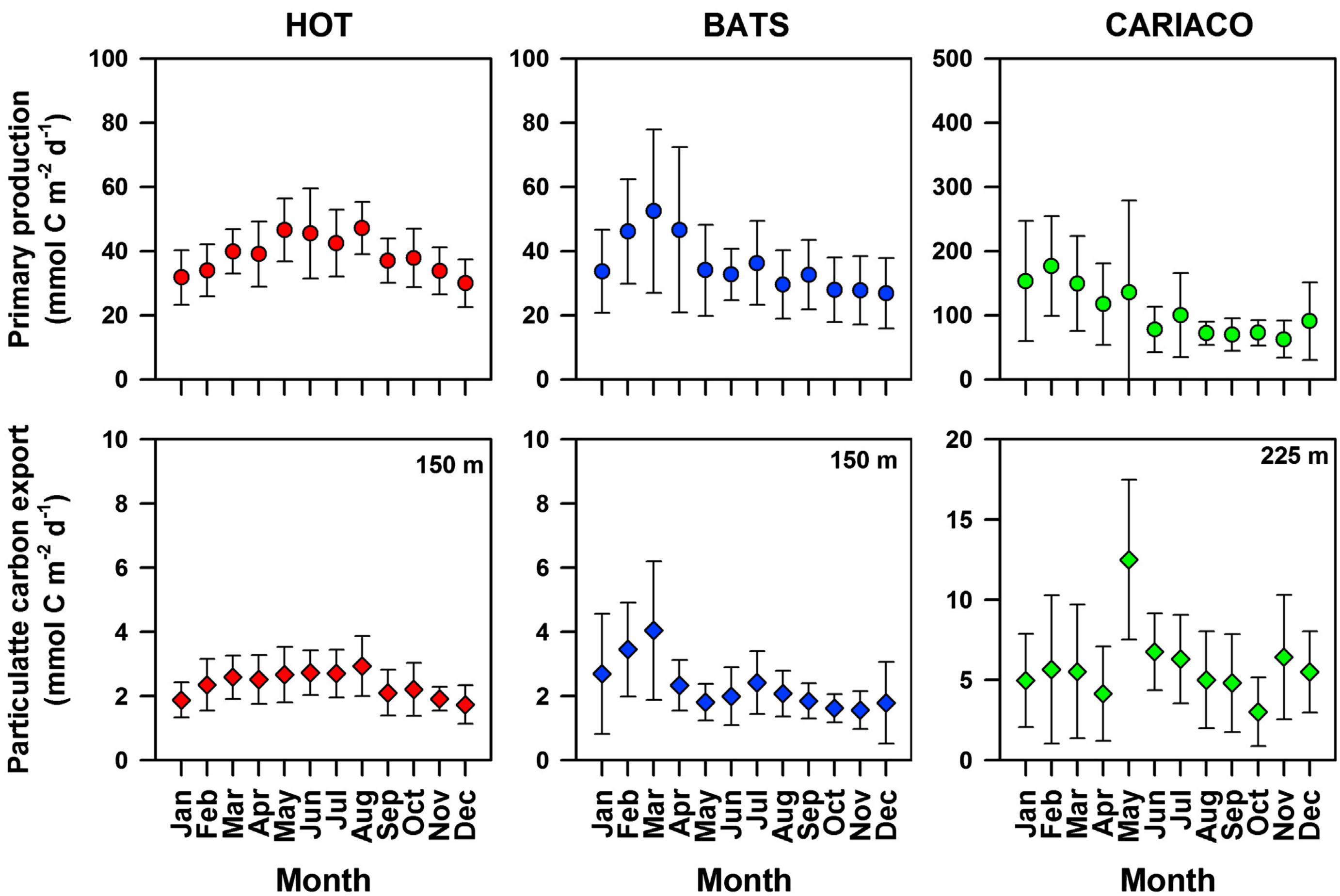

Fig. 5. Mean monthly primary production and upper-ocean particulate carbon export at HOT, BATS, and CARIACO. Symbols represent depth-integrated (0–100 m) rates of productivity or particle flux (150 m for HOT and BATS, 225 m for CARIACO); error bars are standard deviation of the monthly means. Note differences in *Y*-axes.

Table 2
Range of annual estimates of net organic matter production and export at HOT and BATS. Where available uncertainties associated with the determinations are shown in parentheses.

Time series site	Method	Rates mol C m^{-2} yr^{-1}	Period of measurements	References
HOT	Mixed Layer O_2+Ar budgets	1.1–3.7 (±1.0)	1992–2008	Emerson et al. (1997), Hamme and Emerson (2006), Juranek and Quay (2005), Quay et al. (2010)
	DIC+DI^{13}C budgets	2.7–2.8 (±1.4)	1988–2002	Quay and Stutsman (2003), Keeling et al. (2004), Brix et al. (2004)
	Mooring O_2/N_2	4.1 (±1.8)	2005	Emerson et al. (2008)
	Sub-mixed layer float profiles	1.1–1.7 (±0.2)	2003–present	Riser and Johnson (2008), Johnson et al. (2010)
	Sub-mixed layer glider surveys	0.9 (±0.1)	2005	Nicholson et al. (2008)
	150 m sediment traps+migrant zooplankton flux	0.9–1.1	1989–2011	HOT core data; Emerson et al. (1997), Landry et al. (2001), Hannides et al. (2009)
BATS and Station S	Sub mixed layer O_2+Ar, He budgets	4.3 (±0.7)	1985–1987	Spitzer and Jenkins (1989)
	DIC+DI^{13}C budgets	2.3 (±0.9)	1991–1994	Gruber et al. (1998)
	^{3}He and NO_3^- fluxes	2.9–4.5	1985–1987,	Jenkins and Doney (2003, 1992)
	Sub-mixed layer O_2 profiles	3.3–4.7	1961–1970	Jenkins and Goldman (1985), Jenkins and Wallace (1992)
	150 m sediment traps+migrant zooplankton flux	0.6–2.0	1989–2011	BATS core data; Lomas et al. (2002), Steinberg et al. (2000, 2001, 2012))

yr^{-1}, respectively (Table 2). Such results are intriguing given differences in the timing and magnitude of vertical delivery of nutrients to the upper ocean observed at these sites (Fig. 3). Moreover, these geochemical mass balances appear as much as 4-fold greater than predicted based on sediment trap estimates of carbon export (Table 2), and estimates derived from ocean circulation (Schlitzer, 2004) and satellite ocean-color models (Laws et al., 2000). Such discrepancies provide sobering reminders that there remain a number of unresolved issues central to our understanding of ocean ecosystem functioning.

Among the most recognized biogeochemical measurements conducted by these programs are those documenting time variability associated with seawater CO_2 (Fig. 6). These measurements at HOT, BATS, and CARIACO, together with measurements conducted

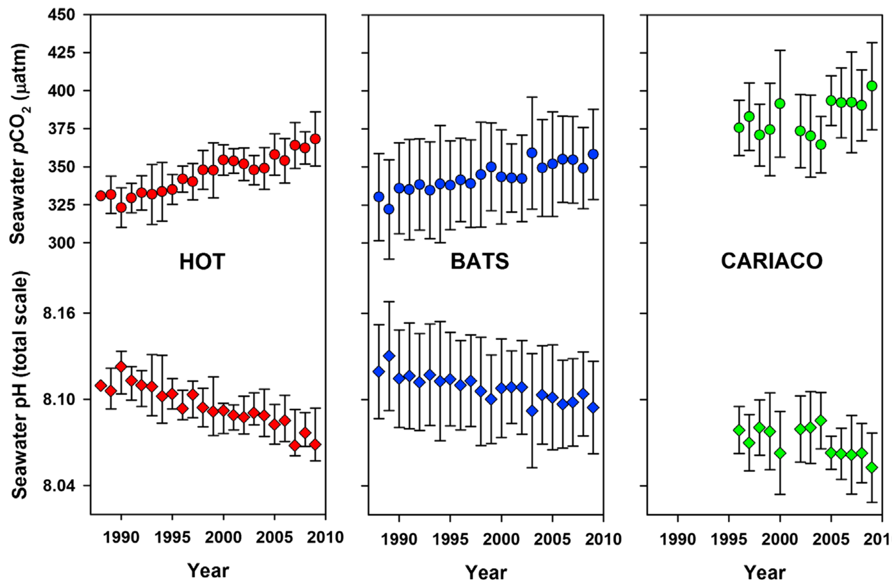

Fig. 6. Mean annual near-surface ocean pCO_2 (red circles) and seawater pH (blue diamonds) at HOT, BATS, and CARIACO. Error bars depict standard deviations of annual means. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

as part of the ESTOC and MBARI time-series programs, comprise some of the most robust decadal-scale datasets available for describing the response of the ocean to progressive increases in atmospheric CO_2. These measurements indicate that over annual time scales, HOT and BATS are both weak to moderate sinks for atmospheric CO_2 (Bates et al., 1996; Winn et al., 1998), while CARIACO is a net source of CO_2 to the atmosphere (Astor et al., 2005, 2013). Time-series measurements at HOT, BATS, and CARIACO document progressive increases in the partial pressure of CO_2 (pCO_2) in the near-surface ocean with concomitant decreases in seawater pH (Fig. 6). The long-term increase in seawater pCO_2 at HOT, BATS and CARIACO appear similar to the rate of CO_2 accumulation in the atmosphere ($\sim$1.7 µatm yr^{-1}), with concomitant long-term decreases in seawater pH ranging -0.0017 to -0.0019 y^{-1}. Despite similar long-term trends, there is substantial interannual to seasonal scale variability in upper ocean CO_2 attributable to local- and regional-scale ecosystem dynamics (Astor et al., 2013; Bates et al., 1996; Dore et al., 2003; Gruber et al., 1998, 2002; Keeling et al., 2004). Interannual variations in pCO_2 and pH at all three sites depends on regional to basin scale fluctuations in ocean-climate connectivity and biological activity, with variations in temperature, evaporation–precipitation, and upper ocean mixing all imparting characteristic signatures on CO_2 system dynamics in these regions (Astor et al., 2005; Bates, 2007; Dore et al., 2003, 2009).

4. Charting the future course

4.1. Where the future meets the past

Ocean time-series programs provide critical long-term records needed for assessing the interactions between chemistry, biology, physics and geology. The scientific value of these programs continues to increase through sustained observations. However, the expansion of ocean time-series research, both in duration of individual programs and the number of programs, during the 1990s taught important lessons, some related to science, others on the realities and logistics of sustaining long-term science programs (Karl, 2010). Time-series programs are resource intensive and thus maintaining ocean community support for these programs requires strong and positive leadership and a dedicated team of people that understand the value of long-term observations. The requirement to maintain consistent, high-quality measurements over long periods of time is the foundation of success for these programs, and retaining well-trained scientists and technical staff are essential to these efforts. While certified reference materials provide a means to trace the quality of an oceanographic measurement, for many of the biogeochemical measurements (particularly most rate measurements), no certified standards exist. Furthermore, developing confidence that measurements conducted at different sites are intercomparable demands that these programs continue to regularly participate in community-wide efforts directed toward standardizing methodologies and analyses.

A significant scientific challenge has been to design sampling schemes appropriate to capturing important modes of ecosystem variability. Despite near-monthly sampling schedules these programs spend < 20% of the year on site observing ecosystem dynamics, implying that some important processes will be under-sampled in both space and time (Wiggert et al., 1994). Episodic events and processes that exert high frequency variability can be missed with this sampling strategy (Levin, 1992; Munk, 2000). Moreover, limited sampling in the spatial domain is also an issue that can lead to aliasing of Eulerian processes attributable to horizontal advection, thereby hindering differentiating time-dependent local changes from those attributable to spatial variability on the regional scale.

4.2. Transformative technologies

The science of observing the ocean has made huge advances since the 1980s. While the disciplinary expansion of oceanography in the 20th century was largely propelled by ship-based expeditionary science, the new generation of ocean observations capitalizes on technological advances in remote and autonomous sensing platforms. Following the end of World War II, during the era often referred to as "golden age of oceanography", shipboard research stood as the primary means of gathering information on the ocean. However, the "golden age" of oceanography rapidly yielded to the "era of the electron" where improved platform engineering, data storage, sensor stability and durability, and communications technologies have thrown the door wide open to new technologies for sensing the sea. A new international wave of contemporary ocean observatories rely on measurements conducted from instrumented remote sensing platforms including satellites, moorings, floats, and various autonomous vehicles (e.g. http://www.eurosites.info/index.php; http://www.oceanobservatories.org/). Advances in sensor technologies now provide small, low-power, stable instrumentation that can be outfitted onto diverse ocean platforms (Johnson et al., 2009; Perry and Rudnick, 2003). Such technological advances therefore have provided new opportunities to enhance observational capacity around shipboard programs.

There are numerous examples of studies that have leveraged ship-based time-series programs with higher frequency, spatio-temporally resolving, autonomous and remote measurements (Conte et al., 2003; Emerson et al., 2002, 2008; Johnson et al., 2010; Letelier et al., 2000; McGillicuddy et al., 1998; Muller-Karger et al., 2004; Nicholson et al., 2008). Such studies yield further insight into scales of variability associated with plankton metabolism and biomass, carbon export, nutrient fluxes, water-mass ventilation, and air–sea gas exchanges, to name a few. In a recent example, with support from NSF and the National Oceanographic Partnership Program, Steve Riser (University of Washington) and Ken Johnson (MBARI) instrumented quasi-Lagrangian, vertically profiling floats with nitrate, oxygen, fluorescence, and backscatter sensors (http://www.mbari.org/chemsensor/floatviz.htm). Several of these floats have now been deployed at HOT, BATS, and Station P, providing new tools for examining similarities and differences in ecosystem processes such as nutrient supply to the euphotic zone (and highlighting potentially underappreciated mechanisms such phytoplankton vertical migration), net community production, and length scales of organic matter remineralization (Martz et al., 2008; Riser and Johnson, 2008). In addition, with support from the Gordon and Betty Moore Foundation and NSF, ocean gliders have been in service at or around Station ALOHA since 2008, providing insight into spatiotemporal variability in temperature, salinity, oxygen, backscatter, and fluorescence (http://hahana.soest.hawaii.edu/seagliders/index.php). These programs highlight a few examples where remote or autonomous sensing approaches leveraged the shipboard programs to test hypotheses generated from the historical time-series data.

Hydrographic and biogeochemical moorings have been deployed for substantial periods of time at each of the OCB stations. The Bermuda Testbed Mooring (BTM) operated for more than a decade (1994–2007) near the BATS site, forging new, collaborative science partnerships that informed understanding of episodic physical forcing on ocean biogeochemistry (Bates et al., 1998; Dickey et al., 1998; McNeil et al., 1999). Since 1997, various hydrographic, biogeochemical, and meteorological moorings have been maintained at or near Station ALOHA, including HALE ALOHA (1997–2000), MOSEAN (2004–2007), and WHOTS (2004–present). These moorings have provided critical observations for understanding high-frequency variability in ecosystem processes (Church et al., 2009; Emerson et al., 2002; Karl et al., 2003). Recently, scientists and engineers from the University of Hawaii led the successful installation of the ALOHA Cabled Observatory (http://aco-ssds.soest.hawaii.edu/ACO/index.php). By taking advantage of an existing seafloor fiber optic cable, the ACO provides a seabed node for powering instruments and transmitting data. Such infrastructure has the promise to transform the sea sensing capabilities at Station ALOHA. At CARIACO, subsurface hydrographic and current moorings have been deployed sporadically over periods spanning several years (Alvera-Azcárate et al., 2008), and moored sediment traps have been sampling routinely since 1996 (Benitez-Nelson et al., 2007; McConnell et al., 2009; Tedesco et al., 2007; Thunell et al., 2007).

These previous and ongoing efforts to enhance the observational capacities at the time-series sites have all relied heavily on the scientific and logistical infrastructure afforded by the shipboard programs. The many years of developing highly skilled workforces and capable infrastructure make the time-series sites ideal for developing, testing, and implementing novel ocean-observing technologies. Moreover, such projects demonstrated that enhancing the observational capacities of the time-series programs does not necessarily require expansion of the existing shipboard programs. Rather, the shipboard programs and their long-term data records serve as the unifying core structure from which new science directions and observational technologies are built.

Over the next decade, the shipboard programs must continue to be proactive about promoting the implementation of new ocean sensing technologies at these sites. However, despite the growing list of potential applications for remote and autonomous sensing of ocean dynamics, there remain several large hurdles to be overcome before ship-based time-series become obsolete. Currently no combination of autonomous or remote sensing technologies could be employed to replace the full suite of high-quality measurements routinely conducted as part of interdisciplinary shipboard time-series programs. In many cases the long-term accuracy of such sensors remains unknown, challenged in part by non-trivial issues associated with biofouling and instrument stability (Dickey, 1991; Johnson et al., 2009). Perhaps most importantly, there are currently a limited set of sensors readily available for detecting many of the key biological and chemical pools and fluxes known to be climate sensitive and play roles in the ocean carbon cycle. While numerous "in water" sensors are currently available and widely used for detecting ocean hydrographic variability, sensors for autonomous and remote detection of ocean biogeochemistry, beyond nutrient and oxygen dynamics, have proven more difficult to develop and implement. For example, to date, there are few tools available for remote quantification of plankton community structure (although see Scholin et al., 2009). Moreover, although sensors for optical based determinations of nitrate are available (Johnson and Coletti, 2002), sensors for detection of phosphate, silicate, and dissolved organic or inorganic carbon are not yet widely available. There are still fewer instruments that can make direct measurements of ecosystem rate processes, versus the time-derivative geochemical estimates of rate processes (e.g., N^* and related variables). Such measurements are fundamental to informing our understanding of plankton ecology and ultimately biogeochemical controls on carbon sequestration in the vast ocean gyres.

4.3. *Improved process-level understanding and linkages to ecosystem models*

The existing ocean time-series records clearly demonstrate biogeochemical and hydrographic variability in ecosystem dynamics occurring over a large range of time scales. Concentrations of chlorophyll, rates of primary production, nutrient inventories and stochiometries, export of organic material from the upper ocean, and stocks of organisms and plankton community structure have all been shown to vary over seasonal to sub-decadal time scales. However, in many of these examples, the mechanisms underlying the observed time-varying changes remain obscure. Long-term increases (HOT, BATS) or decreases (CARIACO) of primary production and inventories of chlorophyll reported at these sites have been attributed to basin-scale climate fluctuations (Chavez et al., 2011; Corno et al., 2007; Saba et al., 2010; Taylor et al., 2012); however, our understanding of the processes linking ocean–climate to changes in seawater biogeochemistry remains rudimentary. Alteration in phytoplankton productivity and biomass at these sites could stem from bottom up processes such as changes in light (as a consequence of changes in upper ocean stratification) or changes in nutrient supply (Bidigare et al., 2009). Alternatively, temporal variations in various top-down processes could control plankton biomass and hence productivity. For example time-varying changes in the activities (or functional types) of phytoplankton predators could have a cascading influence on ecosystem biomass, productivity, pathways of nutrient cycling and material export. At both HOT and BATS, significant increases in mesozooplankton biomass have been observed during the period of increasing primary production and carbon export (Hannides et al., 2009, Steinberg et al., 2012), while at CARIACO increases in zooplankton biomass have coincided with decreased phytoplankton stocks and rates of primary production (Taylor et al., 2012). Such changes suggest complex and time-variable coupling in tropho-dynamics at all three sites. Variability in plankton community structure impacts numerous ecosystem functions, including processes such as the migratory zooplankton mediated carbon fluxes (Hannides et al., 2009; Steinberg et al., 2000) and production and export of dissolved organic matter (Carlson et al., 1994).

While the existing time-series include measurements relevant to detecting and understanding changes in food web structure (e.g., phytoplankton pigment concentrations, measurements of zooplankton biomass); these datasets could be made stronger, thereby solidifying our understanding of the ecology that underpins biogeochemical dynamics. Improving our understanding of food web interactions (e.g., who eats whom and at what rates, the importance of viruses in controlling patterns of plankton community succession, better understanding of how symbiotic interactions alter biogeochemical cycles) will strengthen our predictive understanding of these ecosystems and how they may respond to changing ocean physics. Molecular biology and genetics studies at the time-series sites have revolutionized our understanding of the physiological pathways underpinning plankton metabolism (Béjà et al., 2000; DeLong et al., 2006; Giovannoni et al., 1990; Venter et al., 2004). Inclusion of proteomic and metabolomic approaches at these sites will undoubtedly continue to reveal previously unrecognized pathways for energy capture and nutrient cycling by organisms in these ecosystems, furthering our understanding of the ecology underlying ecosystem change.

Implementation of dynamic, numerical ecosystem models which assimilate shipboard, satellite, and remote platform observations from these sites has already improved our understanding of processes underlying ecosystem variability in these regions (Doney et al., 1996; Fasham et al., 1990, 1993; Fennel et al., 2002; Hood et al., 2001; Walsh et al., 1999). Such efforts are central to developing mechanistic, process-level understanding of ecosystem dynamics. A recent analyses of decadal-scale satellite-based observations of surface ocean chlorophyll concentration together with numerical model results spanning multiple decades highlights that detection of climate driven changes in ocean biology may require upwards of 40 years of sustained time-series observations in mid-latitude ocean systems, with shorter horizons of 20–30 years required for detection in tropical regions (Henson et al., 2010; Beaulieu, 2012). Such results emphasize the importance of maintaining a long-term, high-quality and comprehensive ocean ecosystem time-series in different parts of the world's ocean. There remain numerous opportunities for partnerships and synergies between observationalists and modelers focused around these time-series sites. The time-series data serve a key function in model validation, but these models also benefit the time-series programs. Models serve as important hypothesis-generating tools, providing numerical simulations that synthesize coupled physical–biogeochemical interactions across a wide range of time and space scales. While individual components of ecosystem dynamics can be measured and observed in the field, the strength of a modeling-based approach is to provide insight into the complexity of interactions among these processes. In addition, certain model structures, e.g., inverse models, may be helpful at identifying important but missing observational variables. The existing time-series datasets provide fertile ground for model development and improvement; many of the core time-series measurements available from these sites are key variables (plankton biomass, nutrient stocks, sinking rates, mixed-layer depths, etc.) required for improving coupled ecosystem-ocean circulation models.

4.4. A network approach to detecting ocean change

Detecting global change requires a global vision, and development of a coordinated network of technologies and resources (Baker et al., 2007; Michalak et al., 2011). One of the hallmarks of HOT, BATS, and CARIACO is that the datasets generated by these programs are rapidly made freely and publicly available. As such, these datasets have become increasingly recognized for their utility in identifying biogeochemical and hydrographic changes occurring in these ecosystems. However, the utility of these data for identifying larger-scale, global change could be further enriched through creation of a central depository for ocean time-series datasets that are currently dispersed and site-specific. Creation of a time-series network data depository would not replace the need for local databases; in fact, many of the existing ocean time-series programs have been at the forefront of developing and implementing user-friendly, interactive systems designed specifically for efficient retrieval of ocean time-series data (see for example http://hahana.soest.hawaii.edu/hot/hot-dogs/interface.html). Rather, a networked repository would enable access to these dispersed time-series data in a form of "one stop shopping", broadening their utility for global-scale analyses of ecosystem trends. Creation of centralized repositories for data and information on "all things ocean time-series" provide recognition of the value of the existing shipboard time-series programs, improve access to data, and help disseminating information about the diverse types of measurements currently being conducted across globally distributed programs. Programs such as OceanSITES (http://www.whoi.edu/virtual/oceansites/index.html) and the NSF supported Biological and Chemical Oceanography Data Management Office (BCO-DMO) program have begun to create such information networks and could serve as models for future efforts.

5. Concluding remarks and recommendations for a future vision

Biogeochemical oceanographic time-series programs are an essential component of the emerging network of ocean-climate observatories. Historically, NSF has been the major agency supporting the development of such observing facilities; however, diversifying that funding portfolio to include other federal agencies (e.g. NASA, NOAA), state and local governments, international and intergovernmental agencies and programs, and private foundations would help strengthen the funding base of long term observing programs. The tremendous knowledge gained from the existing shipboard time-series needs to be capitalized on to strategically develop the future global ocean observatories. Time-series programs require community commitment and buy-in that such programs provide unique, invaluable assets that provide some of the only robust and informative data available for discerning ocean change. In summary, the OCB community provided the following recommendations for assuring the shipboard time-series programs remain vital community assets for detecting present and future ocean change:

1) Shipboard time-series programs are vital community resources that provide some of the only means to measure key variables

for observing and understanding changes to the oceans over the past several decades and need to be continued.

2) Biogeochemical time-series programs should continue to prioritize measurements critical to detecting and quantifying time-varying changes in the pools and fluxes of ecologically significant elements and identifying how local- to basin-scale climate variability feeds back onto ocean biogoechemistry.
3) The continued successes of biogeochemical time-series programs depend on maintaining high quality, interdisciplinary measurements focused on assessing the sensitivity and resilience of ocean ecosystems to change.
4) The core time-series science and infrastructure associated with these programs form strong backbones of and remain integral to numerous new individual and interlinked process studies that can develop and push new science frontiers.
5) Leveraged implementation, testing, and validation of transformative sea-sensing technologies at these sites will continue to enrich our understanding of the scales of spatiotemporal variability underlying long-term change at these sites.
6) Studies that seek mechanistic understanding of ecological interactions at these sites should be promoted to improve our understanding of processes and rates underlying biogeochemical dynamics.
7) The utility of biogeochemical time-series data for formulating and validating ecosystem models should be promoted. Broader use of these data in modeling studies will improve our mechanistic understanding of ocean dynamics at these sites, while further highlighting the utility of the time-series observations.
8) Ocean biogeochemistry time series are critical to calibrating and validating satellite observations of physical and biological ocean properties and to anchor basin-scale assessments of climate change impacts based on satellite data.
9) The scientific community and public would benefit from global time-series networks where data and data products from sites around the globe are centralized, publicly accessible, and easily retrievable.

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