

1                   **Sea Change: Charting the course for biogeochemical**  
2                   **ocean time series research in a new millennium**

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## 18 **PREFACE**

### 19 **Time, water, and change**

20 Oceans are vital to Earth's habitability and are important socioeconomic resources. The  
21 massive and diverse oceanic ecosystems play interactive roles in shaping climate, serve as  
22 reactive pools of bioelements, and comprise vast reservoirs of biodiversity. Despite their  
23 importance to planetary health, we currently lack confident predictive understanding of how  
24 oceanic ecosystems may respond to global change. In part this derives from chronic  
25 undersampling of these remote and spatiotemporally complex habitats. There are currently only  
26 a few regions in the sea where we have sustained, decadal-scale observations on the interactions  
27 between ocean biogeochemistry, hydrography, and ecology. These few time series, built largely  
28 around shipboard sampling programs, provide evidence that ocean-climate-human interactions  
29 can have cascading impacts on ecosystem processes across a wide range of time and space  
30 scales. Moreover, these time series records provide the critical data needed to better understand  
31 the ocean's and our planet's sensitivity to change.

32 A major challenge facing ocean scientists is how to advance interdisciplinary, multi-  
33 decadal time series programs that provide high quality data at sufficient spatiotemporal  
34 resolution to inform our understanding of marine ecosystem change. Despite the successes of  
35 ship-based time series in documenting ocean change, sampling from research vessels is relatively  
36 restrictive in its spatiotemporal resolution. Moreover, rising costs associated with operating and  
37 maintaining ships requires continual reassessment and justification of the cost-benefit scenarios  
38 to science and society behind sustaining ship-based oceanographic programs. Moreover,  
39 technology advances in the past decade now allow for high resolution autonomous sampling of  
40 various oceanographic properties. Such factors have partly motivated the current expansion of

41 ocean observational systems designed to rely on remote and autonomous sensing platforms,  
42 promising higher frequency spatiotemporal sampling of ecosystem dynamics difficult to  
43 adequately sample from ships alone, at a potential cost savings. Satellites, floats, gliders,  
44 moorings, and remotely operated vehicles have all become increasingly central to such observing  
45 strategies. However, to date, we lack the capabilities to detect many of the key climate-sensitive  
46 biogeochemical properties and processes we know are fundamental to ecosystem function.  
47 Balancing investments required to maintain comprehensive ocean carbon and biogeochemistry  
48 time series and more autonomous observatory systems is central to the evolving vision of the  
49 ocean sciences.

50         With support from the U.S. National Science Foundation, and motivated by the Ocean  
51 Carbon Biogeochemistry (OCB) program, three contemporary ocean time series programs  
52 convened a “scoping workshop” in September 2010 to gather community input on the future  
53 direction and scope of ship-based time series programs. The workshop largely focused on three  
54 on-going programs whose research aligns with the OCB program objectives: the Hawaii Ocean  
55 Time-series (HOT), Bermuda Atlantic Time-series Study (BATS), and Carbon Retention In A  
56 Colored Ocean (CARIACO). All of these programs maintain near-monthly ship-based sampling  
57 programs in hydrographically and biogeochemically distinct regions: the North Pacific  
58 Subtropical Gyre (NPSG), the subtropical North Atlantic, and the Cariaco Basin in the tropical  
59 North Atlantic, respectively (Table 1). These sites are complemented by systematic observations  
60 collected from other observing platforms including moorings, satellites, floats, and gliders. The  
61 data from these time series programs provide some of the only decadal-scale records available  
62 for assessing seasonal- to interannual-scale changes in ocean hydrographic structure,  
63 biogeochemistry, and biology.

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

73

## 74 **BACKGROUND**

### 75 **If you build it, they will come**

76 The vision to establish shipboard time series sprung from recognition that detecting how  
77 anthropogenic and natural-climate changes influence the biosphere is impossible without time-  
78 resolving measurements collected over long periods of time (Schindler, 1988; Keeling et al.,  
79 1995; Likens et al., 1996). Historical roots for contemporary ocean time series can be traced in  
80 part to use of weatherships, deployed in remote regions of the world's oceans to gather  
81 meteorological data necessary to improve weather forecast models. The value of such repeated  
82 occupations to otherwise inaccessible regions of the oceans attracted the interests of a diverse  
83 group of scientists. The "ancillary" science, conducted alongside the weathership hydrographic  
84 and meteorological sampling, led to important discoveries. For example, ocean productivity and  
85 irradiance measurements at Weathership "M" in the North Sea laid the framework for the  
86 formulation of the critical depth theory explaining the prerequisite interactions between light,

87 mixing, and photosynthesis in controlling formation of phytoplankton blooms (Sverdrup, 1953).  
88 The legacy of these programs continues today. Measurements conducted at Station P (50°N,  
89 145°W) continue the observations started in 1949 from a weathership outpost in the subarctic  
90 North Pacific (Freeland, 2007).

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

98 The establishment of Hydrostation S (32°10'N, 64° 30'E) off Bermuda in 1954 marks a  
99 major historical entry point for modern ocean time series research (Figure 1). Motivated by the  
100 desire to better understand seasonal to interannual variability in meteorological forcing of ocean  
101 physics, and with the support from the Office of Naval Research, Henry Stommel (Woods Hole  
102 Oceanography Institution) and William Sutcliffe (Bermuda Biological Station) initiated a  
103 biweekly sampling campaign to physically characterize the ~2600 m water column at  
104 Hydrostation S in the northwestern Sargasso Sea (Schroeder et al., 1959; Jenkins, 1982).  
105 Providing physical context and regular access to the open sea, facilitated in large part by suitably  
106 equipped research vessels and infrastructure support from the Bermuda Biological Station,  
107 Hydrostation S rapidly attracted new and diversified science programs. Among the first to  
108 capitalize on the Hydrostation S time series were Woods Hole scientists David Menzel and John  
109 Ryther. By placing measurements of productivity and nutrient cycling into the time-resolved

110 hydrographic context afforded by Hydrostation S, their work helped define factors shaping  
111 biogeochemistry in the subtropical ocean gyres (Menzel and Ryther, 1960; Menzel and Ryther,  
112 1961). By the 1970s and 1980s several important biogeochemical studies had coalesced around  
113 the Hydrostation S, including a study that continues today aimed at quantifying temporal  
114 relationships between upper ocean productivity and the downward flux of material to the deep  
115 sea (Deuser and Ross, 1980; Deuser, 1983; Deuser et al., 1990; Conte et al., 2001), and  
116 geochemical approaches to estimate net community productivity (Jenkins, 1982; Jenkins and  
117 Goldman, 1985). These studies revealed that the vast subtropical ocean gyres serve as globally  
118 important carbon reactors, where productivity was greater than historically recognized and  
119 whose carbon storage potential depended on complex biological-physical couplings. By  
120 embedding such measurements into the time-resolving hydrographic framework, Hydrostation S  
121 became one of the few places in the world where quantitative information on seasonal to  
122 interannual scale interactions between plankton ecology, hydrographic forcing, and  
123 biogeochemical cycles in the open sea was available.

124         These early efforts solidified a recurrent theme among contemporary ocean time series:  
125 regular access to the open sea afforded by a ship provides unique opportunities for studying  
126 ocean processes, developing new methods, training students, and testing hypotheses.  
127 Encapsulating these attributes in a rich historical context of physical and biogeochemical  
128 measurements further strengthens the allure of such programs. These efforts inspired questions  
129 that remain at the core of contemporary oceanography, including identifying processes  
130 controlling rates of primary production; examining how plankton community structure influences  
131 productivity and material export; quantifying nutrient supply to the upper ocean; and defining  
132 seasonal to interannual scale variability in stocks of oxygen, carbon, and nutrients essential for

133 life on Earth. The time series sampling approach allows studying ecosystem behavior that would  
134 be otherwise obscured by higher frequency “noise” or time lags between perturbations and  
135 responses (Magnuson, 1990).

136         The scientific and logistical successes of these early studies stimulated recognition that  
137 ocean ecosystems previously considered to be relatively static exhibit significant temporal  
138 variability over a variety of scales. Moreover, these programs highlighted that efforts to  
139 document anthropogenically-induced changes to the sea require a well formulated plan for  
140 sustained, long-term ocean time-series research. By 1984, ocean scientists working under the  
141 umbrella of the Scientific Committee of Oceanic Research (SCOR) formulated plans for a new  
142 oceanographic program to document anthropogenically-induced changes to the sea. The Global  
143 Ocean Flux Study (GOFS) sought better understanding of the processes controlling ocean  
144 biogeochemistry at regional to global scales (Global Ocean Flux Study, 1984). With  
145 international partnerships in place, the Joint Global Ocean Flux Study (JGOFS) emerged as one  
146 of the first core projects of the International Geosphere-Biosphere Program (IGBP). Central to  
147 the objectives of JGOFS were the needs to determine the interactions among elemental cycles in  
148 the sea and understand the processes controlling time-varying fluxes of carbon and associated  
149 bioelements. Ocean time series were included as an essential component of this interdisciplinary  
150 program (Brewer, 2003). At the same time that JGOFS was formulating its science agenda, the  
151 World Climate Research Program (WCRP) was developing plans for the World Ocean  
152 Circulation Experiment (WOCE), a program centered on observations and models of ocean-  
153 climate change. The programs collectively recognized the need for an integrated,  
154 interdisciplinary approach to ocean observing that included relying on time series sampling. In  
155 1987, three separate proposals (two to JGOFS and one to WOCE) were submitted to the NSF for

156 the establishment of HOT and BATS. Starting in October 1988 both HOT and BATS were in  
157 the water, undertaking near-monthly shipboard time series sampling in the NPSG and Sargasso  
158 Sea, respectively (Karl and Michaels, 1996; Michaels and Knap, 1996).

159         HOT and BATS were born from the idea that time series are essential to understand time-  
160 varying fluxes of carbon and associated vital elements in the oceans. The core elements of both  
161 HOT and BATS fell under the auspices of JGOFS and WOCE throughout the lifetimes of these  
162 larger programs. The time-resolved physical and biogeochemical context and regular access to  
163 the open sea stimulated numerous “ancillary” research projects at both locations. Within five  
164 years it became apparent that one of the major strengths of these programs was the  
165 interdisciplinary, multi-investigator approach to studying ecosystem dynamics. The resulting  
166 high quality measurements, together with the scientific and ship-based infrastructure fueled  
167 numerous collaborative scientific interactions. Between the late 1980s and the mid-1990s, many  
168 time series programs were initiated in various marine ecosystems around the globe (Figure 1)  
169 including Monterey Bay (MBARI, 36° 43'N, 122° 24' W; 1989-present), in the Mediterranean  
170 (DYFAMED, 43°25' N, 7° 52' E; 1991-present), in the northeast Atlantic (ESTOC, 29°10'N, 15°  
171 30' W; 1994-present), and in the semi-enclosed Cariaco Basin (CARIACO; 1995-present).  
172 CARIACO was initiated with support from NASA, NSF, and the Venezuelan government; the  
173 project seeks to examine linkages between upper ocean productivity, terrigenous material input  
174 to the enclosed basin, material fluxes from the shelf into deep water, and the preservation of  
175 climate signals in the sediment accumulating at the bottom of this anoxic tropical ecosystem  
176 (Müller-Karger et al., 2010). The region has a rich history of paleo-oceanographic research  
177 (Black et al., 1999; Hughen et al., 2004) that provide additional motivation for contemporary

178 time series studies linking upper ocean biogeochemical processes to sedimentation to the sea  
179 bed.

180 The successes of the time series programs made them among the most transformative  
181 accomplishments of JGOFS. By the end of the JGOFS program in the early 2000s, HOT, BATS,  
182 and CARIACO found themselves lacking a unified programmatic base to facilitate exchange of  
183 ideas on science priorities pursued by these programs. The initiation of the OCB program in  
184 2007 provided a scientific support framework whose research interests aligned well with these  
185 on-going time series efforts. HOT, BATS, and CARIACO remain focused on studying processes  
186 that control the distributions and cycling of elements in the sea, with specific focus on carbon, in  
187 sufficient detail to provide predictive understanding on how global scale perturbations to ocean-  
188 climate might influence biogeochemical transformations. To achieve this broad objective, the  
189 programs seek understanding of the following:

- 190 1) The linkages between seasonal, interannual, and long-term (multi-decadal) variability  
191 and trends in ocean physics, chemistry, and biology;
- 192 2) Processes underlying physical and biogeochemical temporal variability;
- 193 3) The role of physical forcing on carbon fluxes, including rates of biologically-  
194 mediated carbon transformations, air-sea CO<sub>2</sub> exchange, and carbon export;
- 195 4) The response of ocean biogeochemistry to ocean change;

196 The scientific and logistical support afforded by these programs continues to generate activities  
197 that serve as focal points for new science, education, and public outreach. The times series sites  
198 have proven fertile grounds for improving existing methodologies and implementing novel sea  
199 sensing technologies (Figure 1). The short duration (<1 week) cruises in globally significant but  
200 remote habitats continues to attract the interests of diverse science projects that benefit from a

201 time-resolved sampling approach. The core time series benefit from the knowledge of ecosystem  
202 dynamics provided by such ancillary research projects, while the ancillary projects benefit from  
203 time-resolved scientific context and logistical, infrastructural, and technical support provided by  
204 the core programs. As a result, HOT, BATS, and CARIACO have attracted numerous scientists,  
205 students, teachers, and volunteers from all over the world seeking opportunities to participate in  
206 time series research or just to experience science from aboard a research vessel. Between 1988  
207 and 2009, more than 320 “ancillary” scientists and their staff and an additional >140 “core” time  
208 series scientists and staff have participated in HOT, BATS, and CARIACO cruises. Over 420  
209 undergraduate and graduate students and ~50 teachers (elementary to university level) from  
210 around the globe have participated in these cruises for education and training opportunities.  
211 These programs have become models by which other nations are developing their own time-  
212 series programs to assist in understanding local ecosystems and responses to impacts and change,  
213 and which will ultimately help us to understand global-scale ocean change.

214

## 215 **PROGRAM HIGHLIGHTS**

### 216 **From the predictable to the unexpected**

217 All three time series programs measure a core set of physical and biogeochemical  
218 properties on each cruise (<http://hahana.soest.hawaii.edu/hot/>; <http://bats.bios.edu/>;  
219 <http://www.imars.usf.edu/CAR/index.html>); these measurements were selected to provide a  
220 comprehensive and interdisciplinary framework from which to view time-varying changes in  
221 these oceanic ecosystems. The long list of highlights emerging from the time series data records  
222 include documentation of progressive changes in oceanic carbon inventories and fluxes (Bates,  
223 2001; Dore et al., 2003; Keeling et al., 2004; Astor et al., 2005; Bates, 2007; Dore et al., 2009);

224 unexpected variability in the elemental stoichiometry of seawater nutrient pools (Michaels et al.,  
225 1994; Michaels et al., 1996; Karl, 2002; Thunell et al., 2008); complex climate-linked  
226 interactions between plankton ecology and biogeochemistry (Karl, 1999; Corno et al., 2007;  
227 Lomas et al., 2010); elucidation of variability associated with pools and fluxes of organic matter  
228 (Carlson et al., 1994; Emerson et al., 1997), and the importance of plankton community structure  
229 in controlling time-variability in carbon sequestration (Dore et al., 2002; Thunell et al., 2007;  
230 Lomas et al., 2009).

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

243         The physical and biogeochemical characteristics of CARIACO contrast those observed at  
244 HOT and BATS (Figure 2). While HOT and BATS both sample deep ocean locations (>4700  
245 m), CARIACO lies on the continental shelf (bottom depth ~1400 m) off the coast of Venezuela  
246 in a permanently anoxic basin. The physical and biogeochemical conditions at this site are

247 defined by factors influencing oceanography of the tropical and subtropical Atlantic, the  
248 Caribbean Sea, and the continental margin. High near-surface biological productivity and  
249 settling particulate organic matter flux leads to anoxic subsurface waters in the Cariaco Basin.  
250 CARIACO is a mesotrophic tropical ecosystem that experiences seasonally dynamic trade-wind  
251 forced upwelling (January through May), and episodic delivery of terrestrially-derived organic  
252 matter during the rainy season (August through November; (Ho et al., 2004). Anoxia below  
253 approximately 250 m is caused by physical isolation of the deep waters in the basin and the  
254 relatively high biological activity. The lack of oxygen in this region of the water column (>250  
255 m) promotes finely structured vertical redox gradients (Scranton et al., 2001; Taylor et al., 2001),  
256 including complete removal of nitrate by denitrification.

257         HOT, BATS, and CARIACO all rely on near-monthly shipboard sampling. The resulting  
258 time series data capture seasonally recurring patterns in both hydrographic forcing and  
259 biogeochemical dynamics, with both higher and lower frequency variability superimposed on  
260 that seasonal dynamic. Although all three sites undergo relatively weak seasonal variability in  
261 sea surface temperatures (SST), the amplitude and timing of SST variations at BATS are notably  
262 different than observed at HOT or CARIACO. Near surface ocean temperatures at HOT  
263 generally vary <5°C over the course of the year, while SST at CARIACO varies about 5-8°C, and  
264 at BATS SST can vary by >9°C (Figure 3). All three regions also demonstrate seasonality in the  
265 depth of upper ocean mixing. The mixed layer at HOT and CARIACO displays relatively weak  
266 seasonality (Figure 3); at HOT the mixed layer is almost always restricted to the upper 120 m  
267 (and hence within the euphotic zone ~125 m; Letelier et al. 2004) and at CARIACO the  
268 perennially warm and saline upper ocean waters restricts upper ocean mixing to <50 m. In  
269 contrast, mixed layer depths at BATS can exceed 400 m in the late winter (and thus can

270 seasonally exceed the depth of the euphotic zone  $\sim 100$  m; Siegel et al. 2001), then shoal rapidly  
271 to  $<30$  m by the late spring and summer (Figure 3).

272         These seasonal differences in hydrographic forcing imprint unique biogeochemical  
273 signatures on each region. The relatively weak seasonal mixing combined with rapid plankton  
274 growth results in an upper ocean at HOT that is consistently starved of nutrients. Depth-  
275 integrated (0-100 m) inventories of  $\text{NO}_3^- + \text{NO}_2^-$  at HOT are low throughout the year (Figure 3),  
276 but become more variable during the winter periods when mixed layer depths increase and  
277 incident irradiance reaches its annual minima (Letelier et al., 2004; Karl et al., 2008). In  
278 contrast, nutrient inventories at BATS show more prominent seasonality (Steinberg et al., 2001);  
279 upper ocean (0-100 m)  $\text{NO}_3^- + \text{NO}_2^-$  concentrations increase sharply during periods of late winter  
280 mixing, and then rapidly decrease to levels similar to those measured at HOT during the warm,  
281 stratified summer months (Figure 3). Nutrient concentrations in the near-surface waters at  
282 CARIACO are typically relatively low with  $\text{NO}_3^- + \text{NO}_2^-$  generally  $<1 \mu\text{M}$  (Astor et al., 2003);  
283 however, the strong vertical gradient in nutrient concentrations, together with seasonal  
284 upwelling, yields upper ocean (0-100 m) nutrient inventories that are several hundred times  
285 greater than those observed at HOT or BATS (Figure 3).

286         Rates of primary production (as estimated from  $^{14}\text{C}$ -bicarbonate assimilation) and  
287 particulate matter export at all three sites demonstrate variability on seasonal to interannual  
288 scales (Figures 4, 5). Both production and export (and hence rates of new production) are  
289 sensitive to changes in plankton community structure and to interannual variations in  
290 hydrographic forcing (Letelier et al., 1996; Müller-Karger et al., 2001; Corno et al., 2007; Saba  
291 et al., 2010; Chavez et al., 2011). Moreover, the emerging seasonal climatologies in production  
292 and particulate carbon export at these sites highlights several patterns reflective of the unique

293 biological responses to annually recurring ecosystem dynamics (Figure 4). Consistent with the  
294 relatively quiescent physical nature of the NPSG, primary production (0-100 m) at HOT  
295 typically varies ~2-fold over the year ( $\sim 30$  and  $50 \text{ mmol C m}^{-2} \text{ d}^{-1}$ ) (Figure 5). A weak but  
296 predictable seasonal dynamic is observed where rates increase during the summer when  
297 irradiance is maximal and the upper ocean is well stratified. Particulate matter flux (150 m)  
298 increases <2-fold during the more productive spring and summer months (Figure 5), resulting in  
299 a weak seasonal-scale coupling between productivity and export. In contrast, upper ocean  
300 productivity (0-100 m) and export (150 m) at BATS increase in the early spring when nutrient  
301 inventories are at their annual maximum. The amplitude of the seasonal cycle in productivity at  
302 BATS is larger than observed at HOT, with primary production during the spring bloom periods  
303 sometimes  $>80 \text{ mmol C m}^{-2} \text{ d}^{-1}$ . By late spring and early summer production decreases sharply,  
304 often remaining  $<30 \text{ mmol C m}^{-2} \text{ d}^{-1}$  throughout the summer and fall (Figure 5). Despite notable  
305 seasonal differences in upper ocean nutrient availability and greater variability in primary  
306 production and export, on an annual basis rates of production and particulate matter export at  
307 HOT and BATS are comparable, with net primary production averaging  $\sim 14 \text{ mol C m}^{-2} \text{ yr}^{-1}$  and  
308 particulate carbon export (150 m) averaging  $\sim 0.8 \text{ mol C m}^{-2} \text{ yr}^{-1}$ , respectively (Table 1).

309 Upper ocean primary production (0-100 m) at CARIACO is considerably greater than  
310 that observed at either HOT or BATS, with rates typically ranging between  $\sim 80$ - $145 \text{ mmol C m}^{-2}$   
311  $\text{d}^{-1}$  but punctuated by periods of very high productivity ( $>200 \text{ mmol C m}^{-2} \text{ d}^{-1}$ ) in the late winter  
312 and early spring (Figure 4, 5). The observed seasonal cycle of primary production at CARIACO  
313 reinforces the importance of seasonal-scale changes in trade-wind driven upwelling as a major  
314 control on ecosystem variability in this region (Thunell et al., 2000; Müller-Karger et al., 2004).  
315 Although particulate matter export (225 m) at CARIACO is greater than at HOT or BATS, with

316 annual export averaging  $\sim 2.1 \text{ mol C m}^{-2} \text{ yr}^{-1}$ , the export efficiency (*i.e.* e-ratio) is generally  
317 similar to that observed at the open ocean time series. The origin of material sustaining  
318 particulate material export at CARIACO derives from both autochthonous productivity and  
319 terrestrial material introduced through riverine discharge (Müller-Karger et al., 2004). Both  
320 these processes dominate export at different times of the year, with productivity peaking in the  
321 late winter and spring during periods of strong upwelling, and riverine input generally increasing  
322 in the summer (Thunell et al., 2007). As a result, despite relatively strong seasonality in upper  
323 ocean productivity seasonality in particle export is less well defined than at either HOT or BATS  
324 (Figure 5).

325         Among the most recognized and important biogeochemical measurements conducted by  
326 these programs are those documenting time variability associated with seawater  $\text{CO}_2$  (Figure 6).  
327 These measurements at HOT, BATS, and CARIACO, together with measurements conducted as  
328 part of the ESTOC and MBARI time series programs, comprise some of the most robust decadal-  
329 scale datasets available for describing the response of the ocean to progressive increases in  
330 atmospheric  $\text{CO}_2$ . These measurements indicate that over annual time scales, HOT and BATS  
331 are both weak to moderate sinks for atmospheric  $\text{CO}_2$  (Bates et al., 1996; Winn et al., 1998),  
332 while CARIACO is a net source of  $\text{CO}_2$  to the atmosphere (Astor et al., 2005). Time series  
333 measurements at HOT, BATS, and CARIACO document progressive increases in the partial  
334 pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ) in the near-surface ocean with concomitant decreases in seawater pH  
335 (Figure 6). The long-term increase in seawater  $p\text{CO}_2$  at all three sites is nearly identical to the  
336 rate of  $\text{CO}_2$  accumulation in the atmosphere ( $\sim 1.7 \mu\text{atm yr}^{-1}$ ), with concomitant long-term  
337 decreases in seawater pH ranging  $-0.0017$  to  $-0.0019 \text{ y}^{-1}$ . Despite similar long-term trends, there  
338 is substantial interannual to seasonal scale variability in upper ocean  $\text{CO}_2$  attributable to local-

339 and regional-scale ecosystem dynamics (Bates et al., 1996; Gruber et al., 1998; Gruber et al.,  
340 2002; Dore et al., 2003; Keeling et al., 2004). Interannual variations in  $p\text{CO}_2$  and pH at all three  
341 sites depends on regional to basin scale fluctuations in ocean-climate connectivity and biological  
342 activity, with variations in temperature, evaporation-precipitation, and upper ocean mixing all  
343 imparting characteristic signatures on  $\text{CO}_2$  system dynamics in these regions (Dore et al., 2003;  
344 Astor et al., 2005; Bates, 2007; Dore et al., 2009).

345

## 346 **CHARTING THE FUTURE COURSE**

### 347 *Where the future meets the past*

348 Ocean time series programs provide critical long-term records needed for assessing the  
349 interactions between chemistry, biology, physics and geology. The scientific value of these  
350 programs continues to increase through sustained observations. However, the expansion of ocean  
351 time series research, both in duration of individual programs and the number of programs, during  
352 the 1990s taught important lessons, some related to science, others on the realities and logistics  
353 of sustaining long-term science programs (Karl, 2010). Time series programs are resource  
354 intensive and thus maintaining ocean community support for these programs requires strong and  
355 positive leadership with a responsive vision, and a dedicated team of people that truly understand  
356 the value of long-term observations. The requirement to maintain consistent, high quality  
357 measurements over long periods of time is the foundation of success for these programs, and  
358 retaining well-trained scientists and technical staff are essential to these efforts. While certified  
359 reference materials provide a means to trace the quality of an oceanographic measurement, for  
360 many of the biogeochemical measurements (particularly most rate measurements), no certified  
361 standards exist.

362 A significant scientific challenge has been to design sampling schemes appropriate to  
363 capturing important modes of ecosystem variability. Despite near-monthly sampling schedules  
364 these programs spend < 20% of the year on site observing ecosystem dynamics, implying that  
365 some important processes will be undersampled in both space and time. Episodic events and  
366 processes that exert high frequency variability can be missed with this sampling strategy (Levin,  
367 1992; Munk, 2000). Moreover, limited sampling in the spatial domain is also an issue that leads  
368 to aliasing of Eulerian processes, and hinders differentiating time-dependent local changes from  
369 those attributable to spatial variability on the regional scale.

### 370 ***Transformative technologies***

371 The science of observing the ocean has made huge advances since the 1980s. While the  
372 disciplinary expansion of oceanography in the 20<sup>th</sup> century was largely propelled by ship-based  
373 expeditionary science, the new generation of ocean observations capitalizes on technological  
374 advances in remote and autonomous sensing platforms. Following the end of World War II,  
375 during the era often referred to as “golden age of oceanography”, shipboard research stood as the  
376 primary means of gathering information on the ocean. However, the “golden age” of  
377 oceanography rapidly yielded to the “era of the electron” where improved platform engineering,  
378 data storage, sensor stability and durability, and communications technologies, have thrown the  
379 door wide open to new technologies for sensing the sea. A new international wave of  
380 contemporary ocean observatories relying on measurements conducted from instrumented  
381 remote sensing platforms including satellites, moorings, floats, and various autonomous vehicles  
382 (*e.g.* <http://www.eurosites.info/index.php>; <http://www.oceanobservatories.org/>). Advances in  
383 sensor technologies now provide small, low power, stable instrumentation that can be outfitted  
384 onto diverse ocean platforms (Perry and Rudnick, 2003; Johnson et al., 2009); however not all

385 relevant variables can be easily measured by autonomous sensors. Such technological advances  
386 therefore, have provided new opportunities to enhance observational capacity around shipboard  
387 programs.

388         There are numerous examples of studies that have leveraged shipbased time series  
389 programs with higher frequency, spatiotemporally-resolving, autonomous and remote  
390 measurements (McGillicuddy et al., 1998; Letelier et al., 2000; Emerson et al., 2002; Conte et  
391 al., 2003; Müller-Karger et al., 2004; Emerson et al., 2008; Nicholson et al., 2008; Johnson et al.,  
392 2010). Such studies yield further insight into scales of variability associated with plankton  
393 metabolism and biomass, carbon export, nutrient fluxes, water mass ventilation, and air-sea gas  
394 exchanges, to name a few. In a recent example, with support from NSF and the National  
395 Oceanographic Partnership Program, Steve Riser (University of Washington) and Ken Johnson  
396 (MBARI) instrumented quasi-Lagrangian, vertically profiling floats with nitrate, oxygen,  
397 fluorescence, and backscatter sensors (<http://www.mbari.org/chemsensor/floatviz.htm>). Several  
398 of these floats have now been deployed at HOT, BATS, and Station P, providing new tools for  
399 examining similarities and differences in ecosystem processes such as nutrient supply to the  
400 euphotic zone (and highlighting potentially underappreciated mechanisms such phytoplankton  
401 vertical migration), net community production, and length scales of organic matter  
402 remineralization (Martz et al., 2008; Riser and Johnson, 2008). In addition, with support from  
403 the Gordon and Betty Moore Foundation and NSF, ocean gliders have been in service at or  
404 around Station ALOHA since 2008, providing insight into spatiotemporal variability in  
405 temperature, salinity, oxygen, backscatter, and fluorescence  
406 (<http://hahana.soest.hawaii.edu/seagliders/index.php>). These programs highlight a few examples

407 where remote or autonomous sensing approaches leveraged the shipboard programs to test  
408 hypotheses generated from the historical time series data.

409 Hydrographic and biogeochemical moorings have been deployed for substantial periods  
410 of time at each of the OCB stations. The Bermuda Testbed Mooring (BTM) operated for more  
411 than a decade (1994-2007) near the BATS site, forging new, collaborative science partnerships  
412 that informed understanding of episodic physical forcing on ocean biogeochemistry (Bates et al.,  
413 1998; Dickey et al., 1998; McNeil et al., 1999). Since 1997, various hydrographic,  
414 biogeochemical, and meteorological moorings have been maintained at or near Station ALOHA,  
415 including HALE ALOHA (1997-2000), MOSEAN (2004-2007), and the WHOTS (2004-  
416 present). These moorings have provided critical observations for understanding high frequency  
417 variability in ecosystem processes (Emerson et al., 2002; Karl et al., 2003; Church et al., 2009).  
418 Recently, scientists and engineers from the University of Hawaii led the successful installation of  
419 the ALOHA Cabled Observatory (<http://aco-ssds.soest.hawaii.edu/ACO/index.php>). By taking  
420 advantage of an existing seafloor fiber optic cable, the ACO provides a seabed node for  
421 powering instruments and transmitting data. Such infrastructure has the promise to transform the  
422 sea sensing capabilities at Station ALOHA. At CARIACO, subsurface hydrographic and current  
423 moorings have been sporadically deployed (Alvera-Azcárate et al., 2008), and robotic sediment  
424 traps have been sampling since 1996 (Benitez-Nelson et al., 2007; Tedesco et al., 2007; Thunell  
425 et al., 2007; McConnell, 2009).

426 These previous and ongoing efforts to enhance the observational capacities at the time  
427 series sites have all relied heavily on the scientific and logistical infrastructure afforded by the  
428 shipboard programs. The many years of developing highly skilled workforces and capable  
429 infrastructure make the time series sites ideal for developing, testing, and implementing novel

430 ocean observing technologies. Moreover, such projects demonstrated that enhancing the  
431 observational capacities of the time series programs does not necessarily require expansion of the  
432 existing shipboard programs; rather, the shipboard programs and their long-term data records  
433 serve as the unifying core structure from which new science directions and observational  
434 technologies are built.

435         Over the next decade, the shipboard programs must continue to be proactive about  
436 promoting the implementation of new ocean sensing technologies at these sites. However,  
437 despite the growing list of potential applications for remote and autonomous sensing of ocean  
438 dynamics, there remain several large hurdles to be overcome before ship-based time series  
439 become obsolete. Currently no combination of autonomous or remote sensing technologies  
440 could be employed to replace the full suite of high quality measurements routinely conducted as  
441 part of interdisciplinary shipboard time series programs. In many cases the long-term accuracy  
442 of such sensors remains unknown, challenged in part by non-trivial issues associated with  
443 biofouling and instrument stability (Dickey, 1991; Johnson et al., 2009). Perhaps most  
444 importantly, there are currently a limited set of sensors readily available for detecting many of  
445 the key biological and chemical pools and fluxes known to be climate sensitive and play roles in  
446 the ocean carbon cycle. While numerous “in water” sensors are currently available and widely  
447 used for detecting ocean hydrographic variability, sensors for autonomous and remote detection  
448 of ocean biogeochemistry, beyond nutrient and oxygen dynamics, have proven more difficult to  
449 develop and implement. For example, to date, there are few tools available for remote  
450 quantification of plankton community structure (although see Scholin et al. (2009); moreover,  
451 although sensors for optical based determinations of nitrate are available (Johnson and Coletti,  
452 2002), sensors for detection of phosphate, silicate, and dissolved organic or inorganic carbon are

453 not yet widely available. There are still fewer instruments that can make direct measurements of  
454 ecosystem rate processes, versus the time-derivative geochemical estimates of rate processes  
455 (*e.g.*, N\* and related variables). Such measurements are fundamental to informing our  
456 understanding of plankton ecology and ultimately biogeochemical controls on carbon  
457 sequestration in the vast ocean gyres.

458 ***Improved process-level understanding and linkages to ecosystem models***

459         The existing ocean time series records clearly demonstrate biogeochemical and  
460 hydrographic variability in ecosystem dynamics occurring over a large range of time scales.  
461 Concentrations of chlorophyll, rates of primary production, nutrient inventories and  
462 stoichiometries, export of organic material from the upper ocean, and stocks of organisms and  
463 plankton community structure have all been shown to vary over seasonal to subdecadal time  
464 scales. However, in many of these examples, the mechanisms underlying the observed time-  
465 varying changes remain obscure. Long-term increases (HOT, BATS) or decreases (CARIACO)  
466 of primary production and inventories of chlorophyll reported at these sites have been attributed  
467 to basin-scale climate fluctuations (Corno et al., 2007; Saba et al., 2010; Chavez et al., 2011);  
468 however, our understanding of the processes linking ocean-climate to changes in seawater  
469 biogeochemistry remains rudimentary. Alteration in phytoplankton productivity and biomass at  
470 these sites could stem from bottom up processes such as changes in light (as a consequence of  
471 changes in upper ocean stratification) or increased nutrient supply (Bidigare et al., 2009).  
472 Alternatively, temporal variations in various top-down processes could control plankton biomass  
473 and hence productivity; for example time-varying changes in the activities (or functional types)  
474 of phytoplankton predators could have a cascading influence on ecosystem biomass,  
475 productivity, pathways of nutrient cycling and material export. At both HOT and BATS,

476 significant increases in mesozooplankton biomass have been observed during the period of  
477 increasing primary production and carbon export (Hannides et al. 2009, Steinberg et al. 2012),  
478 suggesting closely coupled trophodynamics.

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

493         Implementation of dynamic, numerical ecosystem models which assimilate shipboard,  
494 satellite, and remote platform observations from these sites has already improved our  
495 understanding of processes underlying ecosystem variability in these regions (Fasham et al.,  
496 1990; Fasham et al., 1993; Doney et al., 1996; Hood et al., 2001; Fennel et al., 2002). Such  
497 efforts are central to developing mechanistic, process-level understanding of ecosystem  
498 dynamics. A recent analyses of decadal-scale satellite-based observations of surface ocean

499 chlorophyll concentration together with numerical model results spanning multiple decades  
500 highlights that detection of climate driven changes in ocean biology may require upwards of 40  
501 years of sustained time series observations in mid-latitude ocean systems, with shorter horizons  
502 of 20-30 years required for detection in tropical regions (Henson et al., 2010). Such results  
503 emphasize the importance of maintaining a long-term, high-quality and comprehensive ocean  
504 ecosystem time series in different parts of the world's ocean. There remain numerous  
505 opportunities for partnerships and synergies between observationalists and modelers focused  
506 around these time series sites. The time series data serve a key function in model validation, but  
507 these models also benefit the time series programs. Models serve as important hypothesis-  
508 generating tools, providing numerical simulations that synthesize coupled physical-  
509 biogeochemical interactions across a wide range of time and space scales. While individual  
510 components of ecosystem dynamics can be measured and observed in the field, the strength of a  
511 modeling-based approach is to provide insight into the complexity of interactions among these  
512 processes. In addition, certain model structures, e.g., inverse models, may be helpful at  
513 identifying important but missing observational variables. The existing time series datasets  
514 provide fertile ground for model development and improvement; many of the core time-series  
515 measurements available from these sites are key variables (plankton biomass, nutrient stocks,  
516 sinking rates, mixed layer depths, etc.) required for improving coupled ecosystem-ocean  
517 circulation models.

### 518 *A network approach to detecting ocean change*

519 Detecting global change requires a global vision, and development of a coordinated  
520 network of technologies and resources (Baker et al., 2007; Michalak et al., 2011). The creation  
521 of a centralized repository for data and information on “all things ocean time series” would

522 provide recognition of the value of the existing shipboard time series programs, improve access  
523 to data, and help disseminating information about the diverse types of measurements currently  
524 being conducted across globally distributed programs. Such a network would include sites  
525 routinely visited by ships, moorings, and quasi-Lagrangian time series sampling programs (*e.g.*  
526 measurements on ocean gliders and profiling floats). The overall objective would be to facilitate  
527 information exchange among these time series sites, and to increase public recognition of the  
528 role of time series programs in observing and detecting ocean change and its impacts on society.  
529 Similar efforts are currently facilitated for fixed point, mooring-based observatories through the  
530 OceanSITES program (<http://www.whoi.edu/virtual/oceansites/index.html>).

531         One of the hallmarks of HOT, BATS, and CARIACO is that the datasets generated by  
532 these programs are rapidly made freely and publicly available. As such, these datasets have  
533 become increasingly recognized for their utility in identifying biogeochemical and hydrographic  
534 changes occurring in these ecosystems. However, the utility of these data for identifying larger-  
535 scale, global change could be further enriched through creation of a central depository for ocean  
536 time series datasets that are currently dispersed and site-specific. Creation of a time series  
537 network data depository would not replace the need for local databases; in fact, many of the  
538 existing ocean time series programs have been at the forefront of developing and implementing  
539 user-friendly, interactive systems designed specifically for efficient retrieval of ocean time-series  
540 data (see for example <http://hahana.soest.hawaii.edu/hot/hot-dogs/interface.html>). Rather, a  
541 networked repository would enable access to these dispersed time series data in a form of “one  
542 stop shopping”, broadening their utility for global-scale analyses of ecosystem trends. The NSF  
543 supported Biological and Chemical Oceanography Data Management Office (BCO-DMO)  
544 program has been implemented with the intent of improving access to biogeochemical and

545 ecological ocean data (<http://bco-dmo.org/home>); BCO-DMO could serve as a model from  
546 which to build a time series “centric” data depository.

547

## 548 **CONCLUDING REMARKS AND RECOMMENDATIONS FOR A FUTURE VISION**

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

- 561 1) Shipboard time series programs are vital community resources that provide some of the  
562 only means to measure key variables for observing and understanding changes to the  
563 oceans over the past several decades and need to be continued.
- 564 2) Biogeochemical time-series programs must continue to prioritize measurements critical  
565 to detecting and quantifying time-varying changes in the pools and fluxes of ecologically-  
566 significant elements and biodiversity of organisms, to help understand the influences of  
567 feedback loops in local- to basin-scale climate variability.

- 568 3) The continued successes of biogeochemical time series programs depends on maintaining  
569 high quality, interdisciplinary measurements focused on assessing the sensitivity and  
570 resilience of ocean ecosystems to change.
- 571 4) The core time series science and infrastructure associated with these programs form  
572 strong backbones of and remain integral to numerous new individual and interlinked  
573 process studies that can develop and push new science frontiers.
- 574 5) Leveraged implementation, testing, and validation of transformative sea-sensing  
575 technologies at these sites will continue to enrich our understanding of the scales of  
576 spatiotemporal variability underlying long-term change at these sites.
- 577 6) Studies that seek mechanistic understanding of ecological interactions at these sites  
578 should be promoted to improve our understanding of processes and rates underlying  
579 biogeochemical dynamics.
- 580 7) The utility of biogeochemical time series data for formulating and validating ecosystem  
581 models should be promoted. Broader use of these data in modeling studies will improve  
582 our mechanistic understanding of ocean dynamics at these sites, while further  
583 highlighting the utility of the time series observations.
- 584 8) The scientific community and public would benefit from global time-series networks  
585 where data and data products from sites around the globe are centralized, publicly  
586 accessible, and easily retrievable.

587

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604 support the OCB scoping workshop.

605 **Figure Legends**

606

607 **Figure 1.** Timeline of research conducted at various ocean time series sites around the globe.

608 Colored lines indicate types of sampling and measurement activities (ships, moorings, gliders,

609 floats, and sediment traps). Solid lines reflect sustained measurement program on on at least

610 monthly time scales; dashed lines indicate measurements have continued but at lower than

611 monthly frequency; and gaps in time series records are shown by broken lines. Site

612 abbreviations are: Station S = Hydrostation S, OSP = Ocean Station Papa, and Pal. LTER =

613 Palmer Long Term Ecological Research program in Antarctica. Figure adapted from Karl et al.

614 (Karl et al., 2003).

615

616 **Figure 2.** Study locations of HOT (red circle), BATS (blue diamond), and CARIACO (green

617 triangle) superimposed over 6 year composite of satellite-derived near-surface ocean chlorophyll

618 concentrations. Bottom panels depict temperature-salinity relationships, and vertical profiles of

619 dissolved oxygen and nitrate + nitrite from the three time series sites. Satellite data courtesy of

620 the NASA Ocean Biology Program.

621

622 **Figure 3.** Mean monthly sea surface temperatures, mixed layer depths, and depth-integrated,

623 upper ocean (0-100 m) inventories of nitrate + nitrite at HOT, BATS, and CARIACO. Symbols

624 represent monthly means, error bars are standard deviations of the monthly means.

625

626 **Figure 4.** Time series determinations of net primary production (0-100 m depth integrated rates)

627 and particulate carbon export at HOT (red), BATS (blue), and CARIACO (green). Note that

628 carbon export at HOT and BATS were measured by particle interceptor traps at 150 m; fluxes at  
629 CARIACO were determined using bottom moored sediment trap collections at 225 m. Solid  
630 lines depict mean productivity or export for the time series; dashed lines represent  $\pm$  one standard  
631 deviation of the mean fluxes. Note Y-axes scales differ for CARIACO data.

632

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

637

638 **Figure 6.** Mean annual near-surface ocean  $p\text{CO}_2$  (red circles) and seawater pH (blue diamonds)  
639 at HOT, BATS, and CARIACO. Error bars depict standard deviation of annual means.

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

<b>Program and study site</b>	<b>Period and frequency of shipboard observations</b>	<b>General site characteristics</b>	<b>Annual mean (and range) primary productivity and carbon export (mol C m<sup>-2</sup> yr<sup>-1</sup>)</b>	<b>Sampling infrastructure</b>	<b>Program leadership</b>
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	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-

		(attributable to changes in upwelling)			present); Robert Weisberg (1996-2006); John J. Walsh (1995-2000)
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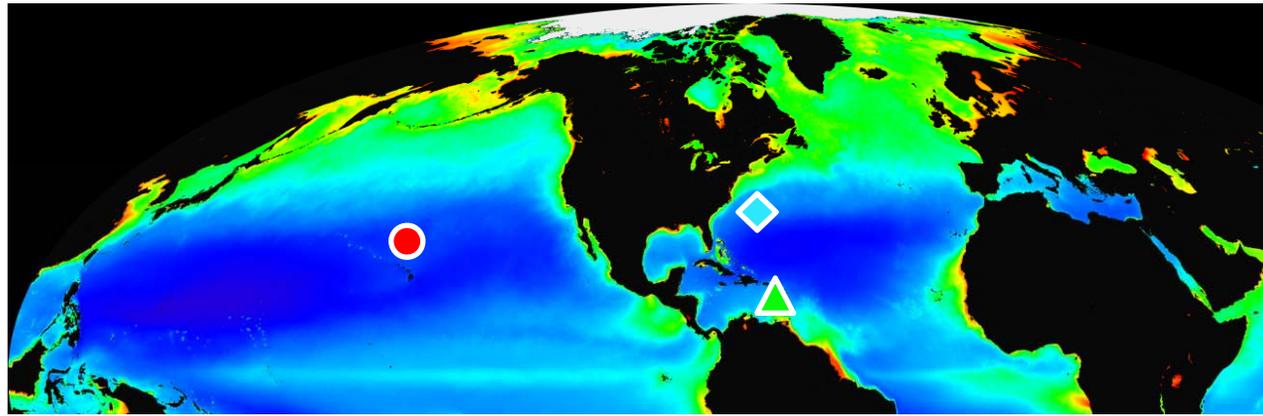
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Site	1950s	1960s	1970s	1980s	1990s	2000s	2010s
<b>Station S</b> (32°10'N, 64°30'W)	Ships						
<b>BATS</b> (31°40'N, 64°10'W)				Deep-sea	Ships	Mooring	Floats
<b>ESTOC</b> (29°10'N, 15°30'W)					Ships	Ships	Mooring
<b>CARIACO</b> (10°30'N, 64°40'W)					Ships	Deep-sea	Mooring
<b>OSP</b> (50°N, 145°W)	Ships			Deep-sea	Ships	Ships	Mooring
<b>HOT</b> (22°45'N, 158°W)				Ships	Deep-sea	Ships	Mooring
<b>MBARI</b> (36°43'N, 122°24'W)				Ships		Mooring	Gliders
<b>Pal. LTER</b> (64°46'S, 64°W)					Ships	Ships	Gliders
<b>DYFAMED</b> (43°25'N, 7°52'E)				Ships	Deep-sea		Mooring





HOT ○ BATS ◇ CARIACO △

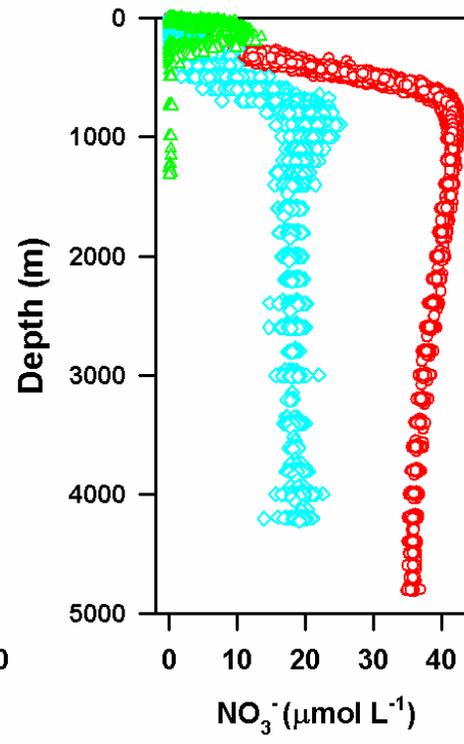
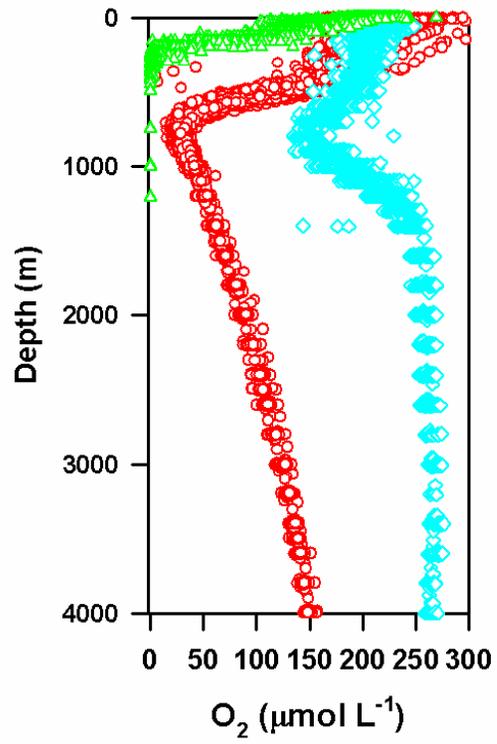
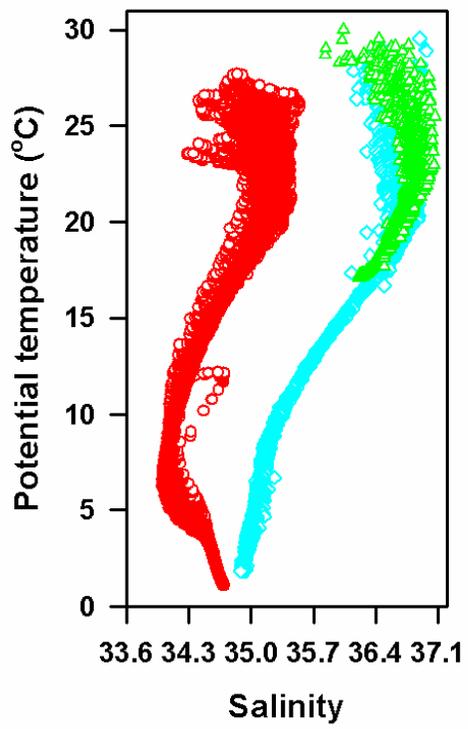


Figure 2.

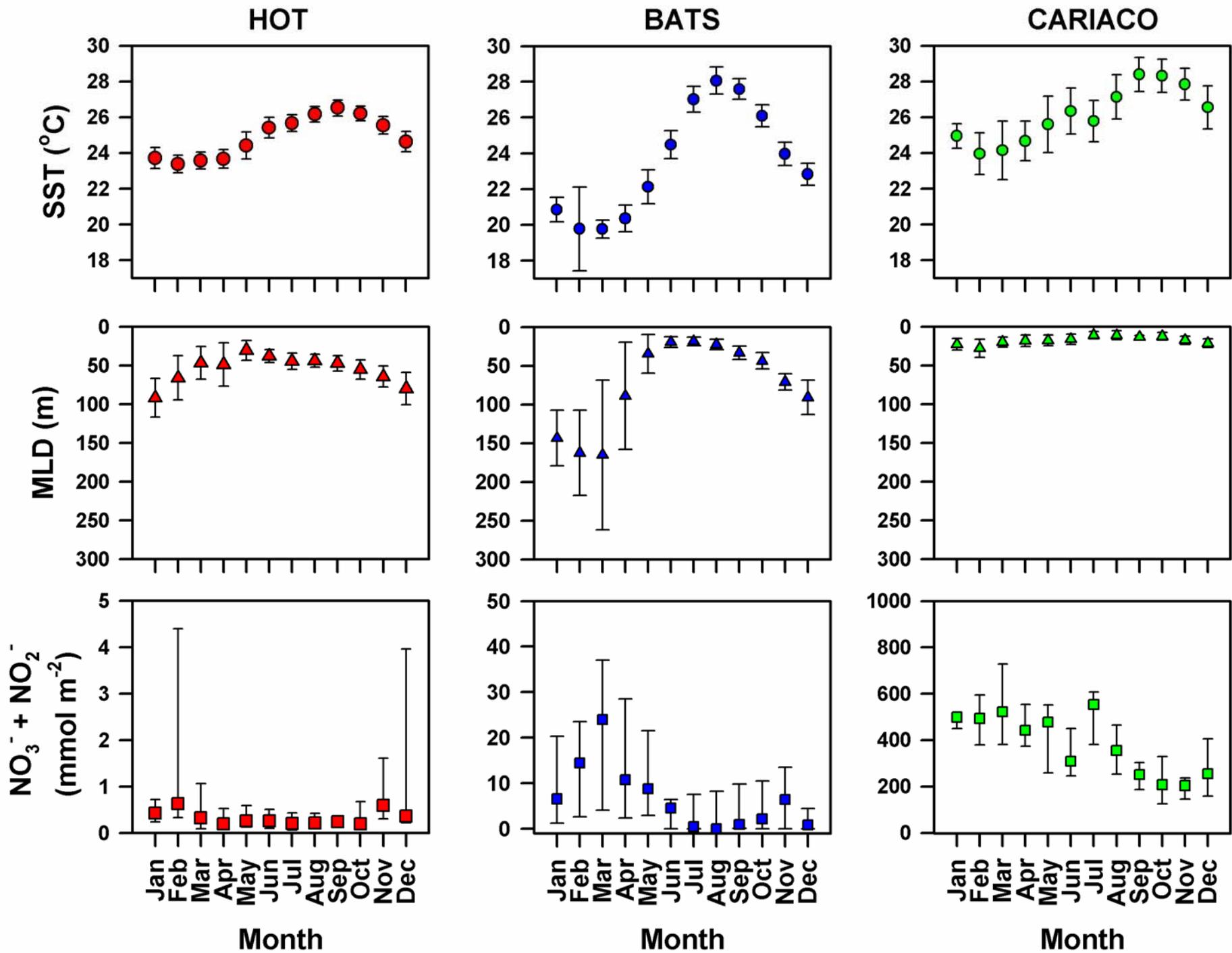


Figure 3.

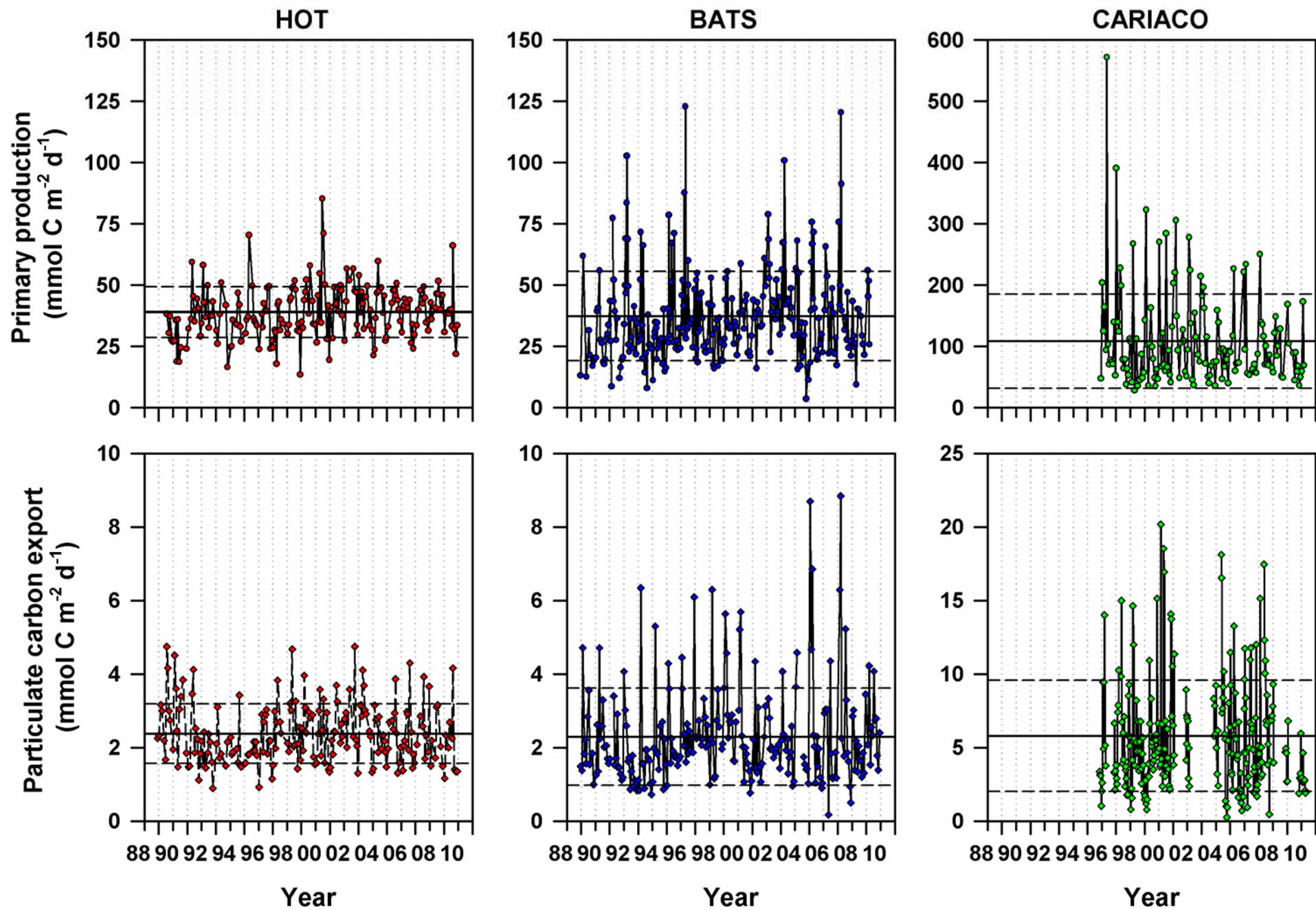


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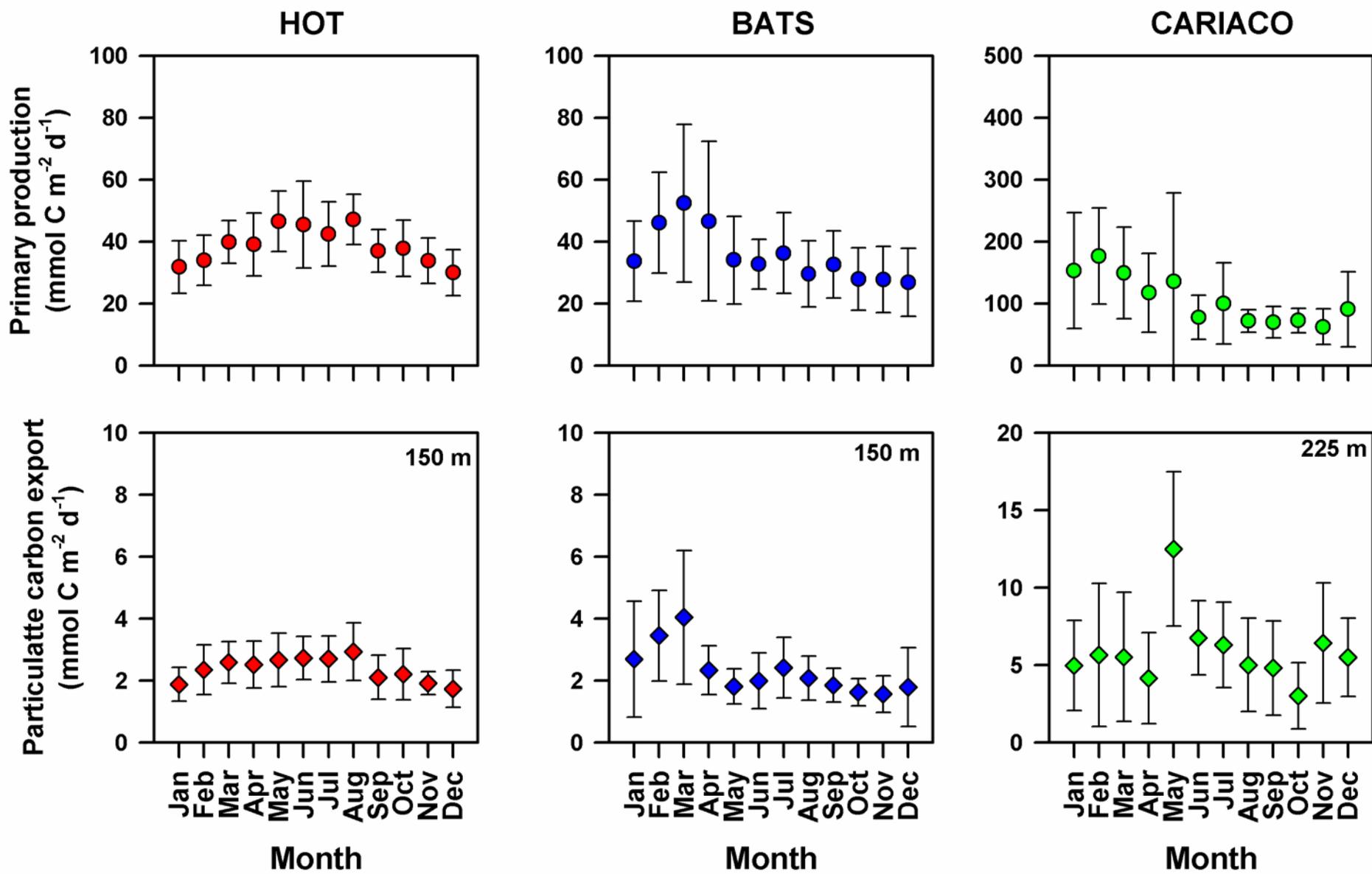


Figure 5.

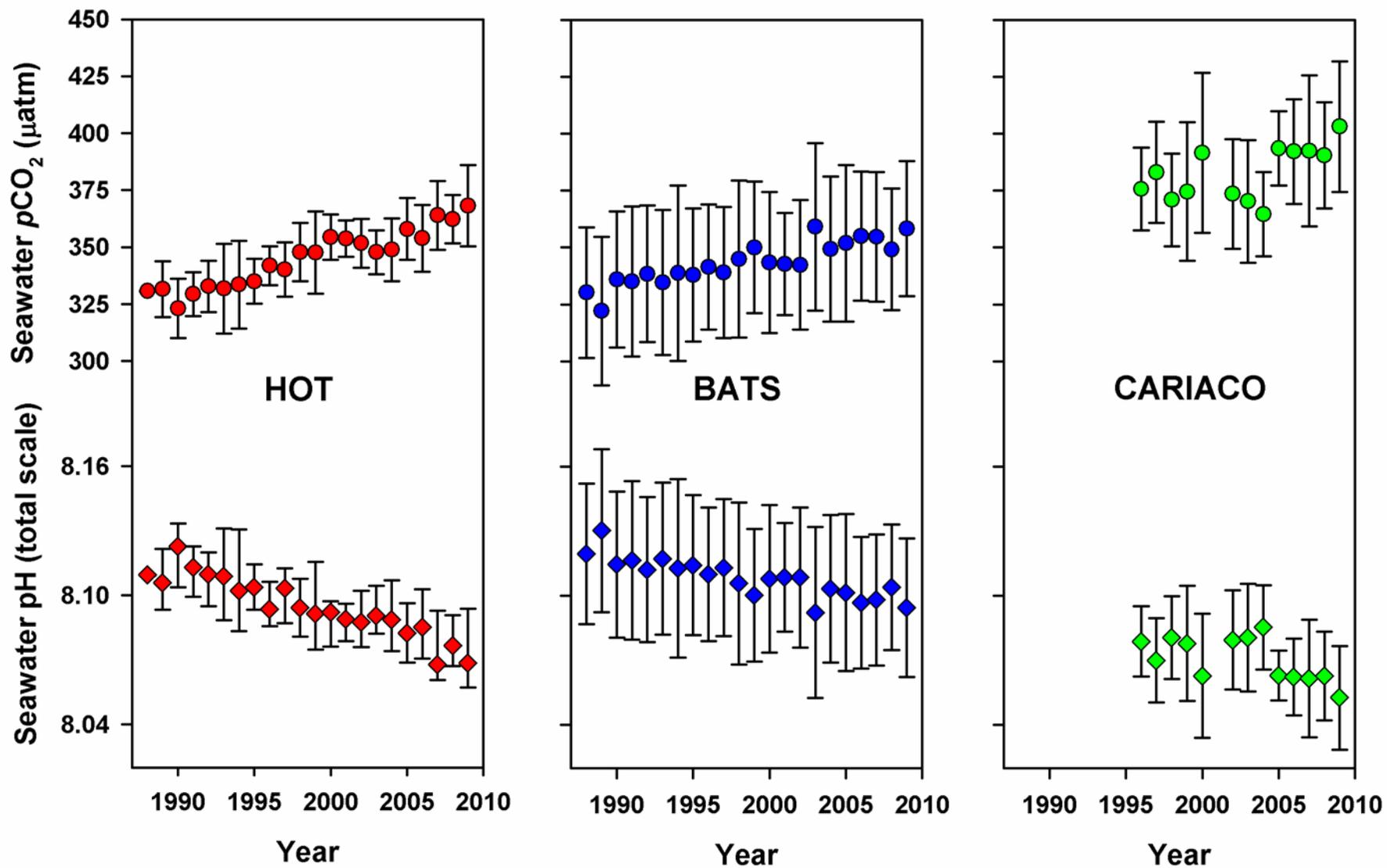


Figure 6.