Ocean Carbon Time Series

(IOCCP inventory, Nick Bates, September 2005)

What are Ocean Time-series?

Long-term continuous open-ocean observations are required for quantifying and understanding interannual-to-decadal changes in ocean circulation, water properties, water mass formation, and ecosystems, for quantifying the role of the oceans in the global carbon cycle, for observing episodic events and their impact, and for providing reference sites for atmospheric time series and quantifying air-sea fluxes.

Ocean time-series sites typically have one or more of the following characteristics:

1. *in-situ* observations of ocean/climate related quantities at a fixed geographic location/region.
2. sustained and continuous observations from ship or mooring, contributing to a long-term record at the site.
3. shipboard observations from regular occupation of a site as at Ocean Weather Stations, historical sites or sites where moorings have not been established.
3. as an alternative or complement to shipboard observations, presence of autonomous moored sampling that can resolve high-frequency variability, achieve high vertical resolution, and obtain coincident multi- disciplinary sampling.

Active ocean time-series sites with CO_2 measurements are listed in **Table 1** and **Table 2**. Other active, planned and recommended multi-disciplinary sites are listed in **Table 3**.

Oceanic CO_2 Changes Observed at Long-term Time-series Sites.

Long-term observations at several ocean time-series show upward trends of dissolved inorganic carbon (DIC) and seawater pCO$_2$ due to the uptake of anthropogenic CO_2 (Bates, 2001; Bates *et al*., 2002; Dore *et al*., 2003; Keeling *et al*., 2004; Brix *et al.,* 2004). Any assessment of long-term trends in oceanic CO_2 is complicated by large seasonal variability of the inorganic carbon cycle due to processes such as seasonal temperature, salinity, and density changes, vertical and horizontal mixing, biological production, diurnal warming/cooling, and storm events. Interpretation of oceanic CO_2 time-series data is further complicated by variability imparted by spatial heterogeneity in the ocean as a result of mesoscale and sub-mesoscale phenomena, and meridional and zonal physical gradients.

Although quite a few open-ocean and coastal ocean CO_2 time-series have been initiated, only four time-series sites are of sufficient length to evaluate longer-term interannual trends. These are (1) ALOHA (A Long-term Oligotrophic Habitat Assessment), located near Hawaii (22°45'N, 158°W) in the North Pacific Ocean; (2) BATS (Bermuda Atlantic Time-series Study), located near Bermuda (32°10'N, 64°30'W) in the NW Atlantic Ocean; (3) Hydrostation S, (32°50'N, 64°10'W)) located near Bermuda in the NW Atlantic Ocean, and; (4) ESTOC (European Station for Time-series in the Ocean Canary Islands (ESTOC), located near Gran Canaria in the NE Atlantic Ocean. Several other ocean CO_2 time-series were not evaluated here due to patchy and intermittent data, relatively short

Commentaire [NB1] : I did not include OWS Mike in the Norwegian Sea (T. Johannessen). I will try to get Truls' data next week at the IMBER/SOLAS meeting (Nov. 2004, Miami) to integrate if necessary.

duration of observations, or insufficient seasonal resolution (**Table 1,2;** e.g., site OSP/line P in the Gulf of Alaska, 50° N, 145° W; site KNOT (Kyodo North Pacific Ocean Time-series) in the North West Pacific Ocean 44° N, 155° E; site OWS (Ocean Weather Station) Station M in the Norwegian Sea, 66° N, 2° E; transect BRAVO in the Labrador Sea, 57° N, 53° W; site DyFAMed (Dynamique des Flux de Matière en Mediterranée) in the Mediterranean Sea, 43° N, 7° E; site observations in the Irminger Sea, 60° N, 36° W]).

The four long-term ocean time-series (i.e. ALOHA; BATS, Hydrostation S, ESTOC) show upward s trends of salinity normalized dissolved inorganic carbon (nDIC) and seawater pCO_2 over time. The anticipated rate of change surface ocean CO_2 due to the accumulation of anthropogenic CO_2 in the atmosphere and the surface ocean buffer factor (assuming that near-surface waters in the subtropical gyres have residence times long enough to equilibrate entirely with the anthropogenic perturbation in atmospheric CO_2) can be theoretically calculated. An equilibrium rate of DIC increase due to anthropogenic CO_2 of +0.9 μmoles kg^{-1} yr^{-1} was calculated for the subtropical gyres (Bates *et al.*, 2002; Gruber and Sarmiento, 2002). At the four long-term ocean time-series, upward trends of CO_2 are variable. The causes of the trend variability is not certain, but is presently thought to relate to sub-decadal basinwide changes in biological (e.g., productivity) and physical properties (e.g., precipitation-evaporation balance; Dore *et al.*, 2003; Keeling *et al.*, 2004; Brix et al., 2004; and atmospheric annular mode influences such as Pacific decadal oscillation and North Atlantic Oscillation; Bates *et al.*, 2002; Gruber et al., 2002) of the subtropical gyres

In the North Pacific Ocean, observations at the ALOHA site near Hawaii (22°45'N, 158°W), show upward trends of salinity normalized dissolved inorganic carbon (nDIC) and seawater pCO_2. Surface ocean nDIC and seawater pCO_2 increased at a rate of $+1.2 \pm 0.1$ μmoles kg^{-1} $year^{-1}$, and $+2.5 \pm 0.3$ μatm $year^{-1}$, respectively (**Table 4**; Dore *et al.*, 2003; Keeling *et al.*, 2004; **Figure 1**) for the 1988-2002 period. The observed rate of change of surface ocean DIC, for example, was slightly higher than the expected oceanic equilibration with anthropogenic CO_2 in the atmosphere.

In the Northwest Atlantic Ocean, observations at the BATS and Hydrostation S sites near Bermuda (32°N, 64°W), also show upward trends of surface ocean salinity normalized dissolved inorganic carbon (nDIC) and seawater pCO_2. During the first 10 years of observations at BATS (1988-1998), nDIC and seawater pCO_2 increased at a rate of +1.6 μmoles kg^{-1} $year^{-1}$, and +1.4 μatm $year^{-1}$, respectively (**Table 4**; **Figure 2;** Bates, 2001). However, merging of BATS and Hydrostation S data show that over a longer twenty year period (1983-2003), nDIC increased at a rate of $+0.83 \pm 0.13$ μmoles kg^{-1} $year^{-1}$ (**Table 4**; **Figure 2;** Bates and Keeling, unpublished data, 2004). Within the 95% confidence levels, this rate of oceanic CO_2 increase was similar to the expected oceanic equilibration (i.e., +0.9 μmoles kg^{-1} yr^{-1}) with anthropogenic CO_2 in the atmosphere. Over the 1983-2003 period, seawater pCO_2 increased at a rate of $+1.25 \pm 0.3$ μatm $year^{-1}$, respectively (**Table 4**; **Figure 2**). Concurrently, seawater pH decreased by 0.0012 ± 0.0004 pH units $year^{-1}$, representing a significant decline of 0.025 pH units (~8.125 to ~8.100) over the last 20 years. In addition, observed alkalinity increased slightly at a rate of $+0.17 \pm 0.08$ μmoles kg^{-1} yr^{-1} (**Table 4**; **Figure 2**), though this increase was statistically insignificant.

Long-term observations at the BATS site also indicate that the nDIC of surface and deeper water layers have increased at divergent rates over time since water-column sampling began in 1988. In deeper subtropical mode waters (STMW), the mean rate of change of nDIC over the 1988-2001 period was significantly higher than surface waters, increasing at a rate of 2.2 ±0.26 μmoles kg^{-1} year^{-1} (**Table 4**). The STMW of the North Atlantic Ocean is formed each winter by cooling and convective mixing at the northern edges of the subtropical gyre south of the Gulf Stream (Klein and Hogg, 1996; Hazeleger and Drijfhout, 1998). The shallow depths of the subtropical gyre (~250-400m deep) are ventilated during STMW formation and the STMW layer is found throughout the subtropical gyre. This water mass is classically defined by temperatures ranging from 17.8° to 18.4°C, by a salinity of ~36.5 ±0.05, and by a minimum in the vertical gradient of potential density (or isopycnic potential vorticity) (Klein and Hogg, 1996; Jenkins, 1998; Hanawa and Talley, 2001; Alfutis and Cornillon, 2001). The cause of the divergence between surface ocean and deeper STMW oceanic CO_2 trends is not certain, but is presently thought to relate to atmospheric/climatic variability of the North Atlantic subtropical gyre (Bates *et al*., 2002; Gruber *et al*., 2002),

In the Northweast Atlantic Ocean, observations at the ESTOC site near Gran Canaria (29°N, 15°W), also show upward trends of surface ocean salinity normalized dissolved inorganic carbon (nDIC) and seawater $p\mathrm{CO}_2$. nDIC and seawater $p\mathrm{CO}_2$ increased at a rate of +0.4 ±1.6 μmoles kg^{-1} year^{-1}, and +0.7 ±5.1 μatm year^{-1}, respectively (**Table 4;** Gonzalez-Davila *et al*., 2003) for the 1995-2000 period. The observed rate of change of surface ocean DIC, for example, was slightly lower than the expected oceanic equilibration with anthropogenic CO_2 in the atmosphere. The causes for the lower than anticipated oceanic CO_2 increase are not certain, but probably relate to the relatively short period of observation (i.e., 1995-2000 data reported), and sub-decadal variability of the region close to upwelling off the African coast (Gonzalez-Davila *et al*., 2003).

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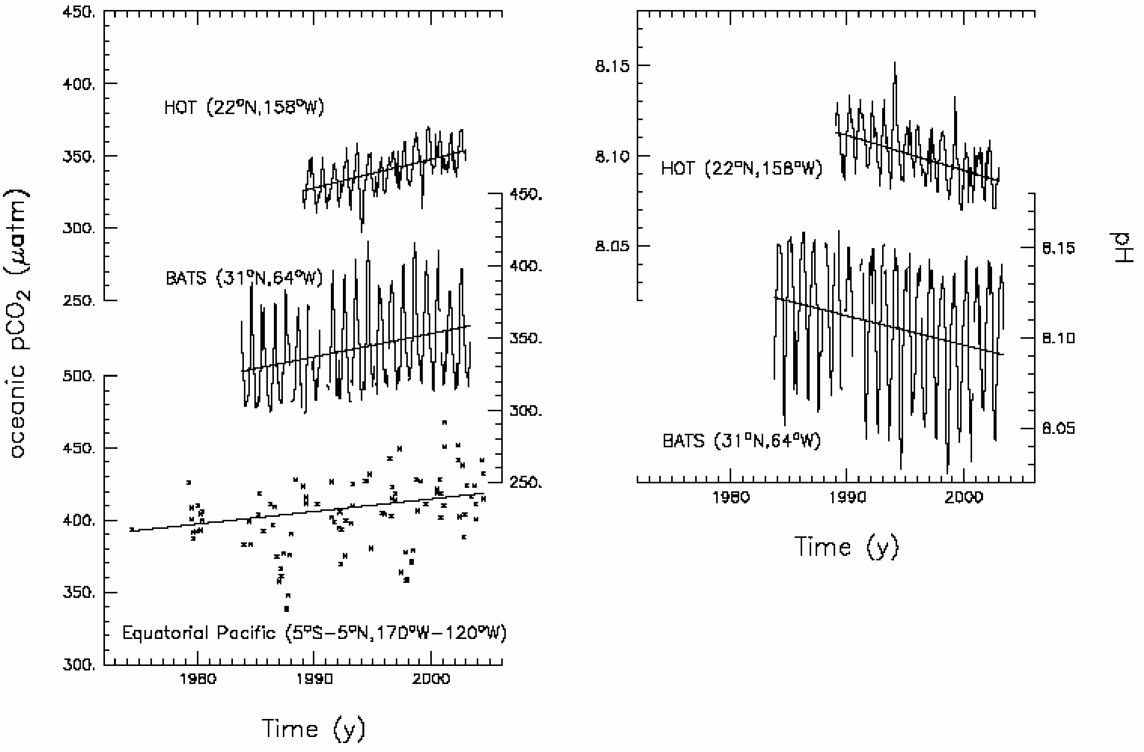

Figure 1. Long-term oceanic pCO_2 and pH changes observed at the BATS (Bermuda Atlantic Time-series Study; 32°10'N, 64°30'W/Hydrostation S 32°50'N, 64°10'W), HOT and Equatorial Pacific time-series sites.

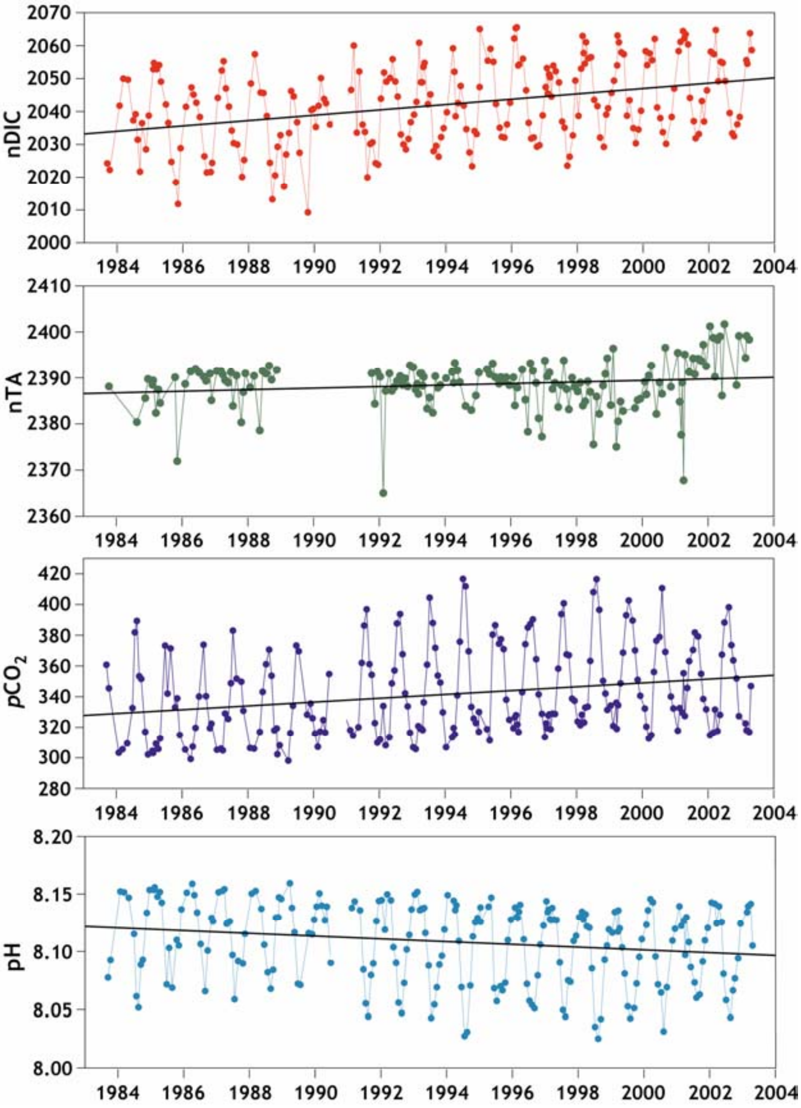

Figure 2. Long-term oceanic CO_2 changes observed at the BATS (Bermuda Atlantic Time-series Study; 32°10'N, 64°30'W) and Hydrostation S (32°50'N, 64°10'W) sites located near Bermuda in the NW Atlantic Ocean. Two oceanic CO_2 datasets were combined herein. Surface DIC and alkalinity data for the period June 1983 to September 1988 were collected at Hydrostation S by C.D. Keeling (Scripps Institution of Oceanography; Keeling, 1993). Surface DIC and alkalinity data for the period October 1988 to June 2003 were collected at BATS by N.R. Bates (Bermuda Biological Station For Research; Bates, 2001; Bates *et al*., 2002). **a.** Salinity normalized DIC (nDIC; µmoles kg^{-1}) changes from 1983-2003 at the BATS site. Here, nDIC data represents DIC data normalized to a constant salinity of 36.6 (the average salinity observed at the BATS site). The long-term trend in nDIC is 0.83

± 0.13 µmoles kg^{-1} year^{-1} (95% confidence levels of 0.55-1.10 µmoles kg^{-1} year^{-1}; *n* of 224). **b.** Salinity normalized alkalinity (nTA; µmoles kg^{-1}) changes from 1983-2003 at the BATS site. Here, nTA data is normalized to a constant salinity of 36.6 (the average salinity observed at the BATS site). The long-term trend in nTA is 0.17 ± 0.08 µmoles kg^{-1} year^{-1} (95% confidence levels of 0.01-0.32 µmoles kg^{-1} year^{-1}; *n* of 165). The low nTA values observed in Nov. 1985, Feb. 1992, and Feb. 2001 reflect non-conservative change in alkalinity associated with $CaCO_3$ production events in the subtropical gyre (Bates *et al.*, 1996a). **c.** Seawater pCO_2 (µatm) changes from 1983-2003 at the BATS site. pCO_2 data was calculated from DIC and alkalinity data using dissociation constants and theoretical considerations outlined in Bates *et al.*, 1996b. The long-term trend in pCO_2 is 1.25 + 0.34 µatm year^{-1} (95% confidence levels of 0.58-1.92 µmoles kg^{-1} year^{-1}; *n* of 221). **c.** Seawater *p*H changes from 1983-2003 at the BATS site. *p*H data was calculated from DIC and alkalinity data using dissociation constants and theoretical considerations outlined in Bates *et al.*, 1996. The long-term trend in *p*H is 0.0012+ 0.0004 pH unit change year^{-1} (95% confidence levels of -0.0019-0.0033 pH unit change year^{-1}; *n* of 221).

Table 1. Active, and quasi-active ocean time-series with CO_2 measurements

Region	Acronym	Position	Dates and Status	Annual frequency	CO_2 Observations	Contact
Norwegian Sea	OWS Station M	66° N, 2° E	1992-present;	Four occupations	Water-column; surface	T. Johannessen
Irminger Sea	n/a	60° N, 36° W	?-present;	Three occupations?	Water-column; surface	J. Olafsson
Labrador Sea	Bravo	57° N, 53° W	?-present;	Annual occupation	Water-column; surface	P. Jones/H. Thomas
NE Atlantic	ESTOC	29° N, 16° W	1994-present	Three occupations	Water-column; surface	M. Gonzalez-Davila
NW Atlantic	BATS/OFP/BTM	32° N, 65° W	1988-present	Monthly occupation	Water-column; surface; mooring	N.R. Bates
NW Atlantic	Hydrostation S	32° N, 65° W	1983-present	Monthly occupation	Surface	A.G. Dickson
Mediterranean	DyFAMed		1991-2001, 2003-present	Seasonal	Water-column; surface	C. Goyet?
NE Pacific	OSP/line P	50° N, 145° W	1970's to present	Three occupations	Water-column; surface	C.S. Wong
Trop. Pacific	TAO/TRITON	2°S, 170°W	1993-present	Continuous	Mooring	F. Chavez/C. Sabine
NW Pacific	HOT	23° N, 158° W	1988-present	Monthly occupations	Water-column; surface; mooring	D.A. Karl
NW Pacific	KNOT	44° N, 155° E	1999-2002	n/a	No	Y. Nojiri

Table 2. Long-term oceanic CO_2 observations at time-series sites.

Region	Acronym	Position	Dates and Remarks
Atlantic Ocean			
N Atlantic, Norwegian Sea	OWS Station M	66° N, 2° E	1995-present, limited sampling
N Atlantic, Irminger Sea		60° N, 36° W	1990-present; limited sampling
N Atlantic, Labrador Sea	Bravo	57° N, 53° W	1980's-present; limited sampling
NE Atlantic, Gran Canaria	ESTOC	29° N, 16° W	1995-present; continuous sampling
NW Atlantic, Bermuda	BATS	32° N, 65° W	1988-present; continuous sampling
NW Atlantic, Bermuda	Hydrostation S	32° N, 65° W	1983-present; continuous sampling
Mediterranean Sea	DyFAMed	43° N, 7° E	1995-2001, 2003-, limited sampling
Pacific Ocean			
NW Pacific, Gulf of Alaska	OSP/line P	50° N, 145° W	1970's, intermittent sampling
NW Pacific, Hawaii	ALOHA/HOT	22.75° N, 158° W	1988-present, continuous sampling
NW Pacific	KNOT	44° N, 155° E	1999-2002,
Equatorial Pacific	TAO Array	47° S, 142° E	1999-present, mooring $p\text{CO}_2$ only
South China Sea	SEATS	20° N, 115° E	1999, 2003-present
SW Pacific, New Zealand		43.5° S, 178.5° E	2003-present
Southern Ocean			
SW Subantarctic Zone, Tasmania		47° S, 142° E	2004
Indian Ocean sector	Kerfix	50° S, 68° E	1990-1995

Table 3. Active, planned and recommended ocean time-series multidisciplinary sites

Region	Acronym and type	Position	Status	Notes	CO$_2$ Obs or History
NE Pacific	OSP and line P subpolar gyre	50°N, 145°W	Operational	Water column physics and biology; mooring; CO$_2$ history	Yes
NW Pacific	KESS/subpolar gyre	40°N, 150°E	Recommended	Mooring	No
NW Pacific	KNOT/subpolar gyre	44°N, 155°E	Planned	Mooring	Yes
NW Pacific	subpolar gyre	50°N 165°E	Planned	Mooring	No
NW Pacific	HOT/subtropical gyre	23°N 158°W	Operational	Water column physics and biology; mooring; CO$_2$ history	Yes
Trop. Pacific	TAO/TRITON/equatorial Pacific	2°S, 170°W	Recommended	Mooring	Yes
Trop. Pacific	TAO/TRITON//equatorial Pacific	0°N, 156°E	Recommended	Mooring	Yes
SE Pacific	Stratus/Peru Basin upwelling zone	18°S, 85°W	Operational	Existing air-sea flux (stratocumulus) site	No
SW Pacific	New Zealand/ Southern Ocean	43.5°S, 178.5°E	Operational	Water column physics and biology	Yes
SW Pacific	TAO/ Southern Ocean	47°S, 142°E	Operational	Mooring	No
SE Pacific	Southern Ocean	55°S,9 0°W	Recommended	Mooring	No
South China Sea	SEATS/marginal sea	20°N, 115°E	Planned	Mooring	Yes
NE Atlantic	Fram Strait	79°N, 9° E/5°W	Operational	Mooring	No
NE Atlantic	Greenland Sea	75°N, 3.5°W	Operational	Mooring	No
NE Atlantic	OWS Station M/Norwegian Sea	66°N, 2°E	Operational	Water column physics and biology; CO$_2$ history	Yes
NE Atlantic	Irminger Sea	60°N, 36°W	Operational	Water column physics and biology; CO$_2$ history	Yes
NW Atlantic	Bravo/Labrador Sea	57°N, 53°W	Operational	Water column physics and biology; CO$_2$ history	Yes
NE Atlantic	Porcupine Abyssal	49°N, 16.5°W	Operational	Mooring	No
NW Atlantic	Grand Banks	44°/41°N, 45°/49°W	Operational	Mooring	No
Mediterranean	DyFAMed/marginal sea	43° N, 7° E	Operational	Mooring; CO$_2$ history	Yes
NW Atlantic	Station W	40°N, 70°W	Operational	Mooring	No
NW Atlantic	Gulf Stream Extension	36°N, 70°W	Planned	Mooring	No
NW Atlantic	BATS/OFP/BTM/ subtropical gyre	32°N, 65°W	Operational	Water column physics and biology; mooring; CO$_2$ history	Yes
NW Atlantic	Hydrostation S/subtropical gyre	32°N, 65°W	Operational	Water column physics and biology;	Yes
NE Atlantic	ESTOC/subtropical gyre	29°N, 16°W	Operational	Water column physics and biology; mooring; CO$_2$ history	Yes
N Atlantic	Edge of subtropical gyre	23°N 44°W	Recommended	Mooring	No
Caribbean	CATS/marginal sea	17°N,63°W	Operational	Water column physics and biology	No
Caribbean	CARIACO/marginal sea		Operational	Water column physics and biology	No
Tropical Atl.	NTAS/MOVE/tropical Atlantic	15°N, 51°W	Operational	Mooring	No
Tropical Atl.	PIRATA/ tropical Atlantic	0°/10°N, 10°/20°W	Planned	Mooring	No
Tropical Atl.	CLIVAR TS	9-13° S, 33-36° W	Operational	Mooring	No
S Atlantic	Brazil/Argentine Basin	42°S 42°W	Planned	Mooring	No
Arabian Sea	Upwelling region	15°N, 65°E	Recommended	Mooring	Yes
Tropical Indian	Triton Array	0°N, 90°E	Recommended	Mooring	No
Tropical Indian	Triton Array	5°S, 95°E	Recommended	Mooring	No
Tropical Indian	Monsoon Array	0°N: 50°E,	Recommended	Mooring	No

Tropical Indian	Monsoon Array	65° E, 80° E	Recommended	Mooring	No
Tropical Indian	Indonesian Throughflow	3°N to 12°S 116° E to 125° E	Planned	Mooring	No

Table 4. Long-term oceanic CO$_2$ changes observed at four time-series sites: (1) ALOHA (A Long-term Oligotrophic Habitat Assessment), located near Hawaii (22°45'N, 158°W) in the North Pacific Ocean; (2) BATS (Bermuda Atlantic Time-series Study), located near Bermuda (32°10'N, 64°30'W) in the NW Atlantic Ocean; (3) Hydro S (Hydrostation S, (32°50'N, 64°10'W)) and BATS combined, located near Bermuda in the NW Atlantic Ocean, and; (4) ESTOC (European Station for Time-series in the Ocean Canary Islands (ESTOC), located near Gran Canaria in the NE Atlantic Ocean.

Site	**Measurement period**	**Layer**	**nDIC (µmoles kg^{-1} yr^{-1})**	**pCO$_2$ (µatm yr^{-1})**	**Reference**
North Pacific Ocean					
ALOHA (HOT) 22°45'N, 158°W	10/88-12/01 (13 years)	Surface Ocean[a]	1.19[b] ± 0.14	2.5[c] ± 0.3	Dore *et al.*, 2003
	10/88-12/02 (14 years)	Surface Ocean[a]	1.22[b] ± 0.08	2.5[c] ± 0.1	Keeling *et al.*, 2004
North Atlantic Ocean					
BATS 32°N, 64°W	10/88 to 12/98 (10 years)	Surface Ocean[a]	1.60[d] ± 5.6	1.4[e] ± 5.1	Bates, 2001
	10/88 to 09/01 (13 years)	Surface Ocean[a]	1.25[f] ± 0.14		Bates et al., 2002
	10/88 to 09/01 (13 years)	STMW[g]	2.22 ± 0.25		Bates et al., 2002
Hydro S/BATS 32°N, 64°W	05/83 to 09/01 (18 years)	Surface Ocean[a]	0.64 ± 0.05	1.5 ± 0.1	Keeling et al., 2004
	05/83 to 04/03 (20 years)	Surface Ocean[a]	0.83 ± 0.13	1.3 ± 0.3	Bates & Keeling, unpub. data
ESTOC 29°N, 15°W	10/95 to 12/00 (5 years)	Surface Ocean[a]	0.4[h] ± 1.6	0.71± 5.1	Gonzalez-Davila et al., 2003

Footnotes:

a. Surface samples were used in this analyses.

b. DIC data was normalized to constant salinity of 35, close to the average salinity observed at the ALOHA site. DIC data was also seasonally detrended (Dore *et al*., 2003; Keeling *et al*. 2004).

c. *p*CO_2 was not seasonally detrended (Dore *et al*., 2003; Keeling *et al*. 2004).

d. DIC data was normalized to constant salinity of 36.6, close to the average salinity observed at the BATS site. DIC data was not seasonally detrended (Bates, 2001).

e. *p*CO_2 data was not seasonally detrended (Dore *et al*., 2003; Keeling *et al*. 2004).

f. DIC data was normalized to constant salinity of 36.6, close to the average salinity observed at the BATS site. DIC data was seasonally detrended (Bates *et al*. 2001).

g. DIC changes in subtropical mode water (STMW) which occurs at a depth of ~250-400 m deep at the BATS site. STMW is characterized by a temperature of ~18 ±0.2°C, salinity of 36.5 ± 0.03, and a potential vorticity minima (Bates *et al*., 2002) .

h. DIC data was normalized to constant salinity of 35 (Gonzalez-Davila *et al.,* 2003)