REGIONAL TESTBEDS: INTERANNUAL VARIABILITY OF THE OCEANIC CARBON CYCLE AT THE U.S. JGOFS BERMUDA ATLANTIC TIME-SERIES STUDY (BATS) SITE.

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Understanding the relationship between Earth's climate and the oceanic carbon cycle requires an understanding of the time and space scales of variability of CO_2 in the ocean, it's exchange with the atmosphere and the rate of uptake of anthropogenic CO_2 by the ocean. One of the primary components of Joint Global Ocean Flux Study (JGOFS) program has been the long-term ocean observations at both the Bermuda Atlantic Time-series Study (BATS) site in the western North Atlantic and the Hawaii Ocean Time-series (HOT) site in the central North Pacific. Since 1988, hydrographic and biogeochemical data have been collected at both sites, and a large degree of variability of both physical and biogeochemical properties has been demonstrated over seasonal, interannual and decadal time scales (e.g., Michaels and Knap, 1996; Karl, 1997; Bates et al., 1998a,b; Karl et al., 2001a; Steinberg et al., 2001; Bates, 2001).

Long-term time-series studies are ideally suited to the study of slow or subtle processes, rare or irregularly spaced events and complex phenomena, all of which are fundamental to our understanding of biogeochemical cycles in the world ocean (Karl et al., 2001b). Monthly and bimonthly (during the January to April period) field expeditions to the BATS site have provided a relatively unbiased seasonal coverage, a prerequisite for unbiased data return and ecological and biogeochemical interpretations.

Both time-series have captured the time and space domain of key hydrographic, ecological and biogeochemical processes. At BATS, the relaxation of oligotrophy during winter convective mixing leads to a recurrent spring phytoplankton bloom, the magnitude and duration of which varies in relation to atmospheric forcing and entrainment of nutrients into the euphotic zone (e.g., Michaels et al., 1994a; Michaels and Knap, 1996; Steinberg et al., 2001). A major enigma is the recurrent summertime removal of inorganic carbon in the absence of nutrients (Bates et al., 1996). The apparent relaxation of chronic oligotrophy is hypothesized to result from N2 fixing microorganisms (Michaels et al., 1994b; Gruber and Sarmiento, 1997), a process potentially important for all subtropical gyre systems (Karl et al., 1997; Lee et al., 2001). The temporal variability of ocean CO_2 and the exchange of CO_2 with the atmosphere is profoundly influenced by this seasonal ecological phenomena. CO_2 variability and oceanic uptake of CO_2 is also influenced by diurnal to seasonal physical forcing (Bates et al., 1998a, 2000; Bates, 2001), with processes such as hurricanes and short-term wind variability important to the rate of oceanic uptake of CO_2 in the North Atlantic subtropical gyre (Bates et al., 1998a, Bates and Merlivat, 2001). The interpretation of key hydrographic, ecological and biogeochemical processes is also complicated by the presence of mesoscale and sub-mesocale variability. For example, the spatial variability of ocean CO_2 and air-sea CO_2 exchange in the subtropical gyre is much influenced by the presence of mesoscale eddies, and the biological response to the uplift of nutrients and carbon (e.g., McGillicuddy et al., 1999).

Secular Increase in Ocean CO_2

With over a decade of oceanographic data at BATS and HOT, the rate at which the subtropical ocean absorbs anthropogenic CO_2 can be determined. Since secular changes of CO_2 are small relative to natural seasonal and interannual variability, accurate and reproducible long-term observations of CO_2 have been required. Between 1988 and 1998, surface seawater total carbon dioxide (TCO_2) and salinity normalized TCO_2 ($nTCO_2$) increased at a rate of 2.2±6.9 and 1.6±5.8 µmol kg^{-1} yr^{-1}, respectively. During the same period, the partial pressure of CO_2 (pCO_2) of seawater increased at a rate of 1.4±10.7 µatm yr^{-1}, similar to the rate of increase in atmospheric pCO_2 (~1.3 µatm yr^{-1}). The increase in seawater TCO_2 and pCO_2 can be attributed to a combination of uptake of anthropogenic CO_2 from the atmosphere and interannual changes in hydrographic properties of the subtropical gyre.

Interannual Variability

Some of the physical and biogeochemical variability observed at BATS over the last decade is linked to natural large-scale climate patterns such as the El Nino-Southern Oscillation (ENSO) or the North Atlantic

Oscillation (NAO). Establishing the underlying links between these large-scale climate patterns and ocean biogeochemistry will help oceanographers and climate scientists understand anthropogenic change in the context of natural variation.

Interannual trends can be examined by determining how hydrographic and biogeochemical anomalies, or deviations from a mean state, vary over time. Statistical analyses, such as cross-correlation coefficient analysis, can be used to determine whether there are significant correlations between biogeochemical anomalies at the BATS site and natural large-scale climate patterns such as ENSO or NAO. These statistical analyses reveal that upper-ocean temperatures are inversely correlated with parameters such as mixed-layer depth, rates of integrated primary production and total carbon dioxide (TCO_2). For example, during negative (cooler) temperature anomaly periods over the decade, mixed-layer depths were deeper by up to 20 meters; rates of integrated primary production were higher by up to 200 mg $Cm^{-2}d^{-1}$, and TCO_2 concentrations were higher by up to 5µmol kg^{-1}. In contrast, during periods with positive (warmer) temperature anomalies, mixed-layer depths were shallower, and rates of primary production and TCO_2 concentrations were lower.

These anomalies of temperature, salinity, mixed-layer depth, primary production and TCO_2 are correlated with variation in the NAO, a periodic shift in the strengths and positions of sub-polar high and low pressure cells in the North Atlantic and the winds associated with them. The coefficients of variability range from 0.32 to 0.52 (Table 1). The correlation between ocean temperature and salinity anomalies and the NAO in the Sargasso Sea is not a new finding. Many other research groups have found a connection between ocean temperatures and the state of the NAO in this region. During positive NAO periods, the westerlies that usually prevail in the region between Florida and Cape Hatteras west of the Azores High weaken, reducing wind stress and heat exchange and leading to warm ocean temperature anomalies. During negative NAO periods, storm tracks appear to shift southward, cooling surface waters and deepening mixed layers. Only now, with long-term time-series observations, can the connections between ocean biogeochemistry and climate phenomena be adequately demonstrated.

The anomalies of salinity and alkalinity are significantly correlated with each other (Table 1) and also correlated with variation in the Southern Oscillation Index (SOI), a periodic shift in winds and pressure areas in the Pacific that is associated with episodic El Nino and La Nina events. The periods of lower salinity and alkalinity followed El Nino events by approximately six months, while a positive (high) salinity anomaly followed the 1997 La Nina event. The correlations between normalized TCO_2, normalized alkalinity and the SOI suggest that water masses passing through the BATS area change with time. Furthermore, changes may occur in the circulation patterns of the subtropical gyre that contribute to interplay between ocean biogeochemistry and climate variability.

	SOI[2]	NAO	SST	Temp (0-100m)	Salinity	TCO_2	$NTCO_2$	TA	nTA	ML	PP
SO Index [1,2]	-	-	-	-	-	-	-	-	-	-	-
NAO Index[1]	-0.43		-	-	-	-	-	-	-	-	-
Surface Temp. (SST)[1]	0.28	0.40	-	-	-	-	-	-	-	-	-
Temp. (0-100m)[1]	0.35	0.42	-0.66	-	-	-	-	-	-	-	-
Salinity[1]	0.52	-0.48			-	-	-	-	-	-	-
TCO_2[1]		-0.46	-0.54	-0.38	0.44	-	-	-	-	-	-
$nTCO_2$[1]	-0.53		-0.65	-0.45	-0.39	0.64	-	-	-	-	-
Alkalinity (TA)[1]	0.34	-0.52			0.69	0.25		-	-	-	-
nTA[1]	-0.41				-0.37	-0.39	0.38		-	-	-
Mixed Layer (ML)[1]	0.35	-0.32	-0.56	-0.45		0.40	0.49		-	-	-
Primary Prod. (PP)[1]	-0.21	-0.33	-0.51	-0.64		0.35	0.32			0.20	-

[1]6 month running mean of anomaly
[2]A lag of 6 months to the SOI Index gives the best correlations between SOI, hydrographic and biogeochemical parameters.

Table 1: Correlation coefficients for hydrographic and biogeochemical anomalies at the BATS sampling site (1988-1998) and large-scale climate patterns, represented by the Southern Oscillation Index (SOI) and the North Atlantic Oscillation (NAO) Index. Coefficients of less than 0.2 were not reported. All figures represent a six-month running mean of the anomaly. A six-month lag with respect to the SOI gives the best correlation between that index and hydrographic and biochemical parameters.

This analysis indicates that NAO and ENSO play a role in modulating interannual biogeochemical variability at BATS. Long-term time-series observations thus provide valuable insight into large-scale ocean variability.

As HOT and BATS continue into a second decade of sampling, the understanding and prediction of how ocean biogeochemistry is influenced by climate variability should continue to improve.

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