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Interannual variability in sea surface temperature and fCO_2 changes in the Cariaco Basin

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ABSTRACT

We examined the variability of sea surface carbon dioxide fugacity (fCO_{2sea}) and its relation to temperature at the Cariaco Basin ocean time-series location (10°30′N, 64°40′W) for the period from 1996 through 2008. Periods of warm (positive) and cold (negative) anomalies at the station were related to variability in coastal upwelling intensity. A positive temporal trend in monthly-deseasonalized sea surface temperatures (SST) was observed, leading to an overall increase of 1.13 °C over 13 years. Surface fCO_{2sea} displayed significant short-term variation (month to month) with a range of 330–445 μatm. In addition to a large seasonal range (58 ± 17 μatm), deseasonalized fCO_{2sea} data showed an interannual positive trend of 1.77 ± 0.43 μatm yr^{-1}. In the Cariaco Basin, positive and negative anomalies of temperature and fCO_{2sea} are in phase. An increase/decrease of 1 °C coincides with an increase/decrease of 16–20 μatm of fCO_{2sea}. Deseasonalized fCO_{2sea} normalized to 26.05 °C, the mean Cariaco SST, shows a lower rate of increase (0.51 ± 0.49 μatm yr^{-1}). Based on these observations, 72% of the increase in fCO_{2sea} in Cariaco Basin between 1996 and 2008 can be attributed to an increasing temperature trend of surface waters, making this the primary factor controlling fugacity at this location. During this period, a decrease in upwelling intensity was also observed. The phytoplankton community changed from large diatom-dominated blooms during upwelling in the late 1990's to blooms dominated by smaller cells in the first decade of the 21st century. The average net sea-air CO_2 flux over the study period is 2.0 ± 2.6 mol C m^{-2} yr^{-1} employing the Wanninkhof parameterization, and 2.1 ± 2.5 mol C m^{-2} yr^{-1} based on Nightingale's model. To further understand the connection between the changes observed in the Cariaco Basin, the relationships between interannual variability in the temperature anomaly with three modes of climate variability (AMO, NAO and ENSO) were examined. The correlations between SSTA and two of these climate modes (AMO and ENSO) only show very weak relationships, although they were significant.

1. Introduction

Although continental margins represent only about 0.5% of the ocean volume and occupy less than 8% of the seafloor, they play an important role in regulating the exchange of carbon dioxide (CO_2) and the storage of carbon within the global ocean (Doney et al., 2009; Liu et al., 2000; Muller-Karger et al., 2005). Due to high primary production and carbon storage rates in sediments, many continental margin areas are considered CO_2 sinks (Chen and Borges, 2009). However, the balance between biogeochemical processes (CO_2 uptake/production, $CaCO_3$ fixation/dissolution), transport (advection/turbulent diffusion), convective mixing, air-sea gas exchange, and riverine input determine whether a particular region functions as a net source or sink of CO_2.

Long-term and frequent observations of fugacity of seawater CO_2 (fCO_{2sea}) are required to help reduce the large uncertainties in the global estimates of CO_2 flux (Nemoto et al., 2009). Indeed, both seasonal and spatial variability of CO_2 concentrations in the ocean may mask any long-term changes if careful observations are not conducted within a time series framework (Bates, 2001).

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Long time-series are a powerful tool for investigating biogeochemical cycles and marine ecosystems and their role in and response to climate variability. This important concept has led to the initiation of a number of biogeochemical ocean time-series stations, both in open ocean and continental margin sites. For example, in the deep North Pacific Ocean at ocean time-series station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45′N, 158°00′W), observations have revealed an increase of $2.84 \pm 0.28\ \mu mol\ kg^{-1}\ yr^{-1}$ in surface total carbon dioxide (TCO_2) between 1989 and 2001 (Dore et al., 2003). In the deep subtropical North Atlantic, at the Bermuda Atlantic Time-series Study (BATS; 31°45′N, 64°10′W), surface TCO_2 increased by $1.37 \pm 0.16\ \mu mol\ kg^{-1}\ yr^{-1}$ between 1983 and 2005 (Bates, 2007), with surface and atmospheric pCO_2 increasing at $1.67 \pm 0.28\ \mu atm\ yr^{-1}$ and $1.78 \pm 0.02\ \mu atm\ yr^{-1}$ respectively over this 22 year period (Bates, 2007).

However, whether surface water CO_2 varies over similar time scales in continental margin settings within the tropics are yet unknown. Since November 1995, the Cariaco Basin ocean time-series program (CARIACO) has conducted biogeochemical and ecological observations at a location on the northern Venezuelan margin (10°30′N, 64°40′W, Fig. 1) to examine the linkages between water column processes and the flux of particles settling to the seafloor. The Cariaco Basin is an ideal location to examine this question because past changes in surface ocean processes are well preserved in the sediment record accumulating in the basin. The Cariaco Basin has a unique set of oceanographic characteristics. The open exchange of water and materials with the Caribbean Sea only occurs above a 140 m deep sill. Consequently, there is a restriction (or limitation) of deep water circulation and mixing, which allows the formation of anoxic waters below 320 m. The restricted circulation within the basin isolates it from the open ocean and makes it a trap for sinking materials. The seasonally alternating coastal wind-driven upwelling controls the high seasonal biological productivity and particulate sediment flux.

While the Cariaco Basin has a long history of oceanographic studies, very few have focused on the carbon dioxide system. Avila-Melean (1976) analyzed the relationship between TCO_2 and dissolved oxygen in the nearby Gulf of Santa Fe. Hastings and Emerson (1988) measured TCO_2 and total alkalinity (TA) in a study of sulfate reduction above the O_2–H_2S interface. Zhang and Millero (1993) measured TCO_2, pH, and TA in the eastern and western basins of the Cariaco Basin. Astor et al. (2005a,b) observed the interactions between physical and biochemical parameters that lead to temporal variations in fCO_{2sea}, finding that even during periods of high production, the CO_2 flux between the ocean and the atmosphere decreased but remained positive, *i.e.* CO_2 escaped from the ocean to the atmosphere.

In this paper, we report the results of CO_2 observations at the CARIACO time-series station. We look at changes observed during periods of upwelling (dry season) and non-upwelling (rainy season). We evaluate the rates of change of several hydrographic parameters over the period 1996–2008, and examine possible connections with different modes of climate variability.

1.1. Study area

The Cariaco Basin, located on the continental margin of Venezuela, is a tectonic depression ($\sim$1400 m deep) subject to seasonal changes in atmospheric forcing that affect the water column's upper layers. Intermittent easterly trade winds ($> 6\ m\ s^{-1}$) are responsible for offshore surface Ekman transport and wind-driven coastal upwelling during winter and early spring (January–April). Rainy conditions and weak winds are typical between September and December, the months of non-upwelling. A transition period occurs between June and August when a short and relatively weak secondary upwelling event occurs with characteristics and timing that vary from year to year (Astor et al., 2003). The causes of this secondary upwelling event are linked to variations in the wind curl (Rueda-Roa, 2012). During the primary upwelling event, high

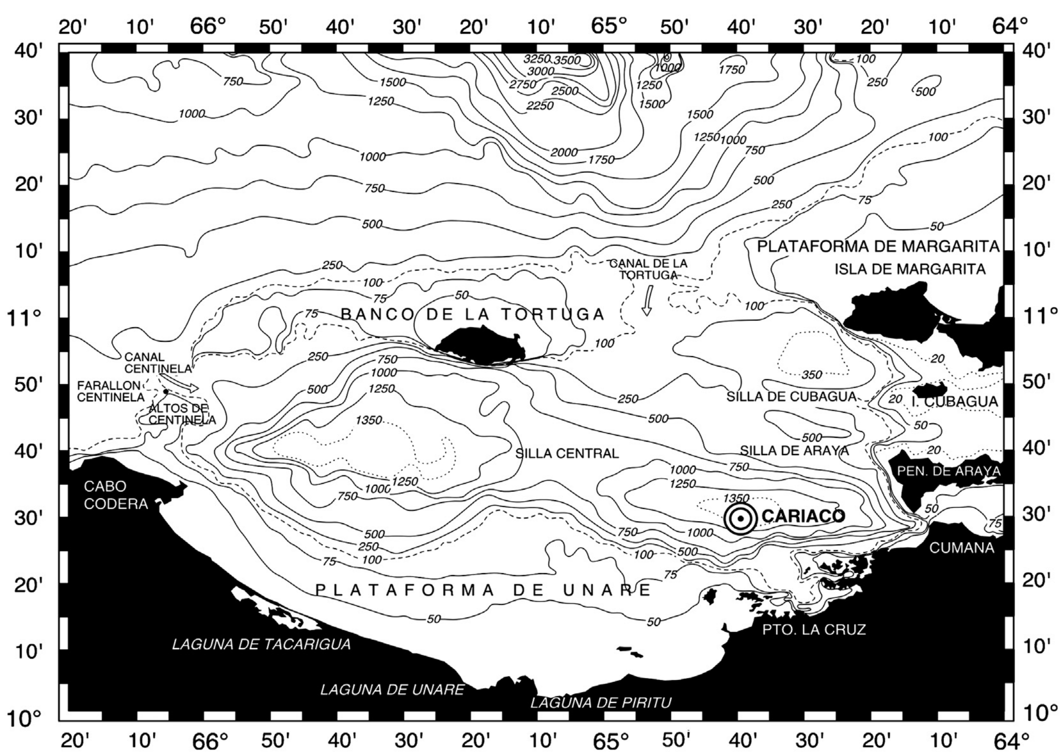

Fig. 1. Map depicting the Cariaco Basin and indicating the location of the CARIACO time series station.