GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L15604, doi:10.1029/2006GL026415, 2006

Changes in wind-driven upwelling during the last three centuries: Interocean teleconnections

Miguel A. Goni,[1] Robert C. Thunell,[2] Mark P. Woodwort,[2] and Frank E. Müller-Karger[3]

Received 25 March 2006; revised 9 June 2006; accepted 13 June 2006; published 8 August 2006.

[1] Analysis of sediments from two wind-driven upwelling systems, Guaymas and Cariaco basins, using the alkenone-based $U_{37}^{K'}$ paleothermometer yielded high-resolution records of sea surface temperatures (SST) from 1700 to 2000 AD. The trends in the $U_{37}^{K'}$ index reveal steady SST increases of 1 to 2°C at both sites since the end of the Little Ice Age. Higher-frequency changes in SST indicate a decoupling in the relative intensity of wind-driven upwelling at the two sites. Periods of enhanced upwelling in Guaymas correspond to periods of decreased upwelling in Cariaco (and vice versa). We propose that these contrasts reflect regional differences in the upwelling response of upwelling to changes in the positioning of the Inter-Tropical Convergence Zone (ITCZ) and the Subtropical High (SH) under current climate conditions. **Citation:** Goni, M. A., R. C. Thunell, M. P. Woodwort, and F. E. Müller-Karger (2006), Changes in wind-driven upwelling during the last three centuries: Interocean teleconnections, *Geophys. Res. Lett.*, *33*, L15604, doi:10.1029/2006GL026415.

1. Introduction

[2] Wind-driven coastal upwelling is a common feature of many ocean margins. The physical connection between wind and upwelling occurs through Ekman transport, which is responsible for the transport of deep, nutrient rich waters to the surface. Upwelling directly impacts primary and secondary production, which in turn controls carbon export from the euphotic zone, CO_2 exchange between the atmosphere and ocean, and carbon sequestration in the ocean interior. Global climate phenomena such as El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO) have significant influence on both ocean and atmospheric circulation [e.g., *Biondi et al.*, 2001; *Enfield and Mestas-Nunez*, 1999]. However, the manner in which different ocean margins respond to changes in atmospheric circulation is in a large part related to their location relative to prevailing wind fields. Hence, the response of different wind-driven upwelling systems to climate change may be quite distinct, with atmospheric circulation providing the common forcing mechanism (i.e., '*teleconnection*').

[3] In this study, we investigated the recent history of SST conditions in two upwelling systems, Guaymas Basin (GB) in the Gulf of California and Cariaco Basin (CB) off the northern coast of Venezuela, using the alkenone-based $U_{37}^{K'}$ paleothermometer. Both of these systems undergo marked seasonal changes in SST of 6–12°C that are associated with wind-driven upwelling and thermal stratification cycles. Most significantly for paleoclimatic reconstructions, both GB and CB contain suboxic to anoxic waters that result in the deposition of undisturbed, varved sediments.

2. Seasonal Cycle of Upwelling-Stratification

[4] The present-day atmospheric forcing mechanisms controlling wind-driven upwelling at GB and CB are illustrated in Figure 1. During boreal winter, when northern hemisphere insolation is at its lowest, the SH over the eastern Pacific resides at its most southern position [*Cheshire et al.*, 2005; *Dean et al.*, 2004], while the ITCZ is located at or below the equator in both the Atlantic and Pacific Basins [*Chiang et al.*, 2002; *Poore et al.*, 2004]. Under these conditions, strong northwesterly winds dominate the Gulf of California, whereas strong and sustained easterly trade winds are prevalent along the northern Venezuelan coast. As a result, intense upwelling occurs in both of these regions during this period [e.g., *Astor et al.*, 2003; *Bray and Robles*, 1991], leading to large increases in the primary productivity of surface waters and associated maxima in the sinking fluxes of biogenic materials [*Müller-Karger et al.*, 2001; *Thunell*, 1998].

[5] During the boreal summer when northern hemisphere insolation is at its maximum, both the SH and the ITCZ move northward (Figure 1). The resulting atmospheric regime is one in which weak winds dominate the central and southern regions of the Gulf of California [*Parés-Sierra et al.*, 2003]. In the Caribbean, the northward migration of the ITCZ causes the trade winds to move into the Gulf of Mexico, so that weak winds prevail over the Venezuelan margin [*Astor et al.*, 2003]. Under these conditions, upwelling shuts down in both GB and CB, leading to the progressive warming and thermal stratification of the sea surface. Consequently, primary production and the export of biogenic materials from the euphotic zone undergo marked decreases in both regions. In terms of precipitation, southerly summer winds bring the onset of the North American monsoon to parts of northern Mexico and southwest USA [*Mitchell et al.*, 2002], while the northward migration of the ITCZ coincides with the rainy season over the Venezuelan coastal region [*Müller-Karger et al.*, 2001].

[6] Time series records of SST for GB and CB illustrate the closely coupled annual upwelling-stratification cycles at these two sites (Figure 2). In both regions, upwelling starts in early winter (November–December) and is characterized

[1]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[2]Department of Geological Sciences, University of South Carolina, Columbia, South Carolina, USA.
[3]Department of Marine Science, University of South Florida, St. Petersburg, Florida, USA.

0094-8276/06/2006GL026415$05.00

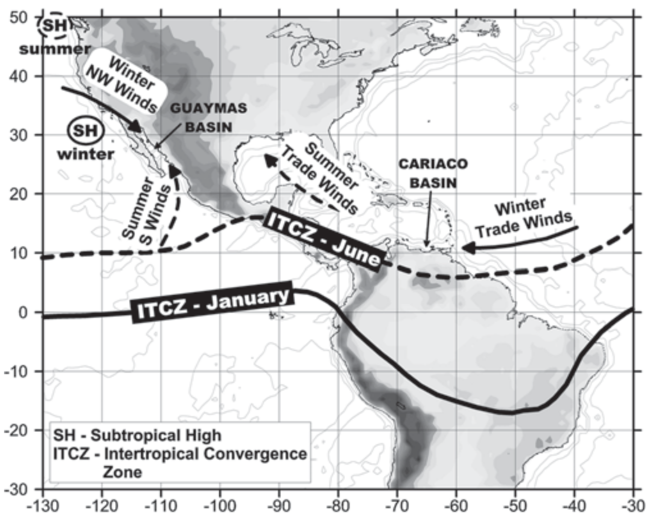

Figure 1. Map showing the location of the ITCZ and SH during the boreal winter and summer relative to the locations of Guaymas and Cariaco Basins. Also shown are the generalized paths of the prevailing winds during Northern Hemisphere winter and summer. Adapted from *Poore et al.* [2004] and *Cheshire et al.* [2005].

by a rapid decrease in SST as colder, nutrient–rich subsurface waters are brought to the surface due to the wind-driven displacement of surface waters. Upwelling in both GB and CB ends in spring (April–May), when upwelling-favorable winds subside due to the northward migration of the SH and ITCZ. Once upwelling ceases, thermal stratification starts to build up during late spring and early summer, with SST's increasing steadily and reaching maxima in late summer (July–September).

3. Alkenone SST Reconstructions

[7] Haptophyte algae, including the coccolithophore *Emiliania huxleyi*, are major producers of a suite of long-chain unsaturated ketones called alkenones [*Volkman et al.*, 1980]. These ubiquitous algae alter the degree of unsaturation of individual ketones (quantified by the $U_{37}^{K'}$ index), as a physiological response to changes in the temperature of the surrounding water [*Prahl et al.*, 1988]. Alkenone analyses of sediment trap samples collected from both GB and CB show that the seasonal changes in SST cycles driven by coastal upwelling-stratification phenomena (Figure 2) are accurately recorded in the $U_{37}^{K'}$ index of particles sinking from the euphotic zone [*Goni et al.*, 2001, 2004]. Specifically, we saw no evidence for seasonal biases related to inter-annual variability in the sinking fluxes of alkenone producers. Furthermore, the observed relationship is consistent with the widely used SST-$U_{37}^{K'}$ laboratory-based calibration equation [*Prahl et al.*, 1988], which has been proven to agree with ocean-wide field calibrations [e.g., *Müller et al.*, 1998]. Our work shows that the $U_{37}^{K'}$ signal preserved in seafloor sediments from GB and CB can be used to accurately reconstruct variations in the mean annual temperature of the overlying water column, which at both of these sites is directly related to variations in wind-driven upwelling intensity.

[8] We analyzed sediments from box cores collected in GB and CB to produce high-resolution records of SST from 1700 to 2000 AD (Figure 3). Both cores are varved throughout their entire length and their age models, which are based on ^{210}Pb and ^{14}C AMS chronologies, are consistent with average accumulation rates of ~1.1 mm/y at both sites [*Goni et al.*, 2001, 2004]. Given the 0.5 cm sample intervals analyzed, the temporal resolution of these records is about 5 years. The trends in the $U_{37}^{K'}$ index reveal general increases in SST of 1 to 2°C at both sites over the last 300 years, in association with the end of the Little Ice Age. In addition to this long-term trend, higher-frequency (~50 years) changes in SST that range from 1–3°C are also evident in both records. For example, in GB, the SST record shows an increase of over 1°C from 1750 to 1800 while a similar magnitude decrease in SST is evident from ca. 1950 to 2000. In CB, 1 to 2°C changes in SST also are observed over the last two centuries. We suggest that these decadal changes in SST reflect variability in the intensity of wind-driven upwelling at these sites. Most interestingly, there is a marked difference in the timing of the SST variations between the two basins so that periods of enhanced upwelling in GB are characterized by decreased upwelling in CB (and vice versa).

4. Discussion and Conclusions

[9] In order to better quantify contrasts in upwelling between the two basins, we reconstructed the SST records at both sites with similar temporal resolution using two different approaches. First, we calculated SST averages for each decade (starting from 1721 to 1730) at both sites using a box-bin approach. Secondly, we used Gaussian filter over 20 year intervals to estimate a 5-year SST averages at both sites for the same dates (staring on 1727). We then calculated the SST difference (Δ $U_{37}^{K'}$SST) between GB and CB by subtracting their respective reconstructed records (Figure 4). In the resulting graph, negative Δ $U_{37}^{K'}$SST excursions indicate conditions of enhanced upwelling in

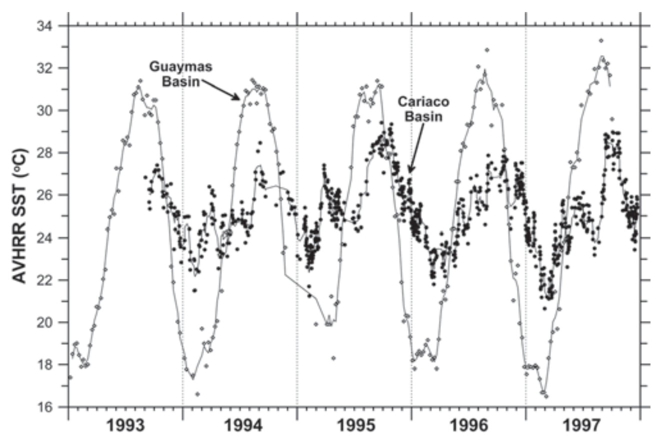

Figure 2. Records of satellite derived SST for Guaymas and Cariaco Basins illustrating the annual upwelling-stratification cycle at both locations. The line for Guaymas Basin corresponds to a 3-point running average, while the line for the Cariaco Basin is a 5-point running average. Data are from *Goni et al.* [2001, 2004].

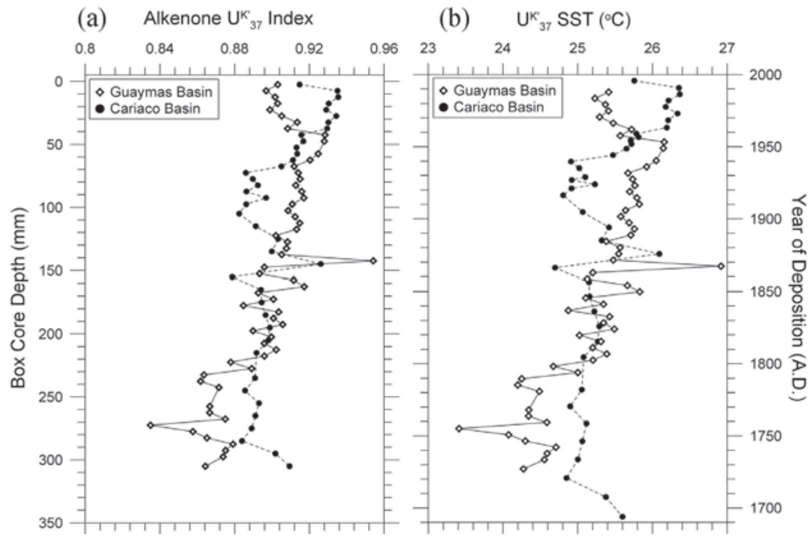

Figure 3. Sedimentary records of (a) alkenone-derived $U_{37}^{K'}$ index and (b) alkenone-derived SST values from box cores collected in Guaymas and Cariaco Basins. The $U_{37}^{K'}$ index was calculated from the concentrations of the di- and tri-unsaturated methyl C_{37} ketones. The alkenone derived SST was calculated from the $U_{37}^{K'}$ index according to *Prahl et al.* [1988].

GB relative to CB, whereas positive excursions are consistent with more intense upwelling over CB than in GB. We propose that the decoupling in the SST records from GB and CB reflects differences in the response of wind-driven upwelling to changes in the relative position of the SH over the eastern Pacific and the ITCZ over the western Atlantic. Thus, for example, during the last 50 years, the wind circulation pattern appears to have been conducive to enhanced upwelling in GB relative to CB, while the opposite appears to be the case for the period between ca. 1900 and 1950.

[10] The connection between the two upwelling systems is consistent with previous observations of multi-decadal (50 to 60 year) cycles in other proxies, such as the deposition of diatoms mats in GB [*Pike and Kemp*, 1997], sediment laminations in lake sediments [*Anderson*, 1992], tree rings in the western USA [*Meko*, 1992], coral records from CB [*Reuer et al.*, 2003] and sardine and anchovy populations in the eastern Pacific [*Baumgartner et al.*, 1992]. Analyses of non-ENSO periodicities reveal global SST anomalies since the mid 1800's that have similar frequencies (40–50 years) [*Enfield and Mestas-Nunez*, 1999]. This periodicity roughly coincides with the 57-year sunspot cycle [*Berger et al.*, 1990] and the ~50 year cycles in coronal mass ejections [*Anderson*, 1992], both of which are tied to changes in solar insolation. Other climate phenomena, such as PDO and NAO, do not display such half-century periodicity. Given the temporal resolution of our samples, inter-annual variability in ENSO events are unlikely to be responsible for the observed trends.

[11] We speculate that multi-decadal changes in solar insolation may have caused slight shifts in the positions of SH and ITCZ under post-LIA climatic conditions, providing a mechanism for the contrasts in upwelling intensity between GB and CB recorded in the alkenone SST reconstructions. For example, during the last 300 years, periods of enhanced solar insolation would have resulted in the northward migration of SH, thus enhancing the efficiency of NW winds and

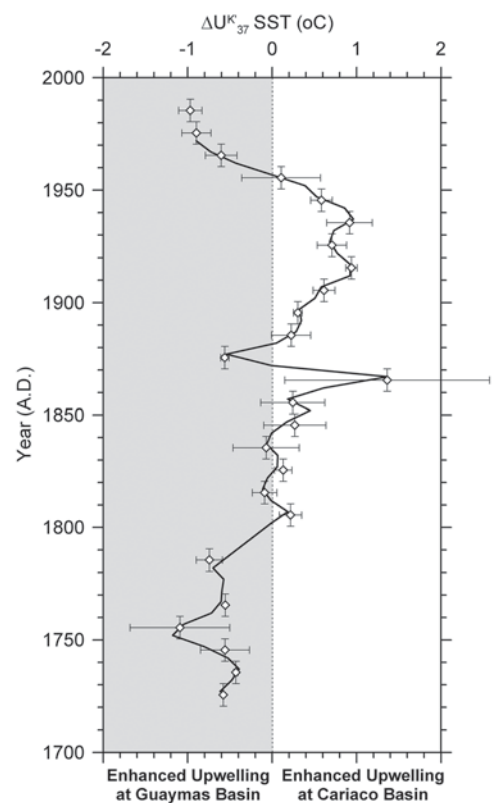

Figure 4. Record of the differences in alkenone-based SST between Guay mas and Cariaco Basins between 1700 and 2000 AD. The differences in SST (Δ $U_{37}^{K'}$ SST) were calculated using both decadal box-bin averages (open diamonds) and Gaussian 5-year averages (thick line; see text for details). The error bars illustrate the standard deviation associated with the box-bin calculations.

increasing upwelling in GB. At the same time, the northward movement of the ITCZ would have caused a northward shift in trade winds, decreasing upwelling intensity in CB. In contrast, during periods of lower solar insolation, the southward migration of the SH and ITCZ would diminish the wind-driven upwelling in GB and increase trade wind-related upwelling in CB.

[12] Historical changes in solar insolation and their effect on the relative positions of the SH and ITCZ are thought to have played a key role in determining the past upwelling regime in GB and CB over glacial-interglacial scales [e.g., *Barron et al.*, 2005; *Black et al.*, 2004; *Cheshire et al.*, 2005; *Haug et al.*, 2001]. The data presented in this paper suggest that a similar mechanism may have led to variability in wind-driven upwelling at these sites during the past 300 years. Such changes likely had significant consequences for the ecology and biogeochemistry of these regions. Additional proxies for upwelling intensity are needed to evaluate the effects and extent of the proposed atmospheric teleconnection between upwelling systems in the eastern Pacific and tropical western Atlantic. Comparative studies with terrestrial records should also be carried out to evaluate the effect of this atmosphere-ocean coupling on moisture transport and precipitation in these regions of South and North America.

[13] **Acknowledgments.** We thank D. Hartz, H. Aceves, E. Tappa and D. Black for their help in analyses and interpretation of the sedimentary records. Funding of this work was provided by NSF grants OCE-0540793, OCE-0315234, OCE-0326313 and OCE-0118349. This paper benefited from comments by two anonymous reviewers. N. Pisias provided invaluable help in performing the Gaussian averaging presented in Figure 4.

References

Anderson, R. Y. (1992), Possible connection between surface winds, solar activity and the Earth's magnetic field, *Nature*, *358*, 51–53.

Astor, Y., F. Muller-Karger, and M. I. Scranton (2003), Seasonal and interannual variation in the hydrography of the Cariaco Basin: Implications for basin ventilation, *Cont. Shelf Res.*, *23*, 125–144.

Barron, J. A., D. Bukry, and W. E. Dean (2005), Paleoceanographic history of the Guaymas Basin, Gulf of California, during the past 15,000 years based on diatoms, silicoflagellates, and biogenic sediments, *Mar. Micropaleontol.*, *56*, 81–102.

Baumgartner, T. R., A. Soutar, and V. Ferreira-Bartrina (1992), Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments in the Santa Barbara Basin, California, *Rep. 33*, pp. 24–40, Calif. Coop. Oceanic Fish. Invest., La Jolla, Calif.

Berger, A., J. L. Melice, and L. van der Mersch (1990), Evolutive spectral analysis of sunspot data over the past 3000 years, in *The Earth's Climate and Variability of the Sun Over Recent Millennia*, edited by J. C. Pecker and S. K. Runcorn, pp. 529–541, R. Soc., London.

Biondi, F., A. Gershunov, and D. R. Cayan (2001), North Pacific decadal climate variability since 1661, *J. Clim.*, *14*, 5–10.

Black, D. E., R. C. Thunell, A. Kaplan, L. C. Peterson, and E. J. Tappa (2004), A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability, *Paleoceanography*, *19*, PA2022, doi:10.1029/2003PA000982.

Bray, N., and J. M. Robles (1991), Physical oceanography of the Gulf of California, in *The Gulf and Peninsular Province of California*, edited by J. P. Dauphin and B. R. Simoneit, *AAPG Mem.*, *47*, 511–553.

Cheshire, H., J. Thurow, and A. Nederbragt (2005), Late quaternary climate change record from two long sediment cores from Guaymas Basin, Gulf of California, *J. Quat. Sci.*, *20*, 457–469.

Chiang, J. C. H., Y. Kushnir, and A. Giannini (2002), Deconstructing Atlantic Intertropical Convergence Zone variability: Influence of the local cross-equatorial sea surface temperature gradient and remote forcing from the eastern equatorial Pacific, *J. Geophys. Res.*, *107*(D1), 4004, doi:10.1029/2000JD000307.

Dean, W., C. Pride, and R. Thunell (2004), Geochemical cycles in sediments deposited on the slopes of the Guaymas and Carmen basins of the Gulf of California over the last 180 years, *Quat. Sci. Rev.*, *23*, 1817–1833.

Enfield, D. B., and A. M. Mestas-Nunez (1999), Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns, *J. Clim.*, *12*, 2719–2733.

Goni, M. A., D. M. Hartz, R. C. Thunell, and E. Tappa (2001), Oceanographic considerations for the application of the alkenone-based paleotemperature UK′37 index in the Gulf of California, *Geochim. Cosmochim. Acta*, *65*, 545–557.

Goni, M. A., M. P. Woodworth, H. L. Aceves, R. C. Thunell, E. Tappa, D. Black, F. Müller-Karger, Y. Astor, and R. Varela (2004), Generation, transport, and preservation of the alkenone-based $U_{37}^{K'}$ sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela), *Global Biogeochem. Cycles*, *18*, GB2001, doi:10.1029/2003GB002132.

Haug, G., K. Hughen, D. Sigman, L. Peterson, and U. Rohl (2001), Southward migration of the intertropical convergence zone through the Holocene, *Science*, *293*, 1304–1308.

Meko, D. M. (1992), Spectral properties of tree-ring data in the United States Southwest as related to El Nino/Southern Oscillation, in *El Nino: Historical and Paleoclimatic Aspects of the Southern Oscillation*, edited by H. F. Diaz and V. Markgraf, pp. 227–242, Cambridge Univ. Press, New York.

Mitchell, D. L., D. Ivanova, R. Rabin, T. J. Brown, and K. Redmond (2002), Gulf of California sea surface temperatures and the North American monsoon: Mechanistic implications from observations, *J. Clim.*, *15*, 2261–2281.

Müller, P. J., G. Kirst, G. Ruhland, V. I. Storch, and A. Rosell-Melé (1998), Calibration of the alkenones paleotemperature index UK′37 based on core-tops from the eastern South Atlantic and the global ocean (60°N–60°S), *Geochim. Cosmochim. Acta*, *62*, 1757–1772.

Müller-Karger, F., et al. (2001), Annual cycle of primary production in the Cariaco Basin: Response to upwelling and implications for vertical export, *J. Geophys. Res.*, *106*, 4527–4542.

Parés-Sierra, A., A. Mascarenhas, S. G. Marinone, and R. Castro (2003), Temporal and spatial variation of the surface winds in the Gulf of California, *Geophys. Res. Lett.*, *30*(6), 1312, doi:10.1029/2002GL016716.

Pike, J., and A. E. S. Kemp (1997), Early Holocene decadal-scale ocean variability recorded in Gulf of California laminated sediments, *Paleoceanography*, *12*, 227–238.

Poore, R. Z., T. M. Quinn, and S. Verardo (2004), Century-scale movement of the Atlantic Intertropical Convergence Zone linked to solar variability, *Geophys. Res. Lett.*, *31*, L12214, doi:10.1029/2004GL019940.

Prahl, F. G., L. A. Muelhausen, and D. A. Zahnle (1988), Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions, *Geochim. Cosmochim. Acta*, *52*, 2303–2310.

Reuer, M. K., E. A. Boyle, and J. E. Cole (2003), A mid-twentieth century reduction in tropical upwelling inferred from coraline trace element proxies, *Earth Planet. Sci. Lett.*, *210*, 437–452.

Thunell, R. C. (1998), Seasonal and annual variability in particle fluxes in the Gulf of California: A response to climate forcing, *Deep Sea Res., Part I*, *45*, 2059–2083.

Volkman, J. K., G. Eglinton, E. D. S. Corner, and T. E. V. Forsberg (1980), Long-chain alkenes and alkenones in the marine coccolithophorids *Emiliania huxleyi*, *Phytochemistry*, *19*, 2619–2622.

M. A. Goni, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA. (mgoni@coas.oregonstate.edu)

F. E. Müller-Karger, Department of Marine Science, University of South Florida, St. Petersburg, FL 33701, USA.

R. C. Thunell and M. P. Woodwort, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA.