Scientists aboard R/V *Atlantis II* during a 1990 cruise deploy a sediment trap mooring in Guaymas Basin.

Continental Margin Particle Flux

Seasonal Cycles and Archives of Global Change

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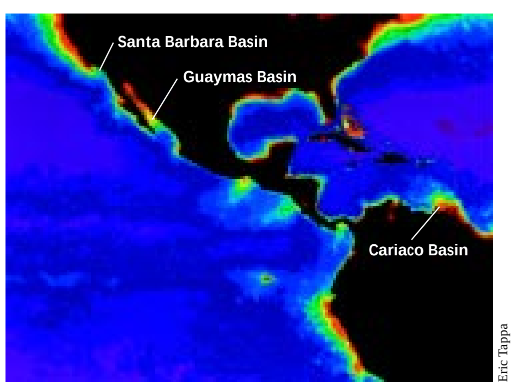
The boundaries between the oceans and the continents are dynamic regions for the production, recycling, and deposition of sedimentary particles. In general, rates of biological productivity along continental margins are significantly higher than in the open ocean. This is due to a variety of factors including coastal upwelling of nutrient-rich waters and nutrient input from continental runoff. While continental margins account for only about 10 percent of the global ocean area, 50 percent of the total marine organic carbon production is estimated to occur in this limited region, with much of it exported to the deep sea.

Despite the recognition that continental margins exert a strong influence on global biogeochemical cycles, there have been relatively few attempts to quantify either the magnitudes or nature of temporal variability in these regions' particle fluxes. In addition, the high sediment accumulation rates that characterize many continental margins make them ideal depositional settings for preserving high resolution records of past climate change.

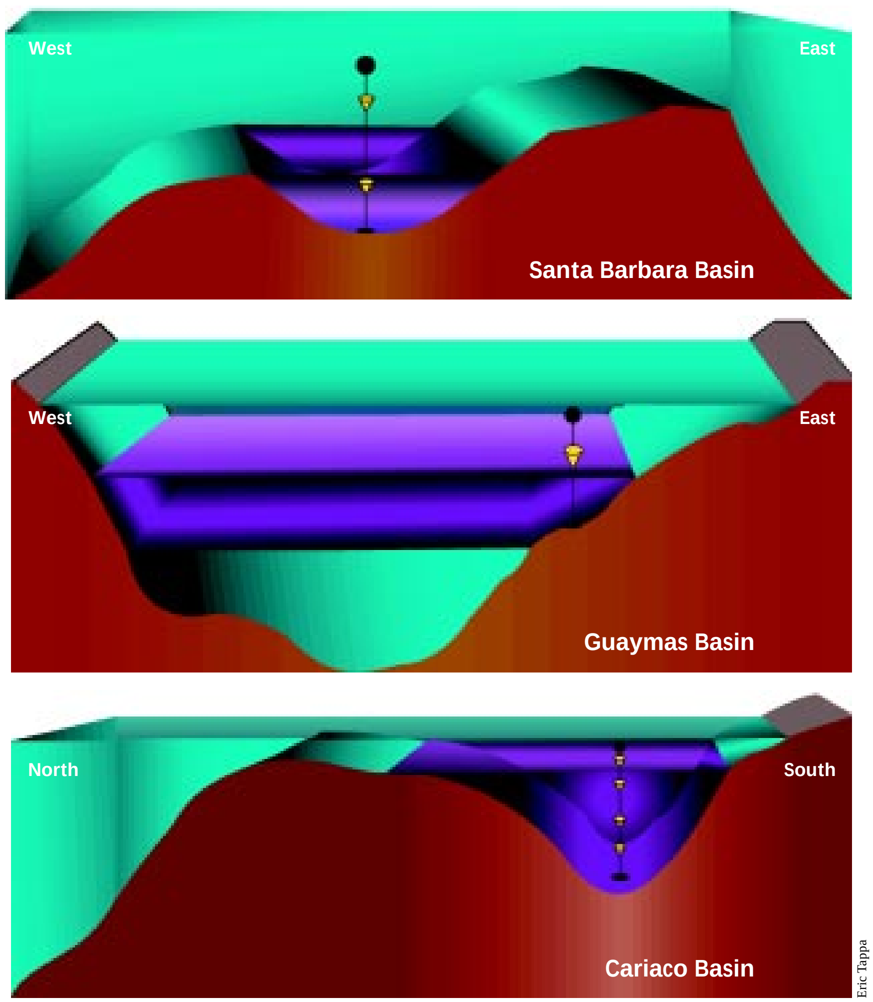


Composite surface ocean pigment concentration map derived from all Nimbus-7 Coastal Zone Color Scanner data acquired between November 1978 and June 1986. The pigment-rich coastal waters reflect the high productivity occurring in these regions and contrast sharply with conditions in much of the open ocean. The author's group is currently measuring particle fluxes in the three basins identified.

In the summer of 1990 my University of South Carolina colleagues (Eric Tappa, Carol Pride, Eileen Kincaid, and Kathy Tedesco) and I initiated the first of three time series sediment trapping programs designed to study particle fluxes in continental margin basins. The basins we selected for study include Santa Barbara Basin (offshore California), Guaymas Basin (Gulf of California), and Cariaco Basin (Venezuelan margin). All three field programs are currently ongoing, with the Guaymas Basin project now in its eighth year. The work in Cariaco Basin is part of a large international effort entitled CARIACO (CArbon Retention In A Colored Ocean) involving researchers from other US and Venezuelan institutions. At all three locations, we are fortunate to have local marine labs that provide much needed logistical and ship support. They are the Southern California Marine Institute (Los Angeles), Estacion de Investigaciones Marinas de Margarita (Isla de Margarita, Venezuela), and CIB (Guaymas, Mexico).

These basins share a number of common features. All three are sites of seasonal, wind-driven coastal upwelling and high primary productivity. Additionally, all three basins are marked by oxygen-depleted conditions (see figure). The Cariaco and Santa Barbara basins are separated from regions farther offshore by sills that isolate the deep waters in the basins and cause them to become anoxic. The situation in the Guaymas Basin is somewhat different, in that the oxygen-depleted waters occur in mid water column and are associated with Pacific Intermediate Water that flows into the Gulf of California at depths between 500 and 1,000 meters. In all three basins, sediments accumulate in clearly defined layers within the anoxic zones due to the absence of benthic organisms and the consequent lack of bioturbation. A pair of these "laminae," referred to as a varve and consisting of one dark layer and one light layer, represents a year of deposition in each basin. Such sediments serve as natural archives for studying annual- to decadal-scale changes in past climatic conditions.

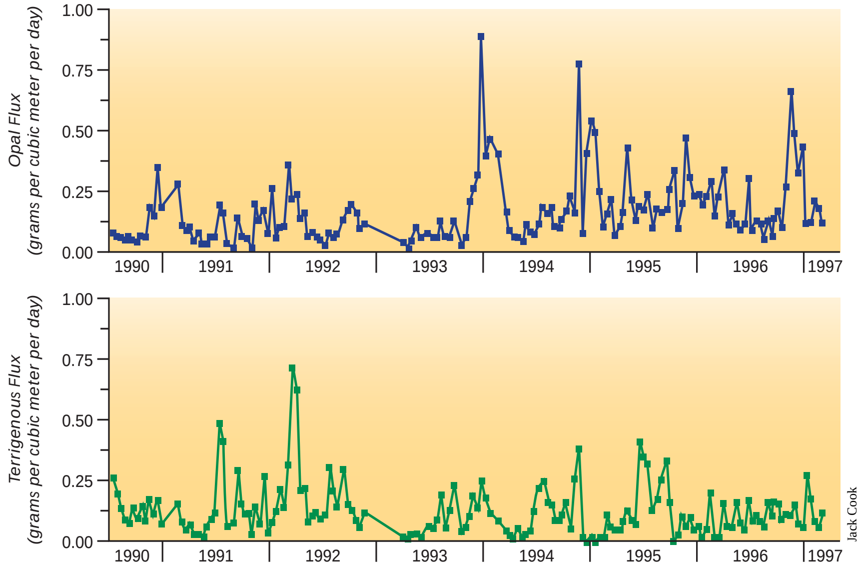
The basic objectives of the sediment trapping programs in all three basins are similar. First, we document seasonal to interannual changes in sediment fluxes and then relate this variability to changing hydrographic and climatic conditions. Second, we use the observed seasonal variability in the fluxes of different sediment types to develop models of varve formation for each basin. Finally, we identify and calibrate the best proxies for studying climate change in each basin and then apply these to sediment cores in order to reconstruct records of past climate change. In addition, for the Cariaco Basin study we are using an array of sediment traps placed throughout the water column to measure changes in carbon flux with depth. This allows us to evaluate whether anoxia results in enhanced preservation of organic matter.



Cross-sections of the Santa Barbara, Guaymas, and Cariaco Basins showing the configuration of the sediment trap moorings. The region of anoxic conditions in each basin is indicated by purple shading. It is beneath these oxygen-deficient zones that laminated sediments are preserved.

Changes in wind intensity and/or direction are the primary physical forcing mechanisms responsible for seasonal variability in the production and flux of sediments in all three locations. In Santa Barbara Basin the winds are predominantly from the north and are strongest during the spring and early summer, with the most intense upwelling of deep waters occurring during this period. Coastal upwelling in Cariaco Basin is associated with

Changes in the relative proportions of biogenic material and terrigenous material in the total sediment flux for Guaymas Basin. These seasonal changes in the composition of the sediment flux result in the deposition of laminae on the seafloor. The high flux of biogenic material from late fall through spring produces the light laminae. In contrast, dark laminae form during the summer when the sediment flux carries high concentrations of terrigenous material.

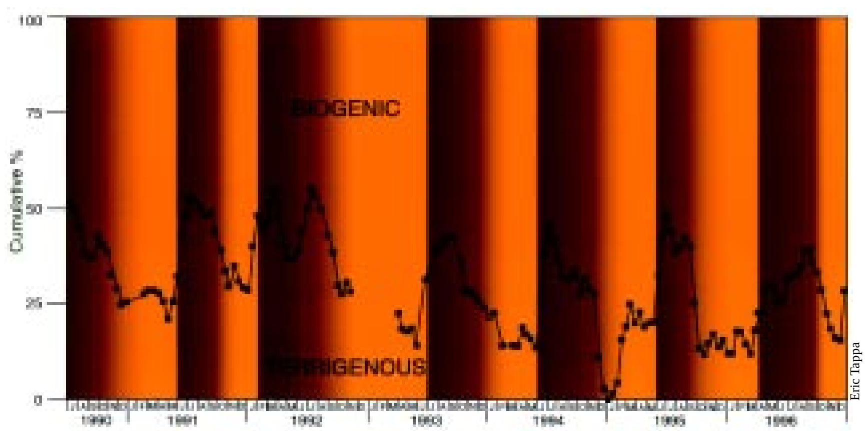


seasonal changes in the position of the Intertropical Convergence Zone (ITCZ) and the strength of the Trade Winds. In the winter and spring, the ITCZ is in its most southerly position, close to the equator, resulting in strong easterly winds and upwelling along the Venezuelan coast. The Gulf of California usually experiences a seasonal change in wind direction in November, when there is a reversal from southerly to northerly winds, causing upwelling and high productivity from late fall to spring.

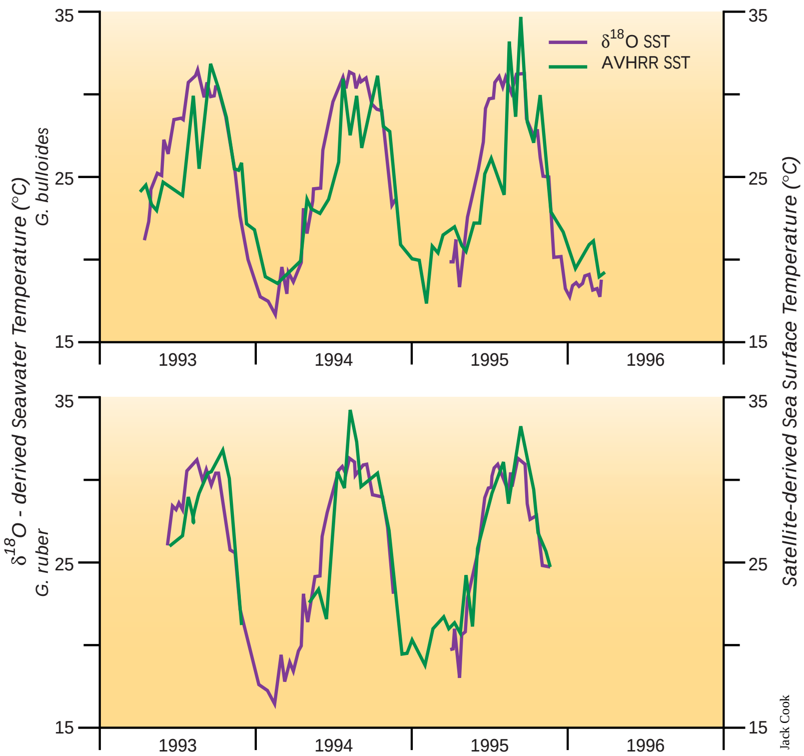
I use our results from the Guaymas Basin to illustrate the relationship between seasonal changes in sediment fluxes and climate forcing. First, it should be pointed out that diatoms are the dominant group of plankton in the Guaymas Basin. Since these organisms produce shells made of opaline silica, this is the most abundant biologically produced sediment in the region. The other major component of the total sediment flux in Guaymas Basin is terrigenous material delivered to the basin from surrounding land masses. Together, opal and terrigenous material account for about 75 percent of the total particle flux in Guaymas Basin. The flux time series for these two sediment types for the period July 1990 through December 1996 reveals distinctive, recurring seasonal patterns (see figure). Each year there is a rapid increase in opal flux in late fall, in direct response to the switch to northerly winds. These winds cause nutrients to be mixed to the surface, and a diatom bloom results. In contrast, the highest fluxes of terrigenous material tend to occur during the summer rainy season. According to Tim Baumgartner (Scripps Institution of Oceanography), most of this material comes from the Sonoran Desert and is atmospherically transported to the basin during thunderstorms.

The six-year time series also displays some interannual variability. For example, opal fluxes from late fall 1991 to spring 1992 are not nearly as high as those recorded for the same time period in subsequent years. Shortly after we began the Guaymas Basin project in summer 1990, El Niño conditions developed in the eastern Pacific and reached their peak in late 1991/early 1992. During El Niño events the strength of the northerly winds blowing down the Gulf of California is diminished and unusually warm equatorial Pacific surface waters migrate northward into the gulf. These conditions suppress mixing of the surface layer and result in lower than normal diatom production.

The alternating light and dark laminae accumulating in all three basins result from seasonal changes in the composition of the material being delivered to the seafloor. Our Guaymas Basin time series clearly illustrates these seasonal changes in basic sediment type as well as how we envision this variability translates into the formation of sediment laminae (see figure). The light laminae, which consist mostly of low density plankton remains, particularly diatoms, are deposited during times of upwelling and high productivity. In Guaymas and Cariaco Basins, the light laminae form from winter to spring, while in Santa Barbara Basin these units represent deposition during the spring and summer. The dark laminae are denser and consist mostly of terrigenous material transported to each of the basins during their rainy seasons—winter in



Biogenic opal (light) and terrigenous material (dark) flux records from Guaymas Basin for the period July 1990 through March 1997 reflect seasonal and interannual changes in climatic conditions. The high opal fluxes are generally associated with the late fall to early spring period of high primary productivity, while terrigenous fluxes are usually high during the summer rainy season.



A comparison of satellite measured sea surface temperatures for Guaymas Basin and temperatures estimated from the oxygen isotopic composition of two species of planktonic foraminifera, *Globigerina bulloides* and *Globigerinoides ruber* collected in sediment traps. The good agreement between the observed and estimated temperatures indicates that the oxygen isotopic composition of shells of these species of foraminifera preserved in the sediments can be used to estimate past sea surface temperatures in the Gulf of California.

the Santa Barbara region and summer in both Guaymas and Cariaco Basins. Thus, each of these layers contains clues about prevailing climate conditions during different times of the year in each of these regions.

Our challenge is to develop the best tools for extracting this climate information from the sediment record. These include biotic, geochemical, and sedimentological proxies of different ocean properties. For example, besides diatoms, other groups of plankton produce shells that accumulate on the seafloor. One such group, the planktonic foraminifera, secrete calcium carbonate shells and have been used extensively to reconstruct paleoclimate conditions. Carol Pride from the University of South Carolina has been studying several species of planktonic foraminifera collected in our Gulf of California sediment traps in an effort to determine how well the oxygen isotopic composition of their shells records the water temperature at the time of their growth. She has found that the isotopic composition of two species, *Globigerina bulloides* and *Globigerinoides ruber*, accurately records sea surface temperature changes in Guaymas Basin (**see figure**). With this observation, we now have a tool for deciphering the past history of sea surface temperature changes in the Gulf of California.

It is now widely recognized that these anoxic, continental margin basins provide high resolution climate records that are unequaled in the marine realm. The recent work of Konrad Hughen (University of Colorado) on Cariaco Basin sediments provides an excellent example of the high resolution records that can be obtained from laminated sediments. By measuring the thickness of individual light lamina and using this as a proxy for past changes in productivity, Hughen and colleagues were able to relate annual- to decadal-scale variability in productivity in Cariaco Basin to changing climate conditions during the last deglaciation. Finally, in the last several years, the Ocean Drilling Program has cored both the Santa Barbara Basin and the Cariaco Basin, and many researchers are actively studying the climate histories preserved in these sediment records.

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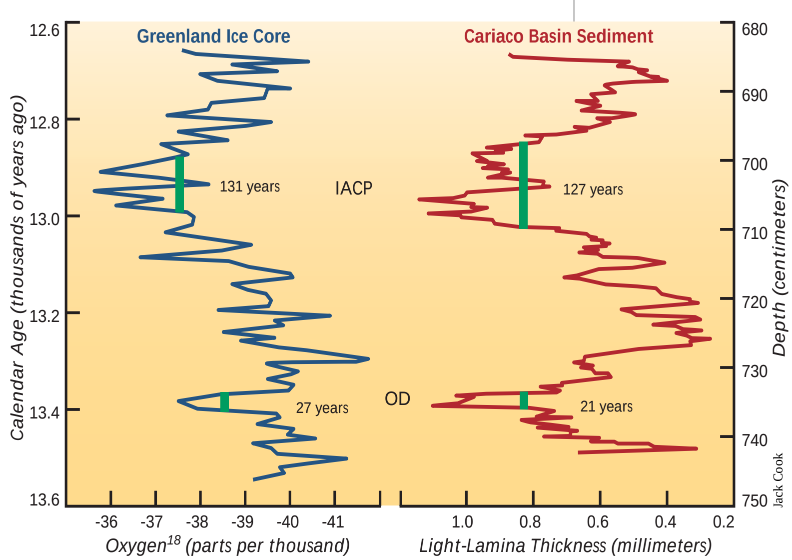
Bob Thunell has served as Chair of the University of South Carolina Department of Geological Sciences for the past nine years. His first foray into the sediment trap/particle flux game came in 1978 when he was a postdoctoral scholar at WHOI and had the good fortune to work with Sus Honjo. Since moving to South Carolina in 1979, Bob has become an avid Gamecock fan and makes sure to schedule his cruises so they don't interfere with football games. In his "spare time," Bob runs a taxi service that transports his three sons to soccer tournaments, basketball games, and swim meets.



Comparison of a Greenland ice core oxygen isotope record and a record of the thickness of light laminae in a Cariaco Basin sediment core for the period 13,600 to 12,600 years ago. The oxygen isotope record provides information on changes in atmospheric temperature over Greenland, while the light-lamina thickness is a function of changes in productivity along the Venezuelan continental margin. The pattern of change on both records is very similar, with high productivity (thicker light laminae) occurring during periods of climatic cooling (lower oxygen isotope values).