

## Climatically driven changes in oceanic processes throughout the equatorial Pacific

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[1] The mass accumulation rates of sedimentary components (carbonate, organic carbon, opal, barite, reactive phosphate, iron, terrigenous minerals, etc.) are used in many paleoceanographic reconstructions to learn about temporal and spatial changes in surficial Earth processes including wind stress and direction, oceanic circulation, weathering rates, marine productivity and ecosystem structure, climate change, and more. In most studies it is assumed/desired that the sediment accumulation represents the production and deposition of particles from the overlying water column since substantial horizontal transport imply homogenization of paleoceanographic proxies and little confidence in any paleoceanographic time series. In this note we highlight some discrepancies between the different approaches used to reconstruct sediment mass accumulation rates and specifically discuss the consequences of these discrepancies to the reconstruction of paleoproductivity in the equatorial Pacific. We pose research questions and suggest possible approaches/research strategies for the community to solve them. *INDEX TERMS:* 4267 Oceanography: General: Paleooceanography; 4558 Oceanography: Physical: Sediment transport; 4863 Oceanography: Biological and Chemical: Sedimentation; *KEYWORDS:* paleoproductivity, sediment focusing, equatorial Pacific

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[2] The equatorial Pacific, an area with relatively high biological productivity, plays an important role in the global carbon cycle [Chavez and Barber, 1987; barber and Chavez, 1987; Mix, 1989; Murray et al., 1994; Archer and Maier-Reimer, 1994; Cane, 1998]. Changes in the strength of the biological pump (e.g., carbon export to depth ( $C_{\text{export}}$ )) may affect the climate system by modulating  $\text{CO}_2$  fluxes between the ocean and atmosphere [Broecker, 1982; Berger et al., 1989; Hansell et al., 1997]. In order to better understand the role of the biological pump in the equatorial Pacific and delineate the relationship between  $C_{\text{export}}$  and climate, better constraints on fluctuations in  $C_{\text{export}}$  must be established. Indeed, since the early days of modern oceanography efforts were concentrated on reconstructing past changes in  $C_{\text{export}}$  in this oceanic area [Arrhenius, 1952; Goldberg and Arrhenius, 1958; Hays et al., 1969].

[3] A wide range of proxies have been used over the years including accumulation rates of sedimentary components related directly or indirectly to  $C_{\text{export}}$  such as organic matter, calcium carbonate, opal, barite or excess Ba [Muller and Suess, 1979; Muller et al., 1983; Calvert, 1987; Sarnthein et al., 1988; Pedersen, 1983; Pedersen et al.,

1988, 1991; Mix, 1989; Berger et al., 1989; Mix, 1989; Lyle et al., 1988, 1992, 2002; Isern, 1991; Rea et al., 1991; Herguera, 1992; Kemp et al., 1995; Snoeckx, 1995; Snoeckx and Rea, 1994; Leinen et al., 1986; Yang et al., 1995; Paytan et al., 1996a; Farrell et al., 1995; Piasias and Mix, 1997; de Garidel-Thoron et al., 2001]; changes in foraminiferal or diatom assemblages [Herguera and Berger, 1991, 1994; Herguera, 2000; Mix et al., 1999; Loubere, 1999, 2000, 2002; Schrader and Sorknes, 1990]; elemental ratios that relate to particle flux such as Al/Ti,  $^{10}\text{Be}/^{230}\text{Th}$  and  $^{231}\text{Pa}/^{230}\text{Th}$  [Murray et al., 1993, 1995, 2000; Bacon, 1988; Anderson et al., 1983, 1990; Lao et al., 1993] and other proxies [Perks and Keeling, 1998; Stoll and Schrag, 2000]. Accurate interpretation of these records is complex due to the fact that each and every one of these proxies responds not only to changes in  $C_{\text{export}}$  but also to multiple other processes including variable preservation, organisms' response to environmental changes, delivery from multiple sources, changes in particle scavenging and in oceanic circulation, and other, not always well understood, parameters [Berger et al., 1989; Zahn et al., 1994].

[4] The prevailing view to emerge from studies of the changes in the accumulation rates of sedimentary components that respond to changes in biological productivity and  $C_{\text{export}}$  is that many sites in the equatorial Pacific, with the exception of the Peru Margin, [e.g., Schrader and Sorknes,

1990; Ganeshram et al., 2000; Loubere, 2002] experienced higher  $C_{\text{export}}$  during glacial times than during interglacials. Such calculations may, however, be a direct function of the bulk sediment accumulation if the sedimentation rates vary much more than the composition (e.g., %CaCO<sub>3</sub> or % organic C) [Middelburg et al., 1997]. Moreover, it is well known that the accumulation rate of sediment at any given place or time includes the vertical particle flux, which is related to contemporaneous surface water biological activity, as well as any lateral input of material either from other sites representing the same age or from predeposited older sediments that are being redistributed. Such sediment redistribution is common on continental slopes, seamount flanks, and in areas where strong, confined, bottom currents prevail, such as in the Southern Ocean [Heezen et al., 1966; Gross et al., 1988; Lao et al., 1993; Gustafsson et al., 1998; Biscaye et al., 1998; Hall and McCave, 2000]. Oceanic coring expeditions since at least the 1980s have tried to target areas of the seafloor that are away from topographic structures that could potentially deliver allochthonous sediments. In addition, paleoceanographers have used various methods in the past to identify and avoid coring sites overly impacted by sediment redistribution. Typically, there are geological-sedimentological indications for sediment redistribution (features characteristic of redeposition) such as evidence for sediment slumping, turbidity flow, grain size sorting, ripple marks, discontinuities in seismic reflectors, age disparity between different components of the sediment etc. [Potter and Pettijohn, 1977; McCave, 1983; McCave et al., 1995; Pearson et al., 2000; Ohkouchi et al., 2002; Mollenhauer et al., 2002]. In open-ocean deep-basin areas, such as those characterizing much of the deep equatorial Pacific seafloor, substantial sediment redistribution is unlikely to be prominent because of the sluggish bottom currents and relatively flat topography.

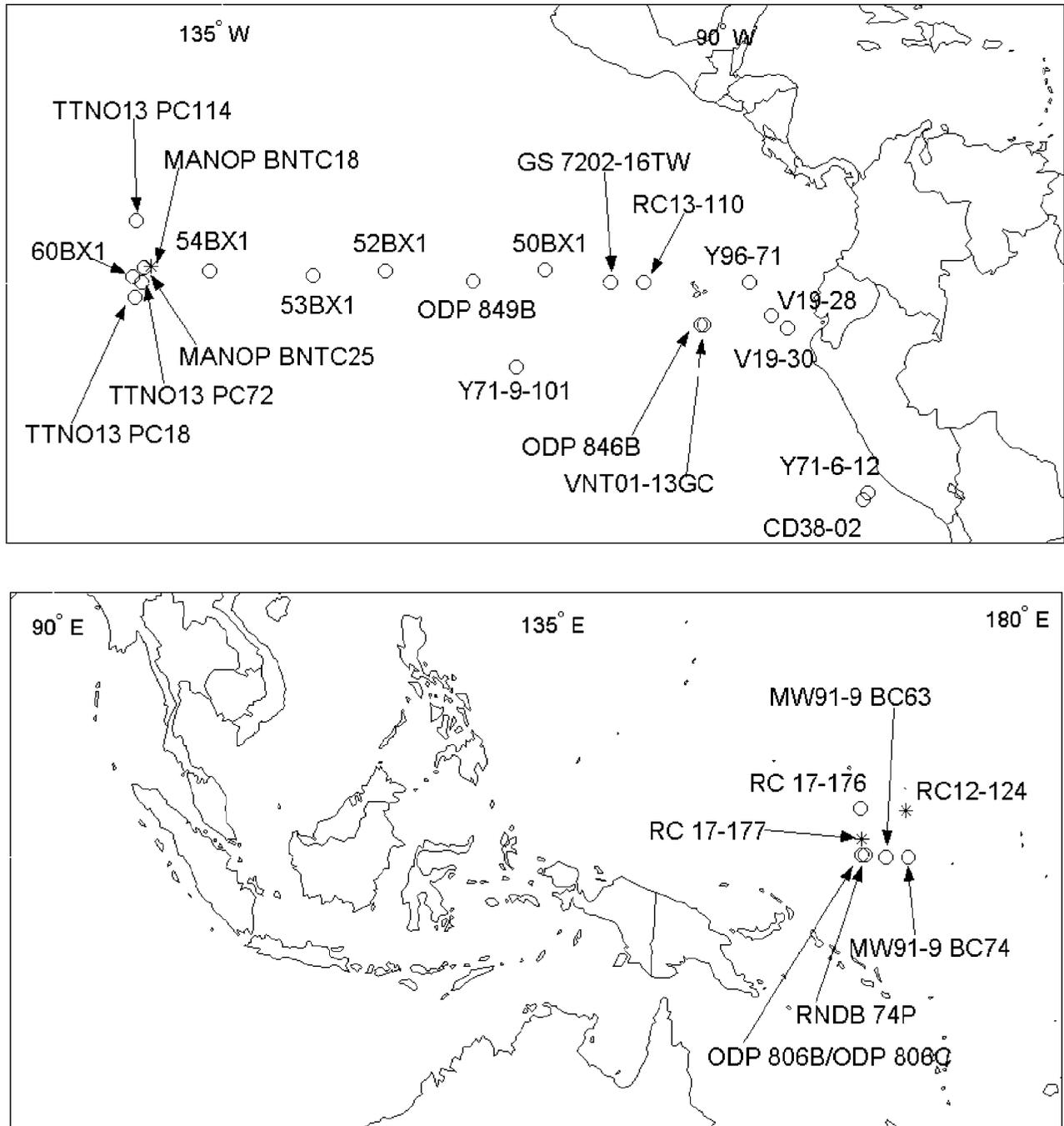
[5] To more rigorously account for the accumulation of sediments that are not deposited from the water column directly above, scientists have used tracers that are produced and delivered to the sediment at a constant rate, such as excess (i.e., scavenged) <sup>230</sup>Th [Bacon, 1984; Suman and Bacon, 1989; Francois et al., 1990] or <sup>3</sup>He [Marcantonio et al., 1995, 1996, 1999, 2001a]. The most important and fundamental requirement from such accumulation rate indicators is that at any given time and at any location their production in the water column (or delivery to the water column) and their transfer from the water column to the sediment is well-known and constant with time [Bacon, 1984; Farley, 1995].

[6] For <sup>230</sup>Th, the production rate is governed by the amount of dissolved uranium in the overlying water column, a parameter which is indeed known and constant. The transfer of <sup>230</sup>Th to the sediment relies on the highly particle-reactive nature of Th [Francois et al., 2004]. This value is less well-constrained than the production rate, but for the purposes of applying the <sup>230</sup>Th normalization procedure, it has been assumed to be equal to the production rate. Modeling efforts suggest this assumption is reasonable in most parts of the ocean, with deviations producing errors in flux of at most 30% [Henderson et al., 1999]. Indeed, excess <sup>230</sup>Th based sediment accumulation calculations

have been widely used to account for sediment redistributions in areas prone to such processes, like the Southern Ocean [Francois et al., 1993; Kumar et al., 1994; Frank et al., 1995, 1996; Dezileau et al., 2000; Fagel et al., 2002; Chase et al., 2003].

[7] The use of <sup>3</sup>He as a constant flux proxy relies on its presumed constant flux to the sediments from extraterrestrial particles. This proxy has been used less frequently than <sup>230</sup>Th mostly because only a few labs are currently capable of performing this analysis. There is also still some debate regarding the validity of the notion of constant extraterrestrial <sup>3</sup>He flux [Farley, 1995; Farley and Patterson, 1995; Patterson and Farley, 1998]. It is interesting that at some sites, where both <sup>230</sup>Th and <sup>3</sup>He were utilized simultaneously, these records yielded generally consistent accumulation rates despite their totally different source functions, which requires a mechanism that will simultaneously concentrate or dilute interplanetary dust particles and the particles responsible for Th adsorption in the water column [Marcantonio et al., 1995; Thomas et al., 2000]. At other sites however, some inconsistencies between accumulation rates derived from these two indicators has been observed, suggesting that the application of these tools could at times be more complex than realized [Marcantonio et al., 2001b].

[8] Recently, both <sup>230</sup>Th and <sup>3</sup>He have been applied to several sites in the equatorial Pacific that had not been suspected of sediment redistribution based on traditional site selection and sedimentary indicators (e.g., evidence for slumping, sorting, age anomalies, etc). Surprisingly, at all sites investigated so far (Figure 1, Table 1) the sediment accumulation rates calculated in the traditional manner, from linear sedimentation rates and sediment dry bulk densities, are significantly different than the accumulation rates based on excess <sup>230</sup>Th and/or <sup>3</sup>He normalization [Yang and Elderfield, 1990; Paytan et al., 1996a; Marcantonio et al., 1995, 1996, 2001a, 2001b; Schwarz et al., 1996; Stephens and Kadko, 1997; Higgins et al., 1999, 2002; Loubere et al., 2003, 2004]. In particular, while most of the sites investigated using traditional mass accumulation rate calculations or just sediment composition (wt % barite or organic C etc.) [Paytan et al., 1996a; Averyt and Paytan, 2004] indicate increased accumulation of various biologically related proxies (e.g., organic C, opal, CaCO<sub>3</sub> or barite) during glacial periods, when using <sup>230</sup>Th and/or <sup>3</sup>He normalized accumulation rates the signal disappears or even reverses (e.g., lower accumulations during glacial periods). The implication is that the fast rates of accumulation of biogenic material during glacials were driven not by fast rates of surface productivity and export, but rather by extensive lateral transport of sediment into the investigated sites during glacial periods (e.g., sediment focusing and redistribution). The majority of cores investigated reveal focusing factors (the ratio of measured <sup>230</sup>Th<sub>ex</sub> flux to the sediment to that expected from production in the water column) higher than 1 and in some cases focusing of up to 8 fold have been reported [Loubere et al., 2004]. A few sites of sediment winnowing have also been identified [Higgins et al., 2002] (Figures 1a–1b). The transported sediment must have been of the



**Figure 1.** Locations of cores in the (top) eastern equatorial Pacific and (bottom) western equatorial Pacific, where sediment focusing during glacial times has been implied from either  $^{230}\text{Th}$  or  $^3\text{He}$  data. Open circles are sites with focusing factors greater than 1, and stars are sites with focusing factors equal or less than 1. Data are from: *Yang and Elderfield* [1990], *Marcantonio et al.* [1996], *Schwarz et al.* [1996], *Higgins et al.* [1999], *Marcantonio et al.* [2001a], *Higgins et al.* [2002], and *Loubere et al.* [2003].

same age as the vertically accumulating sediment (e.g., syndepositional) since isotope-based age models do not identify deposition and mixture with significantly older material that would result in age anomalies (e.g., older than expected ages for glaci-als). Moreover, sedimentation rates obtained from bulk carbonate  $^{14}\text{C}$  and from excess

$^{226}\text{Ra}$  in barite (dominated by the fine fraction) are in good agreement with sedimentation rates based on foraminifera isotope analyses (coarse fraction) indicating that sediment redistribution, if it occurred, was of similar age distribution as the vertical sediment flux [*Pearson et al.*, 2000; *Ohkouchi et al.*, 2002].

**Table 1.** Comparison Between Sedimentation Rates Derived Using Different Methods and Assumptions at TTN013-PC72

Method Used	Holocene	Last Glacial	Reference
	Sedimentation Rate, cm/kyr	Sedimentation Rate, cm/kyr	
$^{14}\text{C}$ (bulk)	2.30	-	<i>Pope et al.</i> [1996]
$^4\text{C}$ (bulk)	3.41	-	<i>Murray and Leinen</i> [1996]
$\delta^{18}\text{O}$	2.30	3.10	<i>Paytan et al.</i> [1996a]
$\delta^{18}\text{O}$	2.45	3.11	<i>Murray et al.</i> [1995]
$^{226}\text{Ra}$	2.95	-	<i>Paytan et al.</i> [1996b]
$^{230}\text{Th}_{\text{ex}}$	1.06	1.21	<i>Marcantonio et al.</i> [1996]
$^3\text{He}$	0.95	1.67	<i>Marcantonio et al.</i> [1995]

[9] This observation challenges our conventional understanding of oceanic processes and thus hampers any potential interpretation of paleoproductivity (or any accumulation rate based records) for this region and possibly other, yet to be tested, oceanic regions. The widespread records of high accumulation of biogenic components during glacial times throughout the equatorial Pacific, at all depth scales and at horizontal scales that can exceed 1000 km (see list of references above), if explained by sediment focusing, imply that deep currents move huge amounts of sediment and selectively deposit it near the equator. One way to explain these observations is to invoke significant climatically driven changes in ocean circulation (either at mid water or deep water depths or both) that would induce extensive basin wide sediment focusing [Hall et al., 2001; Schwarz et al., 1996; Walsh et al., 1997]. What is the nature and origin of the climatically driven dramatic changes in deepwater circulation? Can we reconstruct these circulation changes? Are these circulation changes associated with changes in deepwater chemistry? Are there known climatically related mechanisms that will drive such circulation changes? What is the flow path and strength of such currents? Could these changes in circulation have had other consequences? Can coupled ocean-atmospheric circulation models reproduce these changes? It is very possible that sediment focusing and lateral transport from surrounding topographic heights to some of these sites (in particular those with very high focusing factors) has occurred but it is puzzling that this is evident at so many sites from different depths and that this phenomena is climatically related and does not involve at least at some sites major composition or size-dependent fractionation [Thomas et al., 2000; Averyt and Paytan, 2004].

[10] Alternatively, it may be that the processes that control  $^{230}\text{Th}$  and  $^3\text{He}$  flux and their relation to  $C_{\text{export}}$  have been different in past (in particular glacial) times. It is unlikely that the water column production rate of  $^{230}\text{Th}$  has changed. However, could scavenging processes not common or

observed in the present-day ocean have resulted in the accumulation of more excess  $^{230}\text{Th}$  than expected during glacial times in the equatorial Pacific? Is it possible that higher particle flux coupled with changes in circulation resulted in enhanced delivery and scavenging of  $^{230}\text{Th}$  in this area? Is it reasonable to assume that the residence time of Th in the ocean has been different in the past and thus more localized scavenging of Th may result? Could changes in the burial of authigenic U, which is not accounted for since it may not have been preserved in the sediment, have affected the excess  $^{230}\text{Th}$  calculations? Could extraterrestrial  $^3\text{He}$  flux to earth be modulated by the same processes that affect climate? Will  $^3\text{He}$  particles be scavenged and concentrated in certain parts of the ocean due to changes in productivity and particle dynamics? Note that in order to discount focusing, enhanced burial during glaci- als of both excess  $^{230}\text{Th}$  and  $^3\text{He}$  needs to be accounted for, at least where these records agree with each other.

[11] Resolving these issues will require investigating processes that may result in increased sediment focusing as well as those affecting the chemistry of scavenged and/or cosmogenic elements such as Th and  $^3\text{He}$ . Specifically, future research directions should focus on: understanding oceanographic mechanisms of sediment focusing including resolving the issue of sediment budget by identifying both the source and sink regions for the re-deposited sediments; detailed effects of sediment focusing on different components of the sediment; and, use of high-resolution seismic reflections to identify lateral heterogeneity in sedimentation. In addition, studies of particle flux and scavenging dynamics to gain a more quantitative understanding of radionuclide adsorption/desorption processes and relation to particle aggregations; and, evaluation of factors that control lateral transport of Th in the water column. Finally, physical oceanographic models coupled with sediment, particle, and radionuclide dynamics should be constructed and tested using sedimentary observations from regionally representative sediment cores. Additional research recommendations are laid out in the work of M. Lyle et al. (Do geochemical estimates of sediment focusing pass the sediment test in the equatorial Pacific?, submitted to *Paleoceanography*, 2004).

[12] In conclusion, before we can determine whether biological productivity and  $C_{\text{export}}$  were higher or lower in the glacial ocean we have to critically and thoroughly assess our fundamental understanding of geological (sedimentary processes), physical (circulation) and chemical (scavenging) oceanography during time periods different than the present. Whatever the cause of this inconsistency is it may have important implications for paleoclimate interpretation, biogeochemical fluxes and ocean dynamics throughout the equatorial Pacific Ocean and possibly globally.

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