Chapter 12

VARIABILITY OF THE MARINE ITCZ OVER THE EASTERN PACIFIC DURING THE PAST 30,000 YEARS

Regional Perspective and Global Context

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Abstract

The Intertropical Convergence Zone (ITCZ) is manifested as a circum-global atmospheric belt of intense, moist convection and rainfall, marking the confluence of the northern and southern trades and the rising branch of the Hadley cell. It regulates the hydrologic cycle over the tropical continents and interacts tightly with the tropical oceans, notably with the seasonal appearance of the equatorial cold tongues of the Atlantic and Pacific. While it undergoes a regular seasonal migration, today the ITCZ maintains a nearly permanent Northern Hemisphere bias. Here we address the question of variability in the mean latitude of the marine ITCZ over the eastern Pacific on time scales of 100–10,000 years, with emphasis on the past 30,000 years. Our strategy relies on reconstructing the intensity of the prominent oceanographic front of the cold tongue–ITCZ complex, using oxygen isotope and magnesium thermometry techniques. We show that a weaker cold tongue–ITCZ front prevailed during the last glacial maximum (LGM), which indicates a more southerly ITCZ at that time. We further show that the Holocene history of sea surface temperature (SST) near the Galapagos Islands is consistent with progressive southward migration of the ITCZ during the last ~7,000 years, in accord with records from South America and the tropical Atlantic. In the more recent past, evidence from eastern Pacific corals supports a northward ITCZ shift since the end of the Little Ice Age (LIA), in agreement with the hydrologic record of the nearby Cariaco Basin. Collectively, the evidence points to coherent behavior of the Pacific, Atlantic, and South American ITCZs over a broad range of time scales. All regions have responded to Northern Hemisphere cooling by southward (equatorward) ITCZ displacements. In the Pacific, such displacements are likely to have been unfavorable to divergent upwelling at the equator, resulting in weaker zonal and meridional SST gradients and more uniform equatorial SSTs, analogous to modern El Niño conditions.

1. INTRODUCTION

A peculiar and incompletely understood aspect of the tropical atmospheric circulation concerns the preferred location of the Intertropical Convergence Zone (ITCZ). Over the oceans, particularly over the eastern Pacific and the Atlantic, the ITCZ maintains a nearly permanent Northern Hemisphere bias, rarely crossing the equator or forming spontaneously south of it (Waliser and Gautier 1993). Current theories attribute this northern bias to a variety of mechanisms involving asymmetries in the distribution of land, in the geometry of coastlines, and in stratus cloud cover, or to processes due to upwelling–sea surface temperature (SST) and wind-evaporation-SST feedbacks (Philander et al. 1996; Xie and Saito 2000).

In the modern climate, the ITCZ undergoes a regular seasonal migration toward the summer hemisphere. It reaches its northernmost latitude during late boreal summer (Aug–Sep) and subsequently approaches the equator during boreal winter (Feb–Mar). In the eastern tropical Pacific this annual migration occurs in concert with a large annual cycle in equatorial SST, in excess of 5ºC. Due to the presence of a shallow thermocline in this region, equatorial SSTs are efficiently modulated by the changes in winds that accompany the migration of the ITCZ. When the ITCZ is located farthest north, steady cross-equatorial southeast trades drive enhanced upwelling at the equator, promoting surface cooling (e.g., Chelton et al. 2001). Conversely, as the ITCZ migrates south, the equatorial region comes under the influence of weaker winds (the "doldrums"), which cause the upwelling to subside and SST to rise. An example of the seasonal cycle of the ITCZ in relation to SST in the eastern Pacific is illustrated in Figure 12-1.

Given the susceptibility of the ITCZ to seasonal migration during the annual cycle, an obvious question concerns the factors controlling its position over longer time scales, and the physical mechanisms through which it is linked to the global climate system. Through observations made during the instrumental era, it is now understood that at least over interannual time scales associated with the El Niño/Southern Oscillation (ENSO), the position of the Pacific ITCZ varies predictably with the phase of ENSO (e.g., Deser and Wallace 1990). El Niño events are typically marked by equatorward expansion of the ITCZ, whereas La Niña occurrences are marked by a more northerly ITCZ. On the time scale of decades and longer, however, we must rely on paleoclimatic reconstructions to assess whether systematic variations in the ITCZ accompanied global climate changes, and to understand their forcing mechanisms and impacts. Our objective here is to examine coupled ocean-atmosphere interactions between the equatorial cold tongue and the ITCZ (hereafter referred to as the cold tongue–ITCZ complex) of the eastern tropical Pacific, from the last glacial maximum

(LGM) to the present. We primarily utilize measurements of oxygen isotopic composition ($\delta^{18}O$) and magnesium/calcium ratios (Mg/Ca) in planktonic foraminifera from deep-sea cores spanning the last 30,000 years. In parallel, we attempt to integrate our observations in this region with a growing number of records documenting global-scale ITCZ variability over the same period.

2. THE SEASONAL CYCLE OF THE ITCZ IN THE EASTERN PACIFIC

The seasonal cycle of the eastern Pacific cold tongue–ITCZ complex is illustrated in Figure 12-1. Using an example from 1999, this figure shows that the seasonal appearance and intensification of the cold tongue occurs as the ITCZ moves north and reaches the northern edge of its latitudinal range in peak boreal summer (Aug–Sep). Strong southeast trades blowing across the equator and into the Northern Hemisphere drive intense upwelling at this time. At the same time, Figure 12-1 demonstrates the prominent SST front that develops just north of the equator, marking the transition from the equatorial upwelling source to the stratified warm pool underneath the ITCZ. In the opposite season (boreal winter, Feb–Mar) the ITCZ approaches the equator, bringing with it diminished winds, which fail to induce vigorous upwelling and to sustain the cold tongue and the frontal zone to its north.

This seasonal succession is repeated annually and is punctuated interannually by ENSO episodes. ENSO is presently phase locked to the seasonal cycle so that a typical El Niño event peaks in December–January (the season of weakest upwelling), whereas La Niña events tend to peak between June and September when the seasonal cycle already favors strong upwelling. As a result, the interannual ENSO signal acts as an amplifier of the seasonal cycle of the ITCZ, SST, and the strength of the equatorial front between 0º and 5ºN. Figure 12-2 illustrates this effect using weekly SST data obtained from 1982 to 2003, from a north-south transect of locations across the equator at 90ºW. This comparison confirms that both the seasonal upwelling pulse and its interannual amplification during La Niña conditions (e.g., during 1988) are accompanied by amplification of the meridional SST gradient across the equator. The opposite is true during El Niño conditions, which tend to suppress the SST gradient. A clear example of the latter was observed during the 1997–98 El Niño, which matured early enough to have a discernible impact during the preceding upwelling season (summer of 1997). Figure 12-2 shows that throughout the duration of this event the meridional SST front was severely attenuated or entirely absent. This pattern is also borne out clearly in even longer instrumental records spanning the second half of the twentieth century, allowing a more statistically robust analysis of the ENSO impacts in the cold tongue–ITCZ frontal complex (Deser and Wallace 1990).

Collectively, these observations illustrate the key principle that forms the basis for our strategy; namely, that a reconstruction of the cross-equatorial SST gradient through time can be used as a reliable index of upwelling intensity and relative position of the marine ITCZ with respect to the equator. In the following sections we discuss evidence for past variability in this gradient and place it in the context of evidence for global ITCZ shifts from a tropics-wide network of sites.

3. LGM CONDITIONS IN SOUTH AMERICA

The question of prevailing conditions over tropical South America during the LGM has been subject to prolonged debate and remains contested. This issue is of special relevance here because the continent is flanked by the tropical Atlantic and Pacific, both of which have well-developed "linear" marine ITCZs that undergo considerable modern variability in intensity and position (Mitchell and Wallace 1992; Waliser and Gautier 1993). In particular, while many studies have attributed hydrologic (wet or dry) anomalies in the continent to a shift in the mean latitude of the ITCZ, evidence to this effect requires parallel observations from many locations and can rarely be invoked on the basis of data from a single site. A number of recent studies addressing climatic conditions in and around the Amazon Basin offer new perspective on this issue by placing multiple constraints on the spatial structure of anomalous LGM precipitation.

Varved sediments from the Cariaco Basin offshore Venezuela preserve exceptional high-resolution records of hydrologic variability through the last glacial cycle (Hughen et al. 1996; Peterson et al. 2000; Haug et al. 2001). The basin is situated under the northern limit of the modern seasonal range of the ITCZ and thus experiences a large rainfall cycle, which results in deposition of laminated sediments. Deposition of dark-colored varves occurs during the rainy season (summer) when the ITCZ is positioned overhead and high river runoff supplies dark minerals (Fe and Ti) eroded from the continent. Plankton-rich, light-colored varves are deposited during the dry season (winter) when terrigenous input is reduced and strong northeasterly trades drive coastal upwelling, stimulating the production and sedimentary flux of biogenic carbonate. Thus both the color and mineralogy of the sediments can be used to reconstruct rainfall intensity near Cariaco. The evidence leaves little doubt that significantly cooler and more arid conditions prevailed on the northern margin of the continent during the LGM (Hughen et al. 1996; Peterson et al. 2000; Lea et al. 2003). Glacial aridity in this region and in neighboring Central America is supported by paleoecologic studies in a number of lakes from nearby localities; e.g., Lake Valencia, Venezuela (Leyden 1985; Curtis et al. 1999), Lake Fuquene and the El Abra Valley region, Colombia (van Geel and van der Hammen 1973; Schreve-Brinkman 1978, van der Hammen and Hooghiemstra 2003), Lake El Valle, Panama (Bush 2002), and La Chonta Bog, Costa Rica (Islebe et al. 1995). These studies converge on a consistent picture of enhanced glacial aridity in Central America and northern South America between approximately 10ºN and 5ºN latitude. In addition, in those records where the resolution permits insights on shorter time scales, the deglacial progression bears strong similarity to the Bölling/Allerod–Younger Dryas sequence documented in high latitudes. This is especially true for the Cariaco Basin (Hughen et al. 1996; Lea et al. 2003) but is also evident in the palynologic studies of Islebe et al. (1995) and van der Hammen and Hooghiemstra (1995), from Costa Rica and Colombia, respectively. The rather compelling conclusion from these observations is, therefore, that terrestrial climate in the northern tropics of Central and South America sustained sizable cooling and aridification during the LGM and, moreover, fluctuated in step with the northern high latitudes during deglaciation. Given that the climate of this region is affected prominently by the northward migration of the ITCZ, this observation bears central importance for constraining the northern range of the LGM ITCZ.

Further south, in the Amazon Basin, the evidence is more complex. According to an early paradigm to which some authors still subscribe, widespread Amazonian aridity in glacial times caused the rain forest to shrink and be replaced by savanna, surviving only in isolated patches or "refugia" to later recolonize the basin when the Pleistocene gave way to the more humid Holocene (Haffer 1969; Haffer and Prance 2001). Recent studies, however, refute this hypothesis, and instead indicate biome stability under a persistently wet, albeit cooler, climate (Colinvaux and De Oliveira 2000; Colinvaux et al. 2001). Pollen records from Lake Pata (Colinvaux et al. 1996) and from ODP site 932 in the mouth of the Amazon (Haberle and Maslin 1999) attest to forest stability and imply that moisture availability remained sufficiently high to support tropical rain forest through the LGM. Likewise, offshore Fortaleza in northeastern Brazil (Nordeste), a semiarid region today, Arz et al. (1998) have reported elevated concentrations of Ti and Fe in sediments of the last glacial period. These are especially prominent during the coldest parts of the glacial (corresponding to Heinrich events) and are attributed to increased river runoff and more humid conditions. Wetter LGM conditions in Nordeste are also indicated by travertine and speleothem deposits from local caves (Auler and Smart 2001).

In the Bolivian Altiplano, a wetter LGM climate has been inferred from lake-level fluctuations of Lake Titicaca (Baker et al. 2001), and from the concentration of dust in ice cores from Sajama (Thompson et al. 1998) and Illimani (Ramirez et al. 2003). In Peru, however, the Huascarán ice core has been interpreted to indicate colder and drier conditions, on the basis of depleted $\delta^{18}O$ in LGM ice and elevated dust concentrations at the base of the core (Thompson et al. 1995). Nevertheless, Ramirez et al. (2003) offer an alternative view of the Huascarán data. They attribute the depleted $\delta^{18}O$ values to increased LGM precipitation rather than cooling, and reject the high basal dust content as an artifact of disturbances at the ice-bedrock interface.

It is clear from these collective studies that LGM hydrologic changes in South America did not follow a simple pattern or proceed in a uniform direction. Nevertheless, a consistent picture is beginning to emerge which is composed of three main elements: (1) aridification of the northern part of the continent (as well as of Central America), (2) stability of biomes and persistently moist climate in the Amazon Basin, and (3) enhanced rainfall in the southern tropics, including the Altiplano of Bolivia and Nordeste. Figure 12-3 summarizes the evidence discussed above and explores the emerging spatial pattern. Using as a template the present-day seasonal precipitation cycle (which follows the latitudinal migration of the ITCZ), Figure 12-3 shows that the observed hydrologic anomalies during the LGM can be adequately explained by a generalized shift of the locus of precipitation to the south, not unlike its modern southward displacement during austral summer (Feb). As a whole then, these records are entirely consistent with a more southerly position of the ITCZ over South America during the LGM.

The discussion of these data sets may also be convincingly framed in terms of an LGM increase in the strength of the South American summer monsoon, as a consequence of the austral summer (Jan) insolation maximum 20,000 years before present (YBP). Little formal distinction exists today between ITCZ- or monsoon-type convection schemes over tropical South America, hence it is hard to conceive of much substantive difference between a monsoon- versus ITCZ-centered interpretation of the paleorecords (except perhaps in the context of winter versus summer rainfall budgets, a distinction that for the most part defies present reconstruction skills). In either case, the first-order result remains one of a southerly LGM bias in the continental rainfall belts with respect to the present. Of greater relevance here is the interaction between the monsoon circulation over the continent and the narrow oceanic ITCZs of the Atlantic and Pacific, and this is presently not fully understood even on seasonal time scales despite extensive observational data (e.g., Mitchell and Wallace 1992). Present understanding does not preclude the possibility that meridional shifts of rainfall over the continent are independent of their oceanic counterparts, and for this reason it is essential to obtain independent reconstructions of ITCZ variability over the oceans for comparison with the land records. In the following section we present evidence for a southward LGM shift of the eastern Pacific ITCZ, which we assert represents an extension of the observed pattern over South America.

4. SOUTHWARD SHIFT OF THE EASTERN PACIFIC ITCZ DURING THE LGM

As was discussed earlier, shifts in the latitude of the marine ITCZ over the eastern Pacific are accompanied by profound changes in SST structure. More specifically, the frontal zone between 0º and 5ºN intensifies when the ITCZ moves north, and weakens or vanishes as the ITCZ shifts south (Figs. 12-1 and 12-2). We therefore expect that any long-term systematic shifts in ITCZ position would leave an imprint in the intensity of this front. The $\delta^{18}O$ composition of planktonic foraminifera is well suited to monitor this front and to reconstruct its past variations. Depleted (more negative) $\delta^{18}O$ values result from either warmer SST (–0.21‰ per ºC) or lower surface salinity (0.27‰ per salinity unit). Thus in the northern edge of the front, where warm SSTs are accompanied by strong ITCZ rainfall and low salinity, planktonic $\delta^{18}O$ values are strongly depleted compared to those on and south of the equator, where lower SSTs and higher salinities prevail (Levitus and Boyer 1994).

We use a suite of cores located between 5ºS and 3ºN (Fig. 12-4D) to assess the intensity of this front in the LGM in comparison with the Holocene. $\delta^{18}O$ records of the last 30,000 years from these cores, measured in two species of planktonic foraminifera (*G. ruber* and *G. sacculifer*) are shown in Figures 12-4A and 12-4B. Both species capture the modern (late Holocene) $\delta^{18}O$ gradient of ~1‰ across the front quite well. Both species also reflect a significant decrease of the gradient during the LGM, as would be expected from less intense upwelling due to a more southerly ITCZ (Koutavas and Lynch-Stieglitz 2003). Because the interpretation of these data is complicated by the influence of salinity on $\delta^{18}O$, an independent test of this result is provided by direct reconstructions of SST based on foraminiferal Mg/Ca. Mg/Ca has been calibrated versus temperature in a number of studies (Nürnberg et al. 1996; Lea et al. 2000; Dekens et al. 2002) and has been successfully used for down-core SST reconstructions in many tropical locations (Lea et al. 2000; Stott et al. 2002; Koutavas et al. 2002; Rosenthal et al. 2003). Figure 12-4C compares the Mg/Ca SST records from cores V21–30 at 1.2ºS (Koutavas et al. 2002) and TR163-19 at 2.2ºN (Lea et al. 2000; Dekens et al. 2002). This comparison confirms that a reduced SST gradient between the two cores existed at the LGM compared to the Holocene.

In our view, these data reflect a systematic southward shift of the mean ITCZ latitude during the LGM, in the same manner that a severely reduced meridional SST gradient today accompanies the equatorward retreat of the ITCZ seasonally (during winter) and interannually (during El Niño). We hypothesize that the LGM response reflects a more restricted northward range of the summer ITCZ, as a consequence of cooler Northern Hemisphere summers in the face of permanent land ice fields. In light of the preceding discussion of terrestrial conditions in South America, we regard the southward response of the eastern Pacific ITCZ as an extension of the observed pattern over South America and the tropical Atlantic under common LGM forcing.

5. MIGRATION OF THE ITCZ DURING THE HOLOCENE

Following minimum values during the LGM, northern summer (Jul) insolation gradually increased to a maximum centered at about 10,000 BP, and has been declining ever since. This insolation maximum is linked to the early Holocene climatic optimum observed in high-latitude records from land (for example, the North GRIP ice core from Greenland, Fig. 12-5A) and ocean (Liu et al. 2003, and references therein), and is also believed to have forced the strengthening of the Indian and Asian monsoon systems (Clemens et al. 1991; Gupta et al. 2003; Fleitmann et al. 2003, and Chapter 9, "Holocene Records of Rainfall Variation and Associated ITCZ Migration from Stalagmites from Northern and Southern Oman," this volume). Evidence has recently emerged that this period was also marked by a more northerly mean ITCZ latitude followed by gradual southward migration. Support for this hypothesis is provided by several paleoclimatic archives distributed tropics-wide, some of which are illustrated in Figure 12-5. $\delta^{18}O$ values in cave stalagmites from Oman (Fig. 12-5B) are strongly depleted during the early and middle Holocene, indicating enhanced rainfall under the influence of a more northerly Indian Ocean ITCZ (Fleitmann et al. 2003, and Chapter 9, this volume). The terrigenous record from ODP site 658C off West Africa (Fig. 12-5C) indicates an abrupt transition to a more arid climate at about 5,500 BP, which reflects the southward expansion of North African desert at the expense of grassland (deMenocal et al. 2000). And the Cariaco Basin mineralogy (Fig. 12-5D) documents early Holocene increases in riverine input of Fe and Ti, ascribed to a more northerly ITCZ position (Haug et al. 2001). All three of these records are located in the northern tropics between 10ºN and 20ºN, where rainfall is largely controlled by the northerly summer excursions of the ITCZ. All indicate a common pattern of a wetter climate in the early Holocene up to about 5,000–6,000 BP, and a shift to more arid conditions thereafter. These trends are best explained by a more northerly ITCZ position in the early and middle Holocene followed by a gradual southward retreat.

This interpretation is supported by complementary evidence from the Southern Hemisphere. Lake Titicaca in the Altiplano of Bolivia reached its lowest levels on record between 8,000 and 4,500 BP, then rose again toward the present time, signifying a mid-Holocene transition from dry to wetter conditions (Baker et al. 2000). The vegetation also reflects a transition to a more humid climate. Bolivian rain forest expanded southward at the expense of savanna since at least 3,000 BP (Mayle et al. 2000). And the $\delta^{18}O$ record of the ice core from Nevado Illimani, Bolivia, shows progressive isotopic depletion through the Holocene, consistent with a long-term increase in precipitation (Ramirez et al. 2003). Finally, in Lake Malawi in the southern tropics of Africa (10ºS), mid-Holocene increases in biogenic silica and volcanic dust have been tentatively linked to a southward ITCZ shift there as well (Johnson et al. 2002). It appears therefore that the combined evidence from these diverse tropical localities in both hemispheres supports a consistent picture of a southward ITCZ movement through the Holocene. Wetter climatic conditions in the northern tropics during the early and middle Holocene gave way to more arid conditions in the late Holocene, whereas the opposite trend occurred in the southern tropics.In the context of this evidence, we pose the question of whether a coherent pattern of variability is evident in the eastern tropical Pacific, involving an analogous shift of the ITCZ and its impact on equatorial upwelling and SST. The Holocene SST record based on foraminiferal Mg/Ca in core V21-30 in the heart of the equatorial cold tongue (Fig. 12-5E), shows a broad interval of cool SSTs in the early and middle Holocene between 9,000 and 5,000 BP (Koutavas et al. 2002). This is precisely the response expected from a more northerly ITCZ at this time, which would have promoted strong upwelling due to persistent southeast trades blowing across the equator. Likewise, the transition to warmer SSTs after about 5,000 BP in the same record is fully consistent with a more southerly ITCZ in the late Holocene.

One incongruous element in this discussion concerns the timing of the northerly ITCZ extreme, in relation to the summer insolation maximum.

While July insolation peaked between about 11,000 and 8,000 BP, enhanced ITCZ rainfall in the northern tropics (for example in the Cariaco Basin) occurred during the broader interval between about 10,000 and 5,000 BP (Fig. 12-5). We see two reasons for this apparent "lag." In the first place, we argue that it is not a real lag: The more appropriate monthly insolation curves to consider with respect to tropical rainfall and the ITCZ are those of August and September. September (not Jul) is the month during which the ITCZ attains its northernmost position today, and often maintains it well into October (Waliser and Gautier 1993). September insolation peaked between 6,000 and 9,000 BP, which is precisely the time when maximum rainfall is observed in the Cariaco Basin (Fig. 12-5D). This timing also matches the Lake Titicaca low-stand (Baker et al. 2001) and the observed SST minimum in the equatorial cold tongue (Fig. 12-5E). In effect, the 6,000–9,000 BP September insolation maximum may have served to lengthen the northern summer and allowed the ITCZ to linger near its northern limit longer. The second possible reason for the "delayed" ITCZ response may be that the melting of continental glaciers was not completed until about 7,000 BP, as is evident from reconstructions of global sea level (Fleming et al. 1998). More precisely, sea level was 40 m below its present level at 10,000 BP and therefore approximately one-third of the full amount of excess LGM ice remained in place at that time. Land ice restricts the northward migration of the ITCZ by promoting a steep latitudinal temperature gradient, which strengthens the northern trades (Chiang et al. 2003). The final melting of this ice between 10,000 and 7,000 BP combined with maximum September sunshine must have favored the more northerly position of the ITCZ.

An issue related to the ITCZ history concerns the Holocene evolution of ENSO. Evidence indicates less frequent or absent El Niño occurrences in the early and middle Holocene (Tudhope et al. 2001; Moy et al. 2003) and is supported by a simple model of the tropical Pacific forced by insolation (Clement et al. 2000). The onset of El Niño episodes today requires westerly wind anomalies near the equator; that is, weaker easterlies. The easterlies weaken annually during December through April, as part of the seasonal approach of the ITCZ to the equator. El Niño typically matures during the winter months (Dec–Jan), which suggests that it feeds upon and exacerbates the normally encountered conditions of weak easterlies favored by a southerly ITCZ. It is thus likely that a northward-displaced ITCZ in the early to middle Holocene would have a profound effect on the dynamics of ENSO. If the ITCZ were anchored off the equator for a longer season each year, or were forced to oscillate within a range farther removed from the equator, the overall potential for weaker equatorial easterlies capable of triggering El Niño would have been correspondingly reduced. Conversely, it seems plausible that sometime around 5,000 BP, as the ITCZ migrated southward, it attained sufficient proximity to the equator and began to perturb the equatorial easterlies in a manner that favored frequent genesis of El Niño events. In this context it may be significant that some of the largest-amplitude ENSO variability of the last millennium, reconstructed from corals, occurred within the recent Little Ice Age (LIA; Cobb et al. 2003), a period for which there is compelling evidence for a more southerly ITCZ (Haug et al. 2001) (see later discussion). If this reasoning shows validity, one might extrapolate to the future and predict that climatic warming in the next century, natural or anthropogenic, may induce a northward excursion of the mean ITCZ, which in the absence of other forcing would tend to inhibit ENSO. It is likely, however, that this effect would require a hemispherically asymmetric warming favoring the Northern Hemisphere whose source remains unclear.

6. ITCZ VARIABILITY ON SUBORBITAL TIME SCALES

Thus far we have examined variability of the ITCZ over the last glacial-interglacial transition and through the Holocene, periods marked by strong orbital influence due to earth's precession. Nevertheless, climate has varied dramatically on shorter time scales as well, particularly in the millennial frequency band, without an apparent external forcing. The observations of distinctly paced Dansgaard-Oeschger (D-O) oscillations (e.g., Rahmstorf 2003) and ice rafting (Heinrich) events in the North Atlantic region (e.g., Bond et al. 1993) have by now been extended by the discovery of correlative events throughout the globe.

In the tropics the evidence for these events has grown steadily during the past decade and in many cases points to hydrologic variability associated with shifts of the ITCZ. In the Cariaco Basin at 10ºN, the cold phases of the D-O oscillations are marked by correlative reductions in Fe and Ti and increases in sediment reflectance, indicating more arid conditions likely due to more southerly ITCZ confinement (Peterson et al. 2000). Conversely, south of the equator off the coast of Brazil (3.5ºS), Heinrich events correlate with increases in Fe and Ti as expected from more humid conditions due to a more southerly ITCZ (Arz et al. 1998). Likewise, the Altiplano of Bolivia and southern Amazonia experienced wetter climate during the Younger Dryas and possibly Heinrich event 1 (Baker et al. 2001). In the eastern equatorial Atlantic, systematic increases in the relative abundance of *Florisphaera profunda*, a deep-living marine alga, correlate with Heinrich events and indicate decreased divergence due to weaker zonal winds (McIntyre and Molfino 1996) best explained by an equatorward shift of the ITCZ "doldrums." In the Indian Ocean isotopic evidence from stalagmites on Socotra Island suggests a weaker monsoon during cold stadials and is basically consistent with a more southerly ITCZ (Burns et al. 2003), but here it is exceedingly difficult to separate the response of the ITCZ from its interaction with the monsoonal circulation. In the western equatorial Pacific, within the bounds of the modern warm pool, stadial conditions correspond with elevated surface salinities (Stott et al. 2002), pointing to a shift of the locus of convection to the south, or perhaps to the east as during modern El Niño conditions.

Unfortunately, available records from the eastern tropical Pacific are as yet unable to resolve millennial climate changes with enough dating precision to constrain the role of the ITCZ in this basin. Low accumulation rates and uncertainties in the surface ocean ^{14}C reservoir correction make the detection and dating of millennial-scale events here a formidable challenge. Nevertheless, given the patterns of millennial variability observed over adjacent South America and the tropical Atlantic, which support southward ITCZ excursions during stadials, we speculate that a similar pattern may eventually be documented in the eastern Pacific as well. This expectation is based on the fact that both ocean basins possess similar equatorial cold tongue–ITCZ complexes governed by similar physics, and today exhibit coherent seasonal variability (Mitchell and Wallace 1992). If such a millennial response of the eastern Pacific ITCZ is confirmed, it would imply that stadial periods were unfavorable to vigorous equatorial upwelling, perhaps promoting instead a shift to more zonally uniform equatorial SSTs, similar to the modern El Niño pattern (e.g., Koutavas et al. 2002). Alternatively, it is possible that the Pacific ITCZ may have been far less sensitive to millennial-scale climate shifts than the observations suggest for the Atlantic, and correspondingly any impact on equatorial Pacific divergence may have been weak. Distinguishing between these scenarios requires advances in identifying high-resolution marine archives from this region, as well as in narrowing the present dating uncertainties.

Millennial-scale oscillations, while dominant during the last glaciation, have persisted with reduced amplitude into the Holocene (Bond et al. 1997; deMenocal et al. 2000). The most recent millennial oscillation involved the transition from the Medieval Warm Period (MWP) to the Little Ice Age, followed by renewed warming in the latter half of the nineteenth century. The detailed mineralogic (Fe and Ti) records from the Cariaco Basin show that the MWP and LIA had correlative hydrologic events in the tropical Atlantic (Haug et al. 2001). The LIA in Cariaco was evidently a drier interval than the preceding MWP and was followed by increases in Fe and Ti resulting from wetter conditions. According to Haug et al. (2001) these variations are diagnostic of fine-scale century-to-decade shifts of the

ITCZ during the last millennium, and imply a more southerly ITCZ during the LIA followed by return to a more northerly latitude today.

Did these ITCZ shifts extend over the neighboring tropical Pacific? Coral records spanning the last three to four centuries offer a parallel perspective from that region. Figure 12-6 compares the coral $\delta^{18}O$ records of Linsley et al. (1994) and Dunbar et al. (1994) from Panama and the Galapagos, respectively. The two records straddle the cross-equatorial front between the ITCZ and the cold tongue, and their lengths overlap over most of the last three centuries. As was noted by Dunbar et al. (1996), the opposite $\delta^{18}O$ trends evident in these corals both on centennial and decadal time scales can best be explained by movements of the ITCZ, which, as was discussed earlier, have a large impact on the strength of the cross-equatorial SST/salinity gradient (Figs. 12-1 and 12-2). Thus, the increasing $\delta^{18}O$ gradient between the two locations since about AD 1850 is most likely a manifestation of the same northward ITCZ movement that produced the observed increases in Fe and Ti in the Cariaco Basin at the end of the LIA (Haug et al. 2001). It is likely that the higher-frequency fluctuations evident in the coral $\delta^{18}O$ have correlative signatures in Cariaco as well; however, the dating of the latter record is not precise enough to allow exact matching. These observations confirm that the ITCZ has varied coherently over the Atlantic and Pacific during the last three centuries. Moreover, they add to the growing evidence that the position of the mean ITCZ latitude is linked across both basins (and probably on a global scale) and undergoes systematic shifts over a wide range of time scales, such that climatic cooling in the Northern Hemisphere favors a more southerly ITCZ and vice versa.

7. SUMMARY AND CONCLUSIONS

In the present climate, the ITCZ displays a remarkable sensitivity to the annual cycle and to interannual disturbances due to ENSO. The evidence summarized here argues that this sensitivity likely persists over longer time scales in response to a variety of forcing mechanisms, such as the presence and extent of land ice, Earth's orbital geometry, and possibly others operating on shorter time scales. Most important, the patterns of variability across different ocean basins and over the continents appear to share common characteristics: Systematic, coeval ITCZ shifts in the same direction appear to have occurred globally. This finding confronts us with the possibility that variability in the ITCZ will prove to be instrumental in understanding high- to low-latitude climate linkages on a global scale. Nevertheless, the precise dynamical underpinnings through which these and other possible forcing mechanisms (e.g., the strength of the thermohaline circulation or the solar output) operate, or their relative importance, remain elusive. Large gaps remain in the paleoclimate record, both spatial and temporal, which need to be filled in order to gain further insights. Over the eastern tropical Pacific in particular, where the ITCZ is coupled tightly to the dynamics of the equatorial cold tongue and thus controls the distribution of SSTs across the entire basin, it will be exceedingly important to acquire a network of high-quality data sets. The available decadal-scale records from the Cariaco Basin and from Pacific corals leave no doubt that the system has been far from stable in the recent past. Its future evolution is uncertain and so is its potential impact on ENSO, tropical rainfall, and the vast human populations that inhabit the circum-global zone under the influence of the ITCZ.

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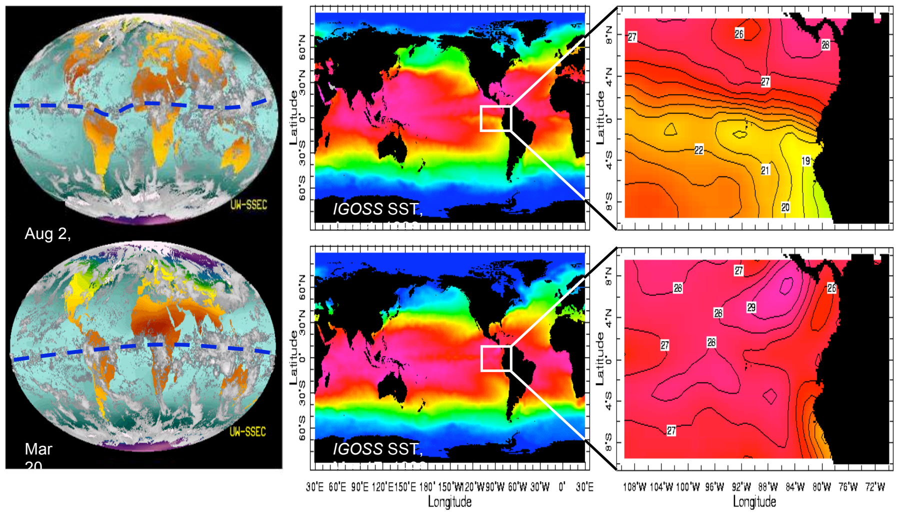


Figure 12-1. Illustration of the annual migration of the ITCZ in relation to SST in the eastern equatorial Pacific. Satellite cloud composites (left, from University of Wisconsin) delineate the approximate ITCZ position on August 2 and March 20, 1999. Corresponding weekly global SSTs from IGOSS are shown at center, and eastern equatorial Pacific SSTs are shown in more detail at right. An intensified equatorial cold tongue and a strong SST gradient to its north accompany the northerly excursion of the ITCZ in boreal summer (Aug–Sep). Conversely, both the cold tongue and SST gradient are suppressed in winter (Feb–Mar), when the ITCZ approaches the equator and the winds diminish.

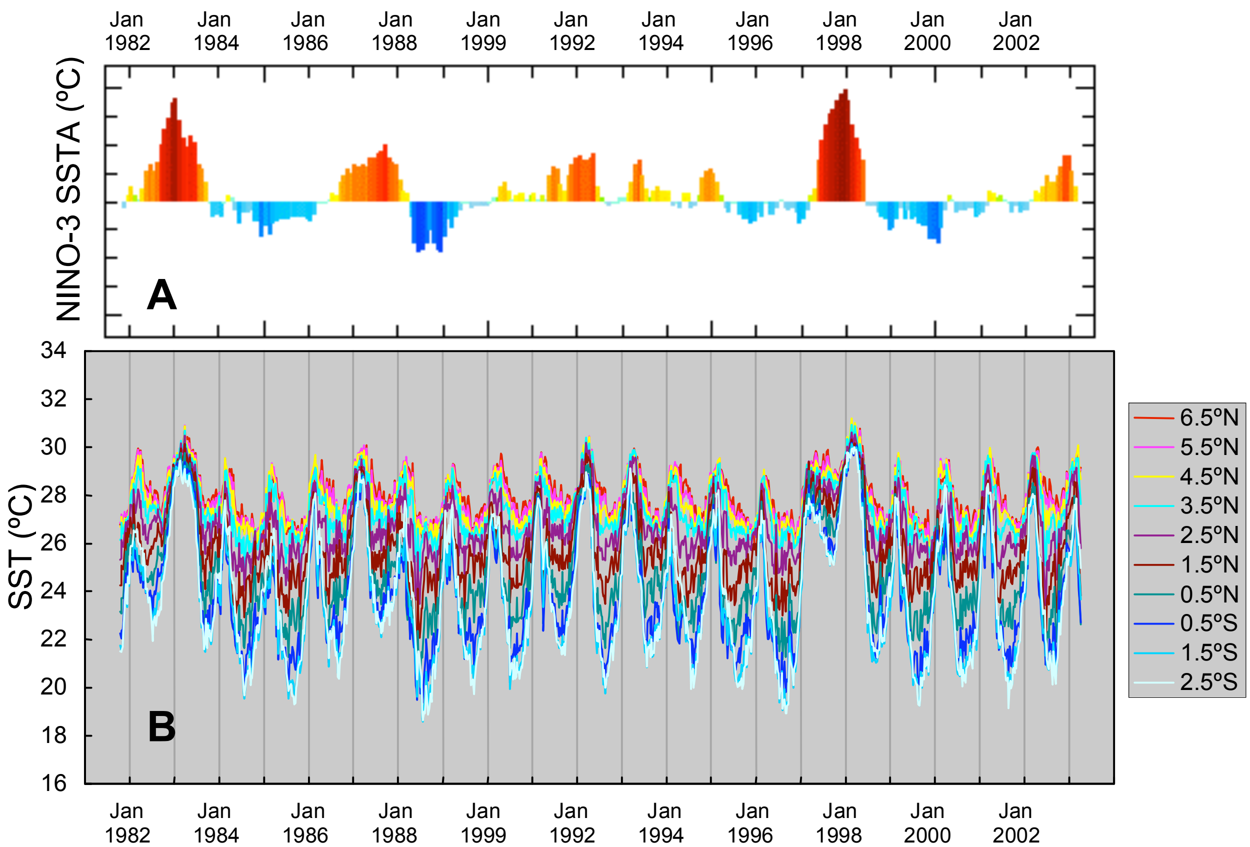


Figure 12-2. Weekly SST time series (IGOSS data accessed at: http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.weekly/sst over the1982–2003 period in ten 1º by 1º grid boxes from 7ºN to 3ºS at 90ºW longitude. These grid boxes were chosen because they traverse the equatorial SST gradient of the eastern Pacific (Fig. 12-1). The "concertina" effect in the data results from the seasonal intensification and collapse of the SST gradient, which accompanies the appearance and disappearance of the equatorial cold tongue in response to shifting ITCZ winds (Fig. 12-1). A weak gradient in the early part of the year occurs under the influence of the "doldrums" while the ITCZ is positioned near the equator. Later in the year, as the ITCZ shifts north, the southeast trades across the equator strengthen and drive enhanced upwelling, hence a strong gradient develops. The top panel shows the monthly NIÑO3 SST anomaly index over the same period. Prominent El Niño anomalies (e.g., 1982–83, 1987, 1997–98) are marked by unusually weak gradients

and more southerly ITCZ, whereas La Niñas (e.g., 1988) are marked by an enhanced and longer-persisting SST gradient, and more northerly ITCZ.

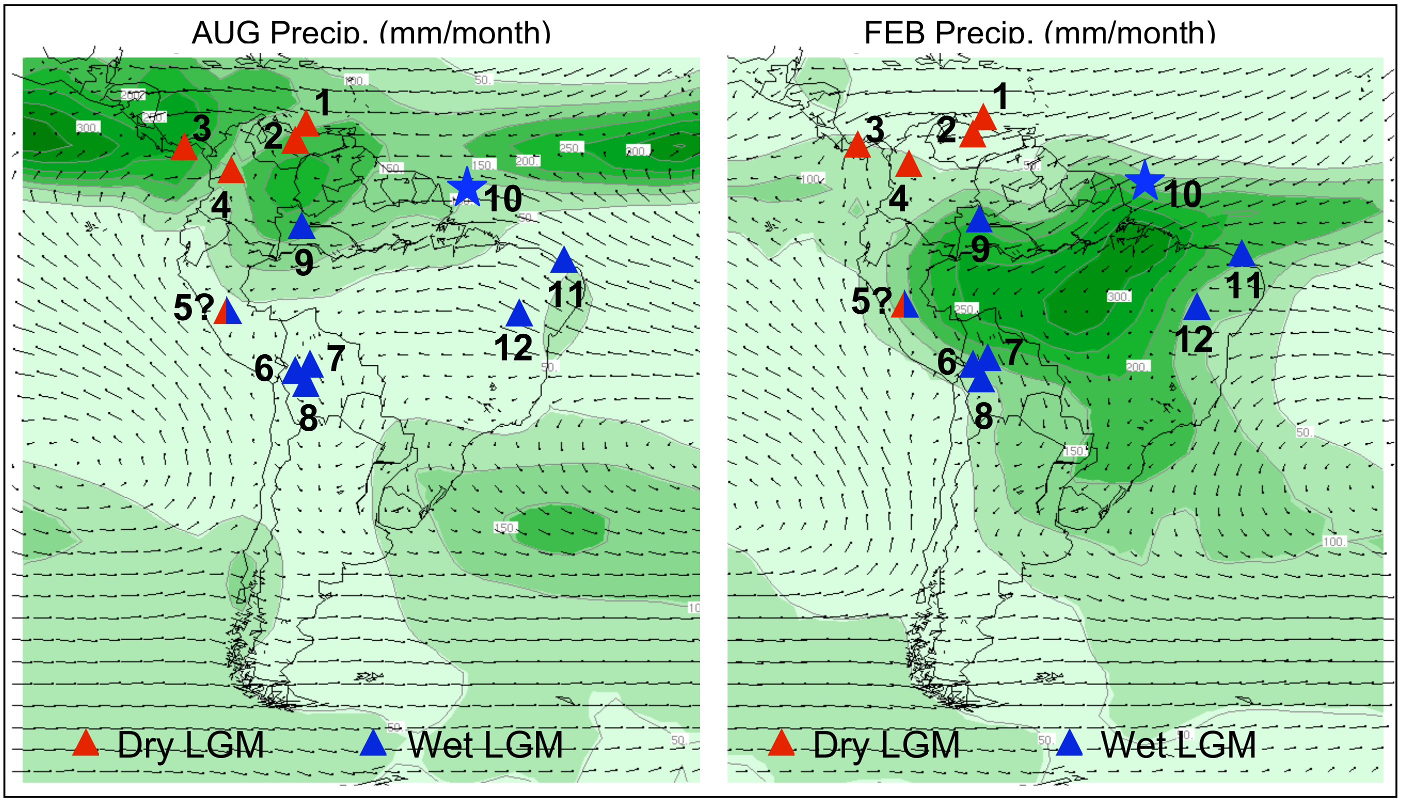


Figure 12-3. Terrestrial records of hydrologic change in South America during the LGM. The background maps show modern monthly precipitation values for August (left) and February (right) in millimeters per month. Vectors indicate prevailing winds at 925 mb. Red symbols indicate more arid conditions during the LGM and blue symbols (more) humid conditions relative to today. The anomalous LGM pattern mimics the pattern arising today from the seasonal southward migration of the ITCZ over the continent. This suggests that to first order the LGM anomalies can be explained by a systematic shift of the ITCZ to the south. Sites are numbered as follows: 1, Cariaco Basin (Peterson et al. 2000); 2, Lake Valencia, Venezuela (Leyden 1985); 3, El Valle Lake, Panama (Bush 2002); 4, Lake Fuquene, Colombia (van Geel and van der Hammen 1973); 5, Huascarán, Peru (Thompson et al. 1995); 6, Sajama, Bolivia (Thompson et al. 1998); 7, Illimani, Bolivia (Ramirez et al. 2003); 8, Lake Titicaca, Bolivia (Baker et al. 2001); 9, Lake Pata, Brazil (Colinvaux et al. 1996); 10, ODP 932, Amazon Fan (Haberle and Maslin 1999); 11, GeoB 3912 (Arz et al. 1998); 12, Northeast Brazil (Auler and Smart 2001). See text for more thorough discussion of these sites. The evidence from site 5 (Huascarán ice core) remains controversial, hence the ambivalent symbol. The star symbol near site 10 (ODP 932) denotes that the pollen record from this marine site is in fact a surrogate for integrated conditions over the inland Amazon Basin.

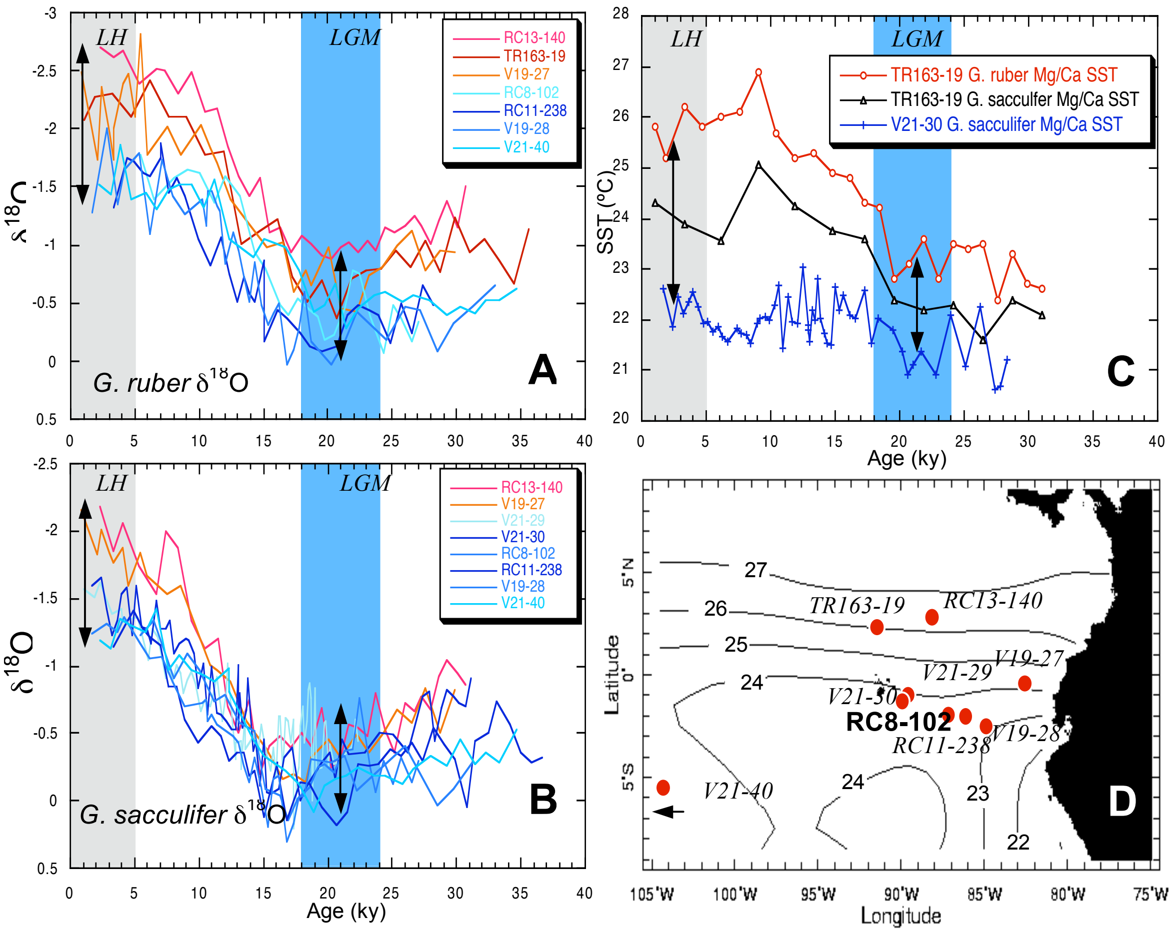
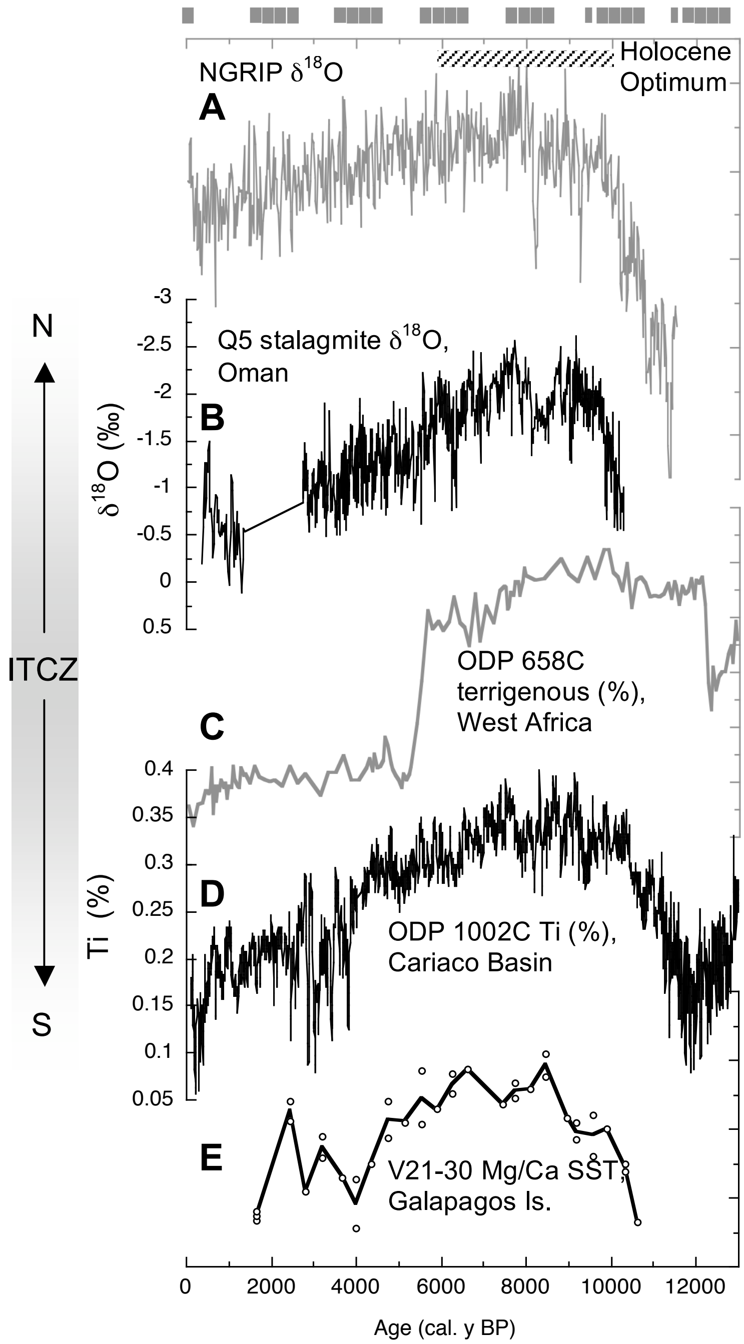


Figure 12-4. $\delta^{18}O$ and Mg/Ca SST reconstructions in a suite of cores from the eastern equatorial Pacific. (A) and (B) show down-core foraminiferal $\delta^{18}O$ profiles of the last 30,000 years from *G. ruber* and *G. sacculifer*, respectively. (C) Mg/Ca reconstructions of SST from cores TR163-19 (Lea et al. 2000; Dekens et al. 2002) and V21-30 (Koutavas et al. 2002). (D) Core locations are relative to annual mean climatologic SST (Levitus and Boyer 1994). Both proxies ($\delta^{18}O$ and Mg/Ca) indicate a reduced meridional SST gradient across the equator during the LGM compared to the Late Holocene (LH) (see vertical arrows in panels A–C). A more thorough discussion of these data is given by Koutavas and Lynch-Stieglitz (2003).



NGRIP δ18O
Holocene Optimum
A
δ18O (‰)
Q5 stalagmite δ18O, Oman
B
δ18O (‰)
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
ODP 658C terrigenous (%), West Africa
C
Terr. (%)
N
ITCZ
S
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Ti (%)
D
ODP 1002C Ti (%), Cariaco Basin
21
21.5
22
22.5
23
SST (ºC)
E
V21-30 Mg/Ca SST, Galapagos Is.
0
2000
4000
6000
8000
10000
12000
Age (cal. y BP)

Figure 12-5. Holocene climate variations with relation to the ITCZ. (A) North GRIP (75ºN) ice core $\delta^{18}O$ (Johnsen et al. 2001) showing the climatic optimum of the early Holocene, followed by progressive cooling. (B) Q5 stalagmite $\delta^{18}O$ from Hunf Cave, Oman (17ºN) (Fleitmann et al. 2003). (C) Terrigenous fraction of ODP 658C (21ºN), off West Africa (deMenocal et al. 2000). (D) Cariaco Basin (10ºN) titanium concentration (Haug et al. 2001). (E) Mg/Ca SST (inverted) from V21-30, Galapagos Islands (1.2ºS) (Koutavas et al. 2002). The records from the northern tropics (B, C, and D) indicate wetter climate in the early to middle Holocene, which is consistent with a more northerly ITCZ in the Indian and Atlantic Oceans. The Galapagos SST record (E) shows early to middle Holocene cooling due to stronger upwelling and supports a more northerly ITCZ in the Pacific as well.

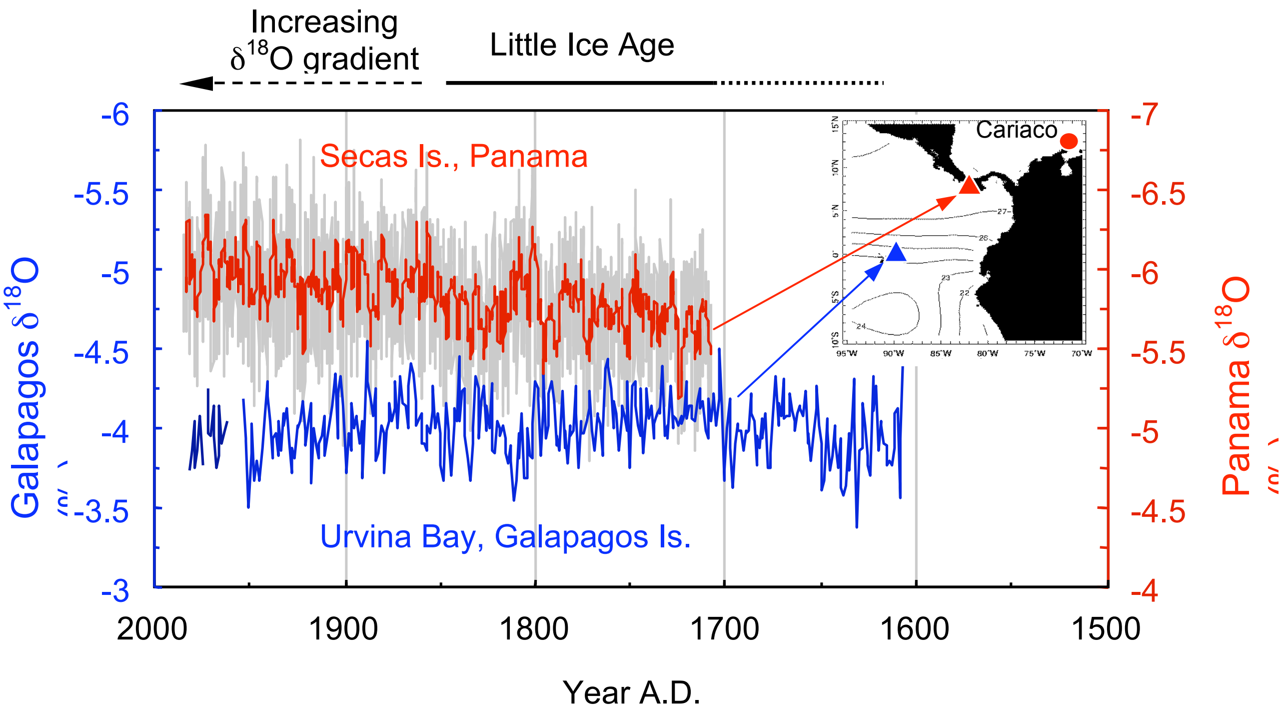


Figure 12-6. Coral $\delta^{18}O$ data of the last ~400 years from two sites straddling the modern SST gradient of the eastern Pacific cold tongue–ITCZ. At the top is the $\delta^{18}O$ record from Secas Island, in the Gulf of Chiriquí, Panama (8ºN) (Linsley et al. 1994). The red curve is a 10-point running average of the raw data, in gray. The blue series (bottom) shows the $\delta^{18}O$ of a coral from Urvina Bay, Galapagos Islands (0.4ºS) (Dunbar et al. 1994). The inset shows the coral locations relative to the annual mean SST front (Levitus and Boyer 1994), and the Cariaco Basin in the Atlantic. Evidence from Cariaco indicates a northward shift of the ITCZ since the end of the LIA (Haug et al. 2001), which is reflected in the Pacific by the increasing isotopic gradient between the two corals since the mid-nineteenth century.