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Key Points:

- Surface temperatures in the Eastern Cordillera of Colombia scale with sea surface temperatures in the eastern Pacific
- A Pliocene warm eastern Pacific suggests ~2°C warmer Eastern Cordillera
- An ~2°C warmer Eastern Cordillera is consistent with no post-Miocene elevation change of the Eastern Cordillera

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Sea Surface Temperatures in the Eastern Equatorial Pacific and Surface Temperatures in the Eastern Cordillera of Colombia During El Niño: Implications for Pliocene Conditions

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Abstract Regressions of surface temperatures in the Eastern Cordillera of Colombia with sea surface temperatures (SSTs) in the equatorial Pacific, and specifically with Niño1+2 and Niño3 temperature anomalies, show that the Eastern Cordillera warms or cools by approximately half of the amplitude of the variation of SSTs in the eastern tropical Pacific. Because Pliocene SSTs in the eastern tropical Pacific resemble those during major El Niño events, when SSTs warm by ~4°C, these regressions suggest that the Pliocene Eastern Cordillera was warmer by ~2°C at both high and low elevations. Such post-Pliocene cooling is smaller than the ~9–12°C inferred from fossil pollen assemblages, but comparable to recent estimates of Anderson et al. of 3 ± 1°C (1σ) since ~8 Ma. This change in surface temperature could be explained by a change in regional climate associated with a different tropical Pacific SST distribution and therefore would require neither an elevation change of the Eastern Cordillera since that time nor a change between Pliocene and present-day temperatures in the tropics that is as large as estimates of the global change of ~2.5–4°C.

1. Introduction

Abundant measurements of past sea surface temperatures suggest a warmer eastern tropical Pacific Ocean in Pliocene than present time (e.g., Dekens et al., 2007; Groeneveld et al., 2006; Herbert et al., 2016; Lawrence et al., 2006; Ravelo et al., 2006; Wara et al., 2005). Estimates of Earth's mean temperature in the Pliocene Epoch are ~2.5–4°C greater than that today (e.g., Brierley & Fedorov, 2010; Fedorov et al., 2010, 2013, 2015; Haywood et al., 2013; Haywood & Valdes, 2004; Salzmann et al., 2013). Inferences of surface temperatures from continental areas in the tropics, however, are sparse. A summary of Pliocene temperature records by Salzmann et al. (2013) included no sites within 10° of the equator. Pollen from the Eastern Cordillera of Colombia at ~4°N may offer the best, if only qualitative, Pliocene temperature record from such a region. The progressive adaptation of vegetation has been interpreted to indicate the surface temperatures warmer by 6–12°C than today, but the result of surface uplift of the Eastern Cordillera since ~6 to ~3 Ma (e.g., Helmens & Van der Hammen, 1994; Hooghiemstra & Van der Hammen, 1998; Hooghiemstra et al., 2006; Van der Hammen et al., 1973; Wijninga, 1996; Wijninga & Kuhry, 1990), but others have challenged this rapid rise (Anderson, 1972; Anderson et al., 2015; Bayona et al., 2008; Mora-Páez et al., 2016). Thus, the question of whether Pliocene temperatures in the tropics differed from those today remains open.

An additional phenomenon complicates the drawing of conclusions about Pliocene tropical surface temperatures. Several authors have hypothesized a permanent El Niño-like sea surface temperature (SST) distribution in Pliocene time (e.g., Fedorov et al., 2006; Lawrence et al., 2006; Molnar & Cane, 2002, 2007; Philander & Fedorov, 2003; Ravelo et al., 2006; Wara et al., 2005). They suggest that at ~3–4 Ma, the difference between SSTs in the eastern and western parts was only 1–2°C compared to today's 5–6°C. As surface temperatures in many regions differ from average values during El Niño events, differences in Pliocene surface temperatures from those today in the Eastern Cordillera might not reflect a global difference, but simply an analogue to El Niño teleconnections. Consequently, we examine how the climate of the Eastern Cordillera might correlate with eastern tropical Pacific SSTs, with the differences between present-day and Pliocene conditions in mind.

Studies of plant macrofossil and microfossil assemblages from the Sabana de Bogotá (2550 m) in the Eastern Cordillera of Colombia show a progressive adaptation over the past several million years from what today

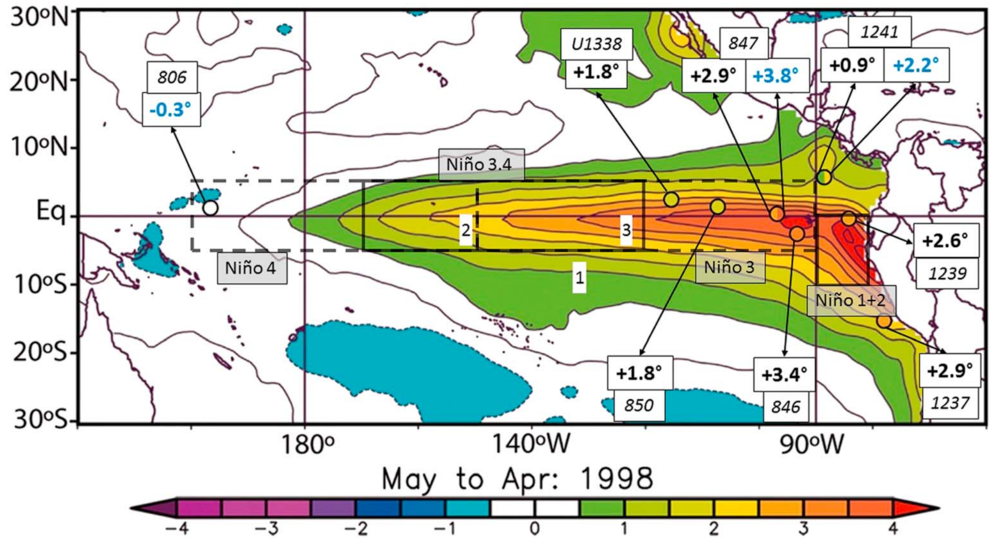

Figure 1. Sea surface temperature (SST) anomalies (in °C) associated with the major El Niño event in 1997–1998 and differences between Pliocene SSTs from ODP sites and those for the present day. The shaded map shows anomalies from the Earth System Research Laboratory division of National Oceanic and Atmospheric Administration (NOAA) database for May 1997 to April 1998. Numbers in italics give ODP site numbers. Temperature differences in black were inferred from the $U_{37}^{k'}$ alkenone index and those in blue from Mg/Ca (Dekens et al., 2007; Groeneveld et al., 2006; Herbert et al., 2016; Lawrence et al., 2006; Wara et al., 2005). The first three regions, from west to east, located within 5° of the equator are Niño4 (160°E–150°W), Niño3.4 (170°W–120°W), and Niño3 (150°W–90°W). The easternmost region, Niño1+2, is located between 0°–10°S and 90°W–80°W.

represents warm tropical taxa to the present-day high mountain taxa (e.g., Helmens & Van der Hammen, 1994; Hooghiemstra & Van der Hammen, 1998; Hooghiemstra et al., 2006; Van der Hammen et al., 1973; Van der Hammen, 1974; Wijninga, 1996; Wijninga & Kuhry, 1990). Fission track dating along with biostratigraphic correlations led to the inference that this progressive adaptation reflects a recent, rapid rise of the Eastern Cordillera, with surface elevations increasing from ~600 m to ~2,600 m between ~6 to ~3 Ma (Andriessen et al., 1993; Hooghiemstra et al., 2006). Thermochronometric estimates and structural analyses along the eastern flank that suggest a rapid exhumation since ~3 Ma have also been attributed to a rapid rise of the entire Eastern Cordillera since that time (Mora et al., 2008, 2010, 2014).

More recent work casts doubt on such large elevation change since ~6 to ~3 Ma. Anderson et al. (2015) used MBT′/CBT indices (methylation of branched tetraethers/cyclization of branched tetraethers) to estimate paleosurface temperatures on three of the original sections of the pollen studies and revised their ages using magnetostratigraphy. They inferred less cooling, 3.2 ± 1.1°C (1σ), since ~8 Ma than had been inferred from pollen studies, and suggested that less than 1,000 m of surface uplift occurred since late Miocene. In addition, GPS measurements show an average shortening rate of ~4 mm/yr across the Eastern Cordillera, a rate that cannot be reconciled easily with the recent rise based on previous pollen studies (Mora-Páez et al., 2016). The ~200 km width of the Eastern Cordillera, the ~100–150 km of shortening inferred from balanced cross sections (e.g., Bayona et al., 2008; Cediel et al., 2003; Cortés et al., 2006; Dengo & Covey, 1993; Egbue & Kellogg, 2012), and the average rate of ~4 mm/yr imply a duration of ~25–40 Ma to build the entire mountain belt (Mora-Páez et al., 2016). The changes in climate since ~2.5–4 Ma, manifested both in the eastern Pacific and throughout much of the world, raise the question of how much the temperature in the Eastern Cordillera of Colombia could have changed since that time.

SST anomalies during the 1997–1998 El Niño resemble differences between Pliocene and present-day SSTs (Figure 1). These inferences of Pliocene SSTs and 1997–1998 El Niño SST anomalies differ by 1.5°C or less. Thus, the small post-Late Miocene warming inferred by Anderson et al. (2015) might be a consequence of a warmer eastern Pacific at that time and might not require any elevation change. In order to examine what effect a permanent El Niño-like SST distribution might have had on temperatures in the Eastern Cordillera of Colombia during Pliocene time, we correlated SST and inland temperature anomalies from 1961 to 2016 between the two inland stations of different elevation and each El Niño region.

2. Tropical Pacific SSTs and El Niño

During normal conditions, cold water and high atmospheric pressure characterize the eastern equatorial Pacific, which contrasts with warm water and lower atmospheric pressure in the western equatorial Pacific. This east-west SST difference is coupled to the thermocline depth, which delimits the warm water near the surface from the colder water below, for the shallowest thermocline lies beneath the cold water in the east. During normal conditions the tropical Pacific air follows a circuit, the Walker Circulation, of surface westward winds, ascent over the warmest region in the western Pacific, returning eastward flow aloft, and subsidence over the coolest region in the eastern equatorial Pacific (e.g., Sarachik & Cane, 2010). Changes in these normal conditions can be associated with coupled ocean-atmospheric processes such as the El Niño–Southern Oscillation (ENSO); when warmer SSTs prevail in the east, the tropical thermocline deepens, the zonal atmospheric pressure difference decreases, and the Walker Circulation weakens. During this phase the Intertropical Convergence Zone moves into its southernmost position, and the Hadley circulation strengthens. This ENSO phenomenon affects global circulation causing temperature and precipitation changes in the midlatitudes (e.g., Sarachik & Cane, 2010).

Four regions are commonly used to quantify the SST state of the equatorial Pacific between 160°E and 80°W longitude (Figure 1). During the warmest phases of ENSO, an El Niño state, the eastern indices (Niño1+2 and Niño3) record the highest SST anomalies. El Niño events, which occur every 2 to 7 years, alter temperatures from the tropics to higher latitudes and global atmospheric circulation (e.g., Cane, 2005). During the last few decades there have been three major El Niño events, 1982–1983, 1997–1998, and 2015–2016, when anomalous high temperatures prevailed in the eastern equatorial Pacific.

3. Modern Data

To address the relationship of both high- and low-elevation sites in the Eastern Cordillera of Colombia with ENSO, we exploited the Koninklijk Nederlands Meteorologisch Intituut Climate Explorer database, which tabulates monthly mean temperature values. We used the two stations in the Eastern Cordillera of Colombia with decades of measurements: a high-altitude station in Bogotá at 2554 m and a low-elevation site in Villavicencio at 431 m on the eastern flank of the Cordillera. From these data we calculated annual mean SSTs and surface temperatures for the period from May of year 1 to April of the next, the period during which El Niño manifests itself. Mean monthly SST values spanning the same May to April period between 1961 and 2016 for each El Niño region were calculated from monthly values given by the Climate Prediction Center of the National Oceanic and Atmospheric Administration database.

To remove variability associated with seasonality, we took the mean surface temperature of the entire 55 year period and subtracted it from the corresponding annual values. Thus, we acquired annual temperature anomalies. In order to correct for warming during this period (e.g., Conroy et al., 2008), we removed the linear trend in the time series for each inland site and El Niño index and use the residuals for our estimations. Using a standard major axis (SMA) regression, we examined relationships between each normalized SST El Niño index and normalized annual temperature anomalies for Bogotá and Villavicencio (Figure 2). An SMA regression (e.g., Sprent & Dolby, 1980) has the form

$$y = b_0 + b_1 x \tag{1}$$

$$b_1 = \mathrm{sgn}(R)\left(\frac{\sigma_y}{\sigma_x}\right) \tag{2}$$

$$\sigma_{b_1} = |b_1|\sqrt{\frac{1-R^2}{n_{eff}}} \tag{3}$$

In our case y corresponds to temperature anomalies in Bogotá or Villavicencio, x corresponds to temperature anomalies of each El Niño index, b_o is the y intercept, which is zero here, because we use anomalies defined as differences from means, b_1 is the slope given by equation (2), where R is the correlation coefficient, σ_y and σ_x represent standard deviations, n_{eff} is the effective number of degrees of freedom, and 95% confidence limits

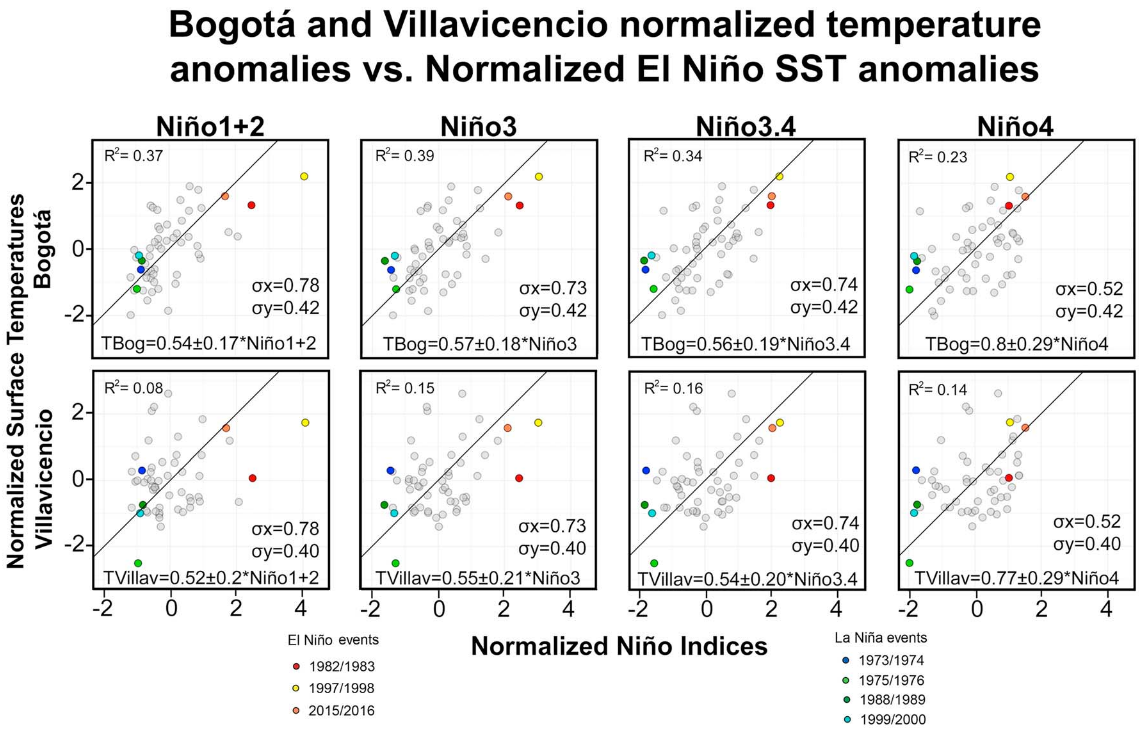

Figure 2. Scatterplots of normalized temperature anomalies (*y*) from (top row) Bogotá and (bottom row) Villavicencio versus normalized SSTs for each El Niño index anomalies (*x*). The normalization was made by dividing temperature anomalies (in °C) by the corresponding standard error (σ, also in °C). SMA regression was applied to all data (solid lines). To convert plotted values to temperatures, they should be multiplied by the corresponding values of σ_x and σ_y (shown in each plot). The highlighted colors indicate the biggest El Niño and La Niña events of the last 55 years (1961–2016). Each point corresponds to the anomaly in average temperature for May of year 1 to April of the next.

are given by $2\sigma_{b_1}$. Livesey and Chen (1983) and von Storch & Zwiers (1999, p. 115) relate the effective number of degrees of freedom, n_{eff}, to the number of data, n, and the autocorrelation of the time series:

$$n_{\text{eff}} = \frac{n}{1 + 2\sum_{k=1}^{n-1}\left(1 - \frac{k}{n}\right)\rho_k} \tag{4}$$

We found that autocorrelations of residuals, ρ_k, in these regressions were significant for only a lag of 1 year, $k = 1$, and values were typically ~0.5. So we used $n_{\text{eff}} \approx n/2 = 27$ in estimates of uncertainties.

In order to illustrate the temperature effect on land with different ENSO events, we highlight major El Niño and La Niña events in plots in Figure 2. Based on the Niño3.4 index, the three biggest El Niño events occurred in 1982–1983, 1997–1998, and 2015–2016, and the four biggest La Niña events in 1973–1974, 1975–1976, 1988–1989, and 1999–2000. The time interval used for each of these events spans 12 months from May of year 1 to April of the next.

During major El Niño events, SSTs in the eastern Pacific increase, and correlate with the warmest temperatures in Bogotá and Villavicencio. Correspondingly, during La Niña events when the eastern equatorial Pacific is relatively cold, negative temperature anomalies occur in Bogotá and Villavicencio. During major El Niño events, temperature anomalies in the eastern equatorial Pacific reach 4°C, whereas Bogotá warms by 2°C and Villavicencio by less than 2°C. During La Niña events, the east equatorial Pacific cools by 2°C, but Bogotá cools by only ~1°C and Villavicencio, in some cases, by ~2°C.

4. Discussion and Conclusions

Major El Niño events correspond to warmer temperatures in both Bogotá and Villavicencio. Taking in account the SMA regressions performed with all data and with only the major El Niño and La Niña events, the approximate slopes based on the three easternmost El Niño indices (Figure 2) are $b_1 \approx 0.5 \pm 0.18$ (2σ) for Bogotá and

$b_1 \approx 0.5 \pm 0.2$ (2σ) for Villavicencio. Because of the high uncertainty of Niño4 ($2\sigma \approx 0.3$) for both stations, we do not use it in our estimates. Using equation (1), we can scale the change in temperatures at Bogotá and Villavicencio when we know the change in SST of a Niño Index. This implies a change of 0.5°C in Bogotá and Villavicencio for every 1°C change in the eastern tropical Pacific.

In general, we expect that with warmer conditions, concentrations of water vapor in the atmosphere should increase, resulting in wetter environments, and reduced free-air lapse rates. This could cause more positive temperature anomalies at high- than low-elevation sites, at least where surface temperatures vary with altitude similarly to free-air lapse rates. Negative anomalies in rainfall, river discharges, soil moisture, and the normalized difference vegetation index (NDVI), however, have been recorded during El Niño events in Colombia (Poveda et al., 2011), which seems to render a water vapor feedback on the lapse rate ineffectual, consistent with our finding similar temperature dependences on El Niño for both elevations.

Because the Pliocene Epoch is the most recent period when global temperatures were warmer than those at present, inland temperature changes due to subsequent climate change should be explored. Paleoceanographic inferences of Pliocene SSTs along the Tropical Pacific match, within ~1.5°C, those of the biggest El Niño event, that of 1997–1998 (Figure 1). Both show a warmer eastern equatorial Pacific by as much as ~4°C. Taking into account the hypothesized El Niño-like SST state during the Early Pliocene, the SMA regressions suggest a modest change in temperature in the Eastern Cordillera of Colombia of 2 ± 1°C at both high- and low-elevation sites. A decrease in temperature of ~9–12°C since Late Miocene time, inferred from pollen (e.g., Hooghiemstra et al., 2006), obviously, cannot be explained by different tropical Pacific SSTs, and such a decrease either must be overestimated or must indeed call for an increase in elevation. For reasons given above, however, we doubt the latter inference. A possible scenario for the large inferred post-Pliocene change in temperature based on the vegetation belts over time could be the combined influence of precipitation and temperature on the distribution of vegetation, soil moisture, and water availability during the hypothesized Pliocene El Niño-like state (Poveda et al., 2001, 2011). Subsequent inferences of surface temperatures in the Eastern Cordillera suggest a cooling of 3 ± 1°C (1σ) since ~8 Ma (Anderson et al., 2015). This small change in temperature could be explained simply by a change in regional climate, associated with a different tropical Pacific SST distribution. Therefore, it would not require an elevation change of the Eastern Cordillera since that time. Moreover, it would not indicate a marked cooling, for example of ~2.5–4°C, as inferred for global temperatures, and would be consistent with negligible cooling of the tropics since Pliocene time.

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