# Quantitative estimates of glacial and Holocene temperature and precipitation change in lowland Amazonian Bolivia

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## ABSTRACT

**Quantitative estimates of temperature and precipitation change during the late Pleistocene and Holocene have been difficult to obtain for much of the lowland Neotropics. Using two published lacustrine pollen records and a climate-vegetation model based on the modern abundance distributions of 154 Neotropical plant families, we demonstrate how family-level counts of fossil pollen can be used to quantitatively reconstruct tropical paleoclimate and provide needed information on historic patterns of climatic change. With this family-level analysis, we show that one area of the lowland tropics, northeastern Bolivia, experienced cooling (1–3 °C) and drying (400 mm/yr), relative to present, during the late Pleistocene (50,000–12,000 calendar years before present [cal. yr B.P.]). Immediately prior to the Last Glacial Maximum (LGM, ca. 21,000 cal. yr B.P.), we observe a distinct transition from cooler temperatures and variable precipitation to a period of warmer temperatures and relative dryness that extends to the middle Holocene (5000–3000 cal. yr B.P.). This prolonged reduction in precipitation occurs against the backdrop of increasing atmospheric $CO_2$ concentrations, indicating that the presence of mixed savanna and dry-forest communities in northeastern Bolivia durng the LGM was not solely the result of low $CO_2$ levels, as suggested previously, but also lower precipitation. The results of our analysis demonstrate the potential for using the distribution and abundance structure of modern Neotropical plant families to infer paleoclimate from the fossil pollen record.**

**Keywords:** late Quaternary, paleoclimate, plant families, kernel density, Bolivia, Noel Kempff Mercado National Park.

## INTRODUCTION

The extent of the climatic change experienced by the lowland Neotropics and subtropics through the late Pleistocene (50,000–12,000 calendar years before present [cal. yr B.P.]), and in particular the Last Glacial Maximum (LGM, ca. 21,000 cal. yr B.P.), remains controversial (Anhuf et al., 2006). The most widely available records of lowland climate are from fossil pollen, but few LGM pollen cores for lowland Amazonia have been recovered (Bush et al., 2004a; Colinvaux et al., 1996; Haberle and Maslin, 1999; Mayle et al., 2000), and most climatic interpretations have been limited to qualitative, binary assessments of wet or dry and warm or cool (Bush and Silman, 2004). Although modern pollen rain analyses have improved the recognition of Neotropical vegetation types (e.g., Gosling et al., 2005; Weng et al., 2004), the disparate effects of temperature, precipitation, and $CO_2$ concentrations on the composition of tropical ecosystems have made quantitative vegetation-based climate reconstructions a challenge. Novel combinations of these environmental variables in the late Quaternary produced combinations of taxa not present today (Bush et al., 2004a), limiting the effectiveness of analogue-based climatic comparisons (Jackson and Williams, 2004).

As a result, the degree and underlying spatial dynamics of LGM climate in tropical and subtropical South America remain uncertain. Global LGM carbon dioxide levels were 35% lower than preindustrial levels (Monnin et al., 2001). Andean ice cores record isotopic evidence that tropical Pleistocene temperatures may have been depressed as much as 8–12 °C at high elevations (Thompson et al., 1998). Lowland cooling is suggested by the presence of *Podocarpus* pollen (Behling, 1996), but this interpretation is complicated by the fact that *Podocarpus* today is not restricted to high-altitude and low-temperature habitats (Gentry, 1986). The few non-plant-based estimates of lowland temperature change suggest an ~6 °C decrease from present, from both isotopic and elemental analyses of Caribbean corals (Guilderson et al., 1994) and Brazilian groundwater noble gases (Stute et al., 1995).

Geophysical evidence of lake levels (Baker et al., 2001) and Andean ice accumulation and dust levels (Thompson et al., 1998) indicate that LGM climate on the Bolivian Altiplano was substantially wetter than present, while hiatuses or reduced sedimentation rates in lowland Amazonian cores suggest a drier LGM climate (Ledru et al., 1998). The strongest evidence for a drier Amazonia comes from Laguna Chaplin in northeastern Bolivia, which today lies within humid rain forest but was surrounded by a mixture of semideciduous forest and savanna during the LGM (Burbridge et al., 2004; Mayle et al., 2000). However, qualitative analysis of this pollen record leaves uncertain the magnitude of precipitation change and the influence of temperature. The early through middle Holocene may also have been markedly drier than present (Mayle and Power, 2008), but as with the LGM, the magnitude of this precipitation decrease is unknown, and whether there were any accompanying temperature changes is even less clear.

In our study, we revisit the pollen records of Laguna Chaplin and neighboring Laguna Bella Vista, and present quantitative reconstructions documenting 50,000 yr of lowland Bolivian temperature and precipitation history. We employ a probabilistic model of plant family abundances (Punyasena, 2008) and identify distinct decreases in mean annual temperature during the Pleistocene (1–3 °C cooler than present) and extended Pleistocene-Holocene drying (300–400 mm/yr below present). In obtain-

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ing numeric estimates of climatic change for these two lowland Bolivian sites, our analysis demonstrates the unexplored potential of fossil pollen in reconstructing quantitative paleotemperature and paleoprecipitation histories when generic or species-level identifications are unavailable.

## LIKELIHOOD MODEL OF VEGETATION ABUNDANCE

Employing fossil plant families in climate reconstruction has inherent difficulties. Many tropical dry-forest clades are subsets of wet-forest families (Pennington et al., 2000). Consequently, only species identifications have been presumed to be climatically diagnostic (Prentice et al., 1992), leaving the palynological record, which is often restricted to family or genus identifications, at a disadvantage. Neotropical climate reconstructions have thus tended to rely on a limited number of indicator taxa (Bush et al., 2001), e.g., *Anadenanthera colubrina* (Fabaceae) as a dry-forest indicator (Mayle et al., 2004) or *Podocarpus* as a qualitative proxy for cooler climates (Behling, 1996; Haberle and Maslin, 1999).

However, analysis of the spatial distribution of Neotropical plant family diversity demonstrates that families exhibit clear climatic optima (Punyasena et al., 2008). This includes many widespread and ecologically important taxa such as Fabaceae, Arecaceae, and Bignoniaceae. Although these families are present across the entire lowland Neotropics, variation in the abundance and species richness within these clades diverge with respect to temperature and precipitation (Punyasena, 2008; Punyasena et al., 2008). A probabilistic model of abundance distributions within families, therefore, can potentially be used to reconstruct paleoclimate from fossil pollen assemblages. The model and methods are described in Appendix DR1 of the GSA Data Repository.[1]

## LAGUNAS CHAPLIN AND BELLA VISTA

Both Chaplin (14°28′S, 61°04′W) and Bella Vista (13°37′S, 61°33′W) are shallow (2.0–2.5 m in dry season), subsidence-formed lakes, 4–6 km in diameter. Both lakes are located ~225 masl within Noel Kempff Mercado National Park, a 15,230 km$^2$ protected area in northeastern Bolivia at the southern margin of Amazonian moist evergreen forests (Fig. 1). Precipitation is seasonal, with a pronounced four-month dry season, 1400–1500 mm of mean annual precipitation, and a mean annual temperature of 25–26 °C. Precipitation falls primarily in the austral summer and is the result of convective activity over the Amazon basin and southward displacement of the Intertropical Convergence Zone (ITCZ).

The Chaplin core is well dated, spans the past 50,000 yr, and is characterized by continuous sedimentation to the present. The Bella Vista core extends >50,850 $^{14}$C yr B.P. Its Holocene sequence is also well dated, but most of its Pleistocene ages are at, or close to, radiocarbon infinity, with a major sediment hiatus between 43,500 and 12,900 cal. yr B.P. Because of this hiatus, our Pleistocene analysis focuses on the Chaplin record. We calibrated all radiocarbon ages using the radiocarbon calibration curve of Fairbanks et al. (2005) (Tables DR1 and DR2 in Appendix DR2). Dates for individual samples are estimated by linear interpolation and are in calendar years B.P. Additional information on the collection, sedimentology, and palynological analysis of these cores is available from Burbridge et al. (2004).

Applying a pollen assemblage approach to these two cores, Burbridge et al. (2004) and Mayle et al. (2000) provide qualitative climate assessments. The appearance of *Podocarpus* in the LGM sediments of the Chaplin core is noted as consistent with cooling of up to 5 °C below present, while high percentages of grass pollen, with *Mauritia/Mauritiella*, Cyperaceae, *Curatella americana*, and negligible values of Moraceae, are indicative of savanna communities and a drier than present

[1]GSA Data Repository item 2008160, supplementary text, tables, and figures (Appendices DR1–DR3), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

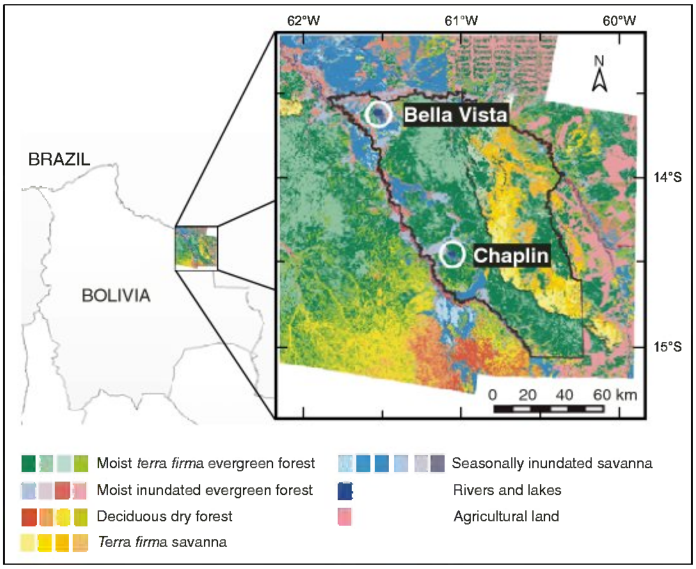


**Figure 1. Location of Lagunas Chaplin (14°28′S, 61°04′W) and Bella Vista (13°37′S, 61°33′W), with vegetation classifications derived from Landsat TM data. Noel Kempff Mercado National Park is outlined in black. Modified from Killeen et al. (1998).**

climate between ca. 50,000 and 2000 cal. yr B.P. Notably, late Holocene rain forest expansion was not synchronous at the two lakes (beginning ca. 2000 cal. yr B.P. at Chaplin versus ca. 3000 cal. yr B.P. at Bella Vista), and Mayle et al. (2000) suggest that this millennial lag may reflect differing climatic conditions or the time required for rain forest taxa to spread south from Bella Vista to Chaplin.

## CLIMATE RECONSTRUCTION RESULTS

In contrast to these prior studies (Burbridge et al., 2004; Mayle et al., 2000), the application of a family-based vegetation model to the Chaplin and Bella Vista data provides numerical estimates of temperature and precipitation changes, with explicit illustration of the level of uncertainty of these vegetation-based estimates. Weighted by change in percent abundance, these pollen counts demonstrate clear temporal shifts in glacial and Holocene temperature and precipitation. Fifty-three families are shared among the two cores and the likelihood model (Table DR3 in Appendix DR2). Rare families (those families represented by a single pollen grain in a given pollen sample) are excluded from the results illustrated in Figure 2. Estimates with and without these families are provided for comparison in Figure DR1 (Appendix DR2), and the role of rare taxa in reconstructing climate is discussed in Appendix DR3.

Our results indicate a tripartite temperature pattern through the Chaplin core. Intermediate temperatures characterize the oldest part of the core, prior to ca. 43,400 $^{14}$C yr B.P., although these estimates have a high level of uncertainty. The lowest temperatures (~22.5 °C; 1–2 °C below those of the Holocene and present day) occur in the Pleistocene between ~250 cm (ca. 43,400 $^{14}$C yr B.P.) and the LGM (155.5 cm; 21,110 cal. yr B.P.), with some variability in temperatures between 173.5 and 155.5 cm (35,280–21,490 cal. yr B.P.) (Fig. 2A). Immediately preceding the LGM (165.5–159.5 cm; 29,150–24,560 cal. yr B.P.), we see a transition to warmer temperatures, which remain broadly constant around 24 °C through the Holocene, despite high-frequency variability from single-stratum estimates in the middle Holocene (96–79 cm; 4750–3690 cal. yr B.P.) and the last two millennia (43.5–4.0 cm; 1400–70 cal. yr B.P.) (Fig. 2A). Notably, both surface sample estimates for Chaplin and Bella Vista (24 °C) underestimate the modern mean annual temperature by 1–2 °C (Figs. 2A and 2C). There are also three distinct stages in the precipitation history of Laguna

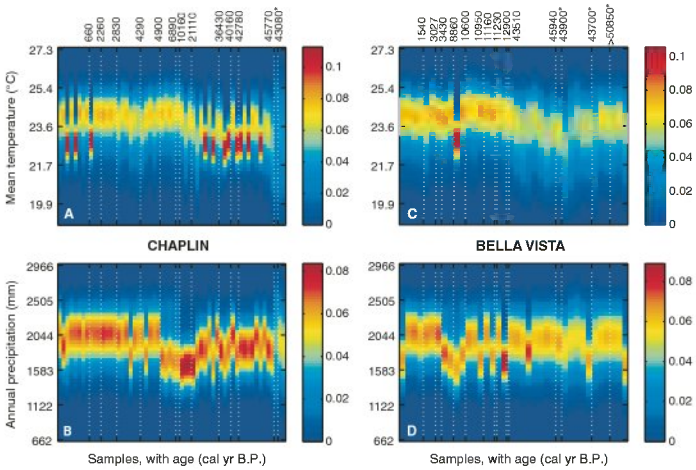


**Figure 2. Likelihood plots of estimated mean annual temperature (A and C) and annual precipitation (B and D) for pollen samples from Lagunas Chaplin (A and B) and Bella Vista (C and D) with rare taxa excluded. Samples are arranged in chronological order from youngest to oldest. Samples are not equally spaced, in terms of either depth or chronology. Radiometric dates from Tables DR1 and DR2 are noted along the *x* axis and are shown as cal. yr B.P. unless noted by an asterisk. Ages marked by an asterisk are in AMS $^{14}C$ yr B.P. Likelihood values range from blue (least likely) to red (most likely) and are measured as the percent likelihood per 0.2° C and 46 mm/yr. Although the range of uncertainty is large, clear shifts in temperature and precipitation are observed in the Chaplin core and, to a lesser extent, duplicated by the Bella Vista core.**

Chaplin (Fig. 2B). The lowest precipitation (~1700–1800 mm/yr) occurs between the LGM and the middle Holocene (159.5–101.5 cm; 24,560–5020 cal. yr B.P.), bracketed by highest precipitation in the late Holocene (~2100 mm/yr) and intermediate levels (fluctuating around 1900 mm/yr) prior to the LGM. A reduction in the Chaplin core sedimentation rates between 177.5 and 127.5 cm depth (36,900–7700 cal. yr B.P.) is roughly contemporaneous with the relative aridity of the late Pleistocene and early Holocene (Fig. 2B). Between 96 and 70 cm (4750–2860 cal. yr B.P.) there is also variability in precipitation, particularly when rare taxa are taken into account (Fig. DR1B). The latter is paralleled by the Bella Vista record, with alternating wet and dry estimates from the sediment hiatus at 132 cm (12,610 cal. yr B.P.) to 76 cm (10,170 cal. yr B.P.) followed by a distinct dry phase to 54 cm (5060 cal. yr B.P.) (Fig. 2D). When rare taxa are factored in, the inferred dry phase extends from the sediment hiatus to 40 cm (2890 cal. yr B.P.) (Fig. DR1D).

## DISCUSSION

Our analysis provides the first quantitative, simultaneous reconstruction of paleotemperature and paleoprecipitation from modern plant family abundance data for the Neotropics. Our results indicate that the LGM marks the greatest climatic transition for northeastern Bolivia, from an earlier glacial period, characterized by cooler conditions and high precipitation variability, to a late glacial through middle Holocene period, characterized by warmer and drier conditions. The middle Holocene also stands out as an important period of precipitation change, from previously drier conditions to a wetter late Holocene and present day, with largely stable temperatures. In identifying glacial cooling and a sustained dry period that persists until the middle to late Holocene, our results do not radically differ from the original qualitative interpretations of the Chaplin and Bella Vista records (Burbridge et al., 2004; Mayle et al., 2000). This increases our confidence in the results obtained using the family-level likelihood model. Our modern surface sample estimates underestimate modern temperatures by 1–2 °C and overestimate precipitation by 350–660 mm/yr, placing doubt on the absolute values derived from this model. Yet, relative changes are clearly evident and are supported by comparisons of other modern pollen samples (Punyasena, 2008).

The discrepancies between the results presented here and qualitative analyses by Burbridge et al. (2004) emphasize the utility of our approach in identifying climatic trends within the broader scope of vegetation change. Within the Poaceae-dominated savanna signal, which begins ca. 48,000 cal. yr B.P., our analysis shows that the most profound drying commences at the LGM (21,000 cal. yr B.P.) and continues into the Holocene, alongside increasing temperatures and $CO_2$ concentrations (Monnin et al., 2001). Although the initial savanna signal may have been induced in part by the physiological drought caused by lower than present $CO_2$ concentrations (Cowling et al., 2001), our results strongly support the hypothesis that the prolonged mixed savanna and dry-forest conditions of the northeastern Bolivian Pleistocene were as much a result of changes in water availability as of changes in atmospheric $CO_2$. The increase in precipitation observed at Chaplin in the late Holocene (5000–3000 cal. yr B.P.) is also earlier than what was qualitatively inferred (2000–660 cal. yr B.P.), and better matches the precipitation estimates of Bella Vista to the north. This suggests that a more generalized climate pattern is being inferred from the model and that it is less sensitive to localized differences in vegetation.

A cooler late Pleistocene Amazonia has been observed in other pollen studies (Behling et al., 2000; Bush et al., 2004b), and many tropical South American sites reveal an extended dry period in the early to middle Holocene (Baker et al., 2001; Bush et al., 2005; Mayle and Power, 2008). However, our results indicate an early deglacial transition to warmer temperatures, between 29,150 and 24,560 cal. yr B.P., in accord with Smith et al. (2005), who show that deglaciation in the tropical Andes preceded Northern Hemisphere deglaciation. This temperature increase coincides with a substantial decrease in rainfall. The lowest rainfall levels of the Chaplin record are at and following the LGM, and earlier glacial precipitation levels are not as high as those of the late Holocene. This is in contrast to the wetter than present climate observed at the LGM in the Altiplano (Baker et al., 2001; Thompson et al., 1998), indicating that unlike today, precipitation patterns in the Altiplano and the Bolivian lowlands were decoupled during the late Pleistocene.

Our approach to reconstructing past climate has several advantages over traditional approaches based on indicator taxa or pollen assemblages, which are concerned with the characterization of an ecosystem or biome and not individual taxa (Birks, 1998). Climatic estimates can be derived even when novel combinations of taxa ("nonanalogues") are observed in the fossil record (Jackson and Williams, 2004). Individualistic dynamics can be incorporated into estimates, and plant communities do not need to be assumed to be in equilibrium, as is the case for regression methods (ter Braak, 1995). However, unlike most regression techniques (e.g., WA-PLS [weighted averaging–partial least squares]), we are unable to extrapolate outside modeled ranges of temperature and precipitation and are limited to the range of climates found in our modern data set.

That climatic trends emerge at the plant family level is an important realization for palynologists and paleobotanists at multiple time scales. The model holds great potential for gleaning climatic information from Neotropical plant fossils, from pollen samples to leaf assemblages, even when faced with unreliable species identifications. This may be particularly valuable when attempting to reconstruct paleoclimate on pre-Quaternary time scales. Such estimates could be used in comparison with other methods of paleoclimate reconstruction, such as leaf margin and area analyses (Wilf, 1997). Family-level differences may be particularly evident in pollen records at ecotones such as Bella Vista and Chaplin, where there have been dramatic changes in the higher taxonomic composition of plant communities. The sensitivity and applicability of a family-based likelihood model to other communities, with more subtle vegetation changes, remain to be tested.

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