4 PALEOENVIRONMENTAL TRENDS IN VENEZUELA DURING THE LAST GLACIAL CYCLE

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This chapter summarizes and updates the main Quaternary paleoclimatic and sea-level trends recorded in Venezuela, and provides a paleoenvironmental framework for studies addressing biogeographical, ecological, and evolutionary topics. Venezuela has a number of localities that have provided paleoenvironmental sequences in the neotropical, circum-Caribbean domain, such as the Cariaco basin, Lake Valencia, the Mérida Andes, and the Guayana region (e.g., Markgraf 2000). Venezuela encompasses a wide range of physiographic, climatic, and biogeographic conditions because of its geographic location. This spatial heterogeneity has led to complex, but interesting, paleoenvironmental reconstructions.

Previous paleoenvironmental reviews (Rull 1996, 1999a) identified several thematic areas that needed further attention: modern analog studies with numerical calibrations, consistent evidence for the period before the Last Glacial Maximum (LGM), high-resolution records for the last millennium, and coordinated multiproxy studies. This review is focused on recent advances in these topics carried out during the last decade. This is not an exhaustive review, containing all the published paleoenvironmental studies, but is an attempt to identify the significant, well-documented climate/environment events and trends. The time frame considered is from the last glacial cycle, ca. 70,000 years onward, which is the period with more reliable, well-dated paleoclimatic evidence. Paleoenvironmental interpretations from poorly dated records are not considered here. Whenever possible, ages are presented as calibrated (or calendar) years or kiloyears before present (cal yr BP or ka BP); otherwise, radiocarbon years or kiloyears before present (^{14}C yr or ka BP) are used.

The review begins with a section on present-day environmental conditions, with emphasis on the relationship between climate and vegetation, a necessary aspect for paleoenvironmental reconstruction. This review is far from exhaustive, but provides the information necessary to understand the sections that follow. The second section is an account of the available paleoenvironmental evidence discussed by region. This basic information has been written by researchers currently working on the paleoecology and paleoclimatology of each area. The final section summarizes and organizes the information in a chronological perspective, from the last glaciation to the present, to identify events that are well established, as well as those that need additional research.

Present-Day Environmental Overview

Geologic and geographic features of Venezuela are described in earlier chapters. Here we emphasize the unique physiographic and biogeographic features of Venezuela, in the neotropical context. Venezuela lies between the Caribbean (N) and the Amazon (S) regions, and between the Atlantic (E) and the Pacific (W) sides of northern South America (plate 1). Physiographically, the country possesses high-mountain Andean environments reaching 5000 m elevation (the Mérida Andes), the northern Coastal Range (up to 2700 m elevation), the huge Orinoco lowland plains (the “Llanos,” around 100–200 m elevation) and the river’s large delta, the unique table mountains of the remote Guayana massif (the Guayana Highlands, up to ~3000 m elevation), part of the northern Amazon basin to the South, and the southernmost Caribbean coasts, which have a large number of small islands and archipelagos. From a biogeographic point of view, the Venezuelan territory forms part of the Neotropical Realm, with three of its regions represented. The Caribbean coasts, the Llanos, and the Lake Maracaibo basin belong to the Caribbean Region; the Mérida Andes is part of the Andean Region; and the Orinoco Delta, the Guayana Highlands, and the northern Amazon basin pertain to the Guayana Region (Berry, Huber, and Holst 1995). Roughly, the boundary between the Caribbean and the Guayana regions is the southern limit of the Orinoco river floodplain. In such a heterogeneous context, it is not surprising to find a high diversity of climatic and biotic conditions. Knowledge of the modern climate and biota is essential to understanding past changes.

Climate

Venezuela has a tropical climate without a cold season. The maximum difference between the average temperature of the hottest and the coolest month of the year is around 2°C or less (McGregor and Nieuwolt 1998). The average annual temperature depends on the altitude, and ranges from 24 to 27°C at sea level to slightly below 0°C in the higher Andean summits (Monasterio and Reyes 1980). In the mountain regions of Guayana and the Andes, a temperature decrease with altitude of ca. -0.6°C/100 m elevation is the norm (Salgado-Labouriau 1979; Huber 1995a). In contrast with the low seasonal temperature variability, the diurnal changes are remarkably high. In the northernmost part of South America, the difference between the daily maximum and minimum temperatures is commonly 10°C (McGregor and Nieuwolt 1998), and may reach 25°C in high mountain environments (Azócar and Monasterio 1980).

The precipitation regime of tropical South America is largely controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ), as a response to the annual insolation cycle (Poveda, Waylen, and Pulwarty 2006). The ITCZ is a low-pressure tropical belt of maximum cloudiness and rainfall, and its position is determined by insolation and the convergence of the northeast and southeast tropical easterlies (McGregor and Nieuwolt 1998). During the austral summer (December to March), the ITCZ is located over the Amazon basin, around 15° lat. S; whereas during the boreal summer (June to September), the ITCZ migrates to the north, reaching the southern Caribbean coast, around 10° lat. N (plate 1). As a result, two precipitation regimes exist: a continuous wet zone near the equator, and a zone with a marked dry season north of the equator. The first prevails over the Amazon basin, the Guayanas, and the northeast coast of Brazil (plate 1), and is characterized by total annual rainfall values >1500 mm, more or less evenly distributed throughout the year. In Venezuela, this occurs in the Orinoco delta, the northern Amazon basin, and the Guayana Highlands, where total annual precipitation may reach 3500 mm (Huber 1995a). The seasonal climate occupies two disjunct areas, to the north and to the south of the equator. Venezuela lies mostly in the northern area, where the dry season extends from December to March, when the ITCZ is in its southernmost position. The Venezuelan Caribbean coast is throughout the year under the control of easterlies, which determine air stability and, as a consequence, dry climates (300–600 mm/year) (plate 1). The presence of the Andean range modifies the general precipitation patterns locally. The southeast side of the Venezuelan Andes (also referred to as the "wet" side) is under the influence of wet trade winds that provide higher precipitation (~1500–2300 mm/year) than in the northwest or "dry" side (~700–900 mm/year), which is in the rainshadow. On the wet side, precipitation shows dependence on altitude; maximum values occur at ~2400 m elevation and decline above and below, a phenomenon not observed on the dry side (Monasterio and Reyes 1980).

Interannual climatic variability in tropical South America is primarily controlled by the quasi-periodic El Niño Southern Oscillation (ENSO), which has an average period of 4 years, with a range of 2–10 years (McGregor and Nieuwolt 1998; Poveda, Waylen, and Pulwarty 2006). The warm and cold contrasting phases of ENSO are characterized in tropical South America by anomalously warmer and drier "El Niño" years, versus anomalously colder and wetter "La Niña" years. In Venezuela, ENSO events are responsible for the intensification of land-sea temperature contrasts, which strongly affects the evolution of trade winds and, therefore, the intensity and distribution of precipitation (Pulwarthy, Barry, and Riehl 1992). A common sequel is the occurrence of wetter or drier than average rainy seasons, resulting in floods or droughts that have potentially catastrophic consequences (Giannini, Kushnir, and Cane 2000). Another source of interannual variability is the North Atlantic Oscillation (NAO), which seems to affect the strength of trade winds and the precipitation regime of tropical South America, but with less intensity than ENSO

(Giannini et al. 2001). The average NAO period is around 8 years, ranging from 2 to 18 years (da Costa and de Verdiere 2006).

Vegetation

Venezuela is among the seventeen megadiverse countries of the United Nations Environment Programme–World Conservation Monitoring Centre (UNEP-WCMC) (http://www.unep-wcmc.org/), and its flora and vegetation have been intensively studied. The vegetation patterns of Venezuela are complex, but relatively well known. Unfortunately, except for the Guayana region (Steyermark, Berry, and Holst 1995–2005) and a few isolated publications of international scope, the information is found in numerous local journals and books, as well as unpublished theses and reports. A well-documented synthetic vegetation map is provided by Huber and Alarcón (1988), who distinguish a dozen major units (plate 1). Most of Venezuela is covered by evergreen forests and savannas, with occasional gallery forests along river systems. Exceptions are the Mérida Andes and the Guayana Highlands, with special montane vegetation types; the northernmost coastal fringe, characterized by mangroves and dry vegetation; and the areas subjected to human disturbance, mainly covered by vegetation mosaics.

The main forested area lies south of the Orinoco and on its delta, close to the Guayana biogeographic region. According to Huber (1995b), forests cover more than 80% of the Venezuelan Guayana, and can be broadly subdivided into lowland and montane forests. Lowland Guayana forests occur from 0 to 500 m elevation and are mostly dense and evergreen, but there are also semi-deciduous and deciduous forests in the drier regions, as well as coastal, estuarine, and riparian forests in the Orinoco delta. Despite their apparent uniformity as seen from the air, these forests are surprisingly diverse in both architecture and floristic composition, due to the high degree of geologic, topographic, and edaphic heterogeneity. The montane forests range from 500 m elevation to the summits of the characteristic table mountains (tepuis), up to 3000 m. These forests are highly complex, due to the variety of physical environments they occupy, and exhibit great variability both horizontally and vertically. They can be roughly classified into basimontane, lower montane, montane, upper montane, and high-tepuian forests. Shrublands are not so extensive as forests, but they have attained an unparalleled degree of physiognomic and floristic diversity in the Venezuelan Guayana (Huber 1995b). As in the case of forests, spatial variability is high, and a similar altitudinal differentiation exists. Lowland grass savannas occur in Guayana in a belt along the southern margin of the Orinoco River, whereas upland savannas are present in a patch to the southeastern corner of the country, in the so-called Gran Sabana region. These savannas are similar to those growing in the extensive Orinoco Llanos, to the north (see below).

The vegetation from the tepui summits is unique in physiognomy and composition, and has provided the basis for the definition of the Pantepui floristic province, within the Guayana region (Berry, Huber, and Holst 1995). One of the most significant formations is the highland meadows, dominated by broad-leaved herbs of the family Rapateaceae (commonly *Stegolepis*), with negligible grasses and sedges, and a high proportion of endemic species.

The Orinoco Llanos are almost entirely covered by lowland savannas, the most extensive vegetation type of the Caribbean biogeographic region in Venezuela, covering around 25% of the country (Huber 1987). These savannas display comparatively low floristic diversity, and are dominated by C_4 tussock grasses of the genus *Trachypogon*. They are commonly referred to as *Trachypogon* savannas. Dispersed small trees of *Curatella* (Dilleniaceae), *Byrsonima* (Malpighiaceae), and the palm *Copernicia* are common in the predominantly herbaceous landscape (Sarmiento 1983). Gallery forests are frequent along the lengthy river courses that drain to the Orinoco western margin. A very characteristic type of gallery forest is the "morichal," formed by monotypic stands of the palm *Mauritia flexuosa*, which are especially abundant in the southern Llanos, and conspicuously absent elsewhere (Rull 1998a).

The orographic gradients largely constrain the vegetation patterns in the Mérida Andes and the Coastal Range. Human activities have also influenced the vegetation of these mountain ranges, especially in the piedmont, as can be seen in the geographic distribution of degraded areas (plate 1). In the Andes, the lowlands on both sides are strongly affected by agriculture and cattle ranching. Degraded terrains are intermingled with the presumably original semi-deciduous forests until about 1000 m elevation, where the evergreen forests begin and extend up to about 3000 m (Monasterio 1980). The uppermost layer (~2000 m upward) is cloud forest, which develops in a perhumid environment thanks to the quasi-permanent fog. These cloud forests are typically dense, with many tree ferns, lianas, and epiphytes. The position of the treeline, around 2800–3000 m, may be altered locally by human activities. Above it, the "páramos" dominate the high altitudes of the northern Andes until the snowline, around 4700 m elevation (Luteyn 1999). The transition from forest to páramo is gradual, characterized by transitional vegetation dominated by shrubs, referred to as "subpáramo." The páramo vegetation is open, with a low stratum dominated by grasses and cushion herbs, and a higher stratum dominated by shrubby columnar rosettes of *Espeletia* (Asteraceae), locally called *frailejones*. The uppermost páramo layer (3800–4000 m upward) shows progressive vegetation impoverishment, and is termed "superpáramo." The altitudinal boundaries of these vegetation types can be depressed by 100 to 500 m on the wet side of the cordillera.

The altitudinal arrangement of Coastal Range vegetation types is a result of the combined effect of elevational gradients, slope orientation, orographic precipitation, and a strong human pressure around the city of Caracas, the capital of the country, at ~900 m elevation. The flora and vegetation has been studied by Steyermark and Huber (1978) and Meier (1998). The lower levels are dominated by secondary savannas, which replaced the presumably original semi-deciduous forests after they were burned. At present, these dry forests still remain in the form of isolated patches around the city. Immediately above the savannas, there is a thin fringe of transitional forest (1600–1800 m elevation) that continues to the montane cloud forest, which extends up to 2200 m. Cloud forests are the most complex, species-rich, and endemic-rich forests in the Coastal Range. They are characterized by dense mists and low clouds. The high abundance of palms (*Geonoma*, *Ceroxylon*), epiphytes, and tree ferns is remarkable. The uppermost altitudinal level (2200–2700 m) is occupied by subpáramo vegetation, dominated by shrubs. Despite some floristic affinities (including a shrubby species of *Espeletia* and several common Ericaceae genera), the subpáramos of the Coastal Range are not analogous to the corresponding Andean formations.

Mangroves, one of the more characteristic tropical coastal communities, are well represented in the Caribbean coasts and the Orinoco delta of Venezuela (Conde and Alarcón 1993; Lacerda et al. 2002). Mangroves are dense evergreen forests living in a thin fringe along the coast, in semi-aquatic, brackish to hypersaline conditions. Along the Venezuelan coasts, as in most of the Caribbean region, these forests are dominated by a few species of the genera *Rhizophora* (Rhizophoraceae) and *Avicennia* (Avicenniaceae). Their prop roots form a complex aquatic habitat with a highly diverse fauna, and thus unique marine benthic communities. Thorn woodlands are xerophytic communities that occur along the dry coastal fringe and the Caribbean islands, but they are especially important in the northwest. The tree layer is dominated by sclerophyllous thorny evergreen species, mostly legumes, for example *Prosopis* (Matteucci 1987; Mateucci, Colma, and Pla 1999). Shrubby and columnar cacti like *Opuntia* or *Ritterocereus* (*cardones*) are frequent, both in the undergrowth and overtopping the tree layer. Columnar cacti are dominant in the so-called *cardonales* (cactus scrubs). The Orinoco delta is a huge (42,000 km^2) wetland system formed by a fluvio-marine sedimentary plain crossed by numerous distributaries and tidal channels. Luxuriant vegetation growing in these environments supports a rich terrestrial and aquatic fauna. *Rhizophora* and *Avicennia* form gallery/coastal forests along riversides and coasts. Swamp forests dominated by *Pterocarpus* (Fabaceae) and *Symphonia* (Guttiferae) grow behind the mangrove belts and develop landward. Meadows are dominated by Cyperaceae and ferns, and *Mauritia* palm stands occur inland. A great variety of lentic and lotic habitats contribute to the diversity of deltaic vascular plants (Huber and Alarcón 1988; Vegas-Vilarrúbia et al. 2007).

Modern Analogs

The use of modern analogs is widely recognized as one of the more sound approaches for Quaternary paleoenvironmental interpretation. This approach is founded on uniformitarianism, according to which present-day processes can be extrapolated to the past, a common procedure in Quaternary study. In this way, patterns of sedimentation of modern proxies and their relation to vegetation and environmental factors are characterized qualitatively or quantitatively, and then used to interpret past assemblages (Jackson and Williams 2004). In Venezuela, these studies began with the classical work of Muller (1959) on the Orinoco delta, in which modern pollen and spore deposition patterns were studied to reconstruct by analogy past (mostly Tertiary) paleoenvironmental sequences from oil-prone basins. Similar approaches were taken using particulate organic matter in the same delta and in a coastal lagoon in front of the Cariaco basin (Lorente 1992; Rull 1995). Modern and submodern sediments of the Orinoco delta were reinvestigated more recently to examine pollen-vegetation relationships, potentially useful for paleoecological reconstruction (Hofmann 2002). Local and surrounding plant taxa were well represented in pollen assemblages, but allochthonous pollens carried by water currents were also significant. The relative abundance of allochthonous pollen is higher in samples along permanent distributary channels than in more closed basins subjected to periodic flooding. In general terms, local and regional patterns of pollen sedimentation were considered satisfactory to characterize the different vegetation types and to use this relationship for inferring past vegetation. Another modern analog study of similar nature is available from northeast Venezuela, between the Orinoco delta and the Cariaco basin, in a sea-land transect involving mangroves and associated coastal communities (Rull and Vegas-Vilarrúbia 1999). The study used both pollen and non-pollen palynomorphs (NPP), and concluded that their pattern of sedimentation may be used for the reconstruction of sea level variations during the Holocene.

In the Mérida Andes, the first modern analog survey was carried out by Salgado-Labouriau (1979), who studied an altitudinal transect from the páramos. One of the main conclusions was the fairly consistent decrease, with increasing altitude, of the pollen of *Podocarpus* and *Hedyosmum* (two tree genera from the upper Andean forests), in a way that allowed estimation of the approximate altitudinal position of the treeline from their pollen percentages. In addition, Salgado-Labouriau (1979) was able to identify the main components of local and regional pollen assemblages from the páramos. Recently, a quantitative analysis on an expanded transect from the same region used Weighted Averaging–Partial Least Squares (WA-PLS) regression to develop transfer functions able to estimate altitudinal ecological displacements and temperature shifts from pollen assemblages deposited in peat bogs and fluvio-glacial sediments (Rull 2006). A representative Andean transect of lake surface samples was collected and will be analyzed using similar methods. Preliminary results of diatom analyses from two lakes are promising (Polissar 2005).

Modern sedimentation in the deep (~1400 m) anoxic Cariaco basin has been studied since 1995 using an array of sediment traps in the water column, coupled with marine current measurements, and periodic water sampling and analysis (Thunell et al. 2000, 2004). From these surveys it is known that sedimentation in the bottom of the basin is controlled by a characteristic annual cycle related to the seasonal migration of the ITCZ. During the rainy season (August to October), the bulk of sediment deposited is terrigenous (transported by rivers) and inorganic, forming a dark mineral-rich layer. During the dry season (November to May), the intensification of the trade winds produces upwelling, causing enrichment in dissolved nutrients and organic carbon, with a corresponding increase in primary productivity (Müller-Karger et al. 2001, 2004). As a result, a light-hued, biogenic, organic-rich layer is deposited. The overall sedimentary imprint is a package of laminated sediments composed by couplets of alternating light and dark seasonal bands (Müller-Kaerger et al. 2000). Terrigenous sediments are characteristically enriched in elements such as Al, Ti, Cr, K, and Fe, which are more resistant to weathering and diagenetic alterations, and reflect their provenance. The relative concentration changes of these elements and characteristic ratios have been interpreted to be related to seasonal changes in precipitation. For example, when the ITCZ is in its northernmost position (rainy season) there is a larger contribution of material with high Fe/Al and Ti/Al ratios, compared to the dry season (Martínez et al. 2007). Another interesting discovery is the strong relationship between the oxygen isotope composition of planktonic foraminifera and sea surface temperature (SST). A recent study using sediment trap data showed that the sediment $\delta^{18}O$ record of *Globigerinoides ruber* can be used to estimate mean annual SST (Tedesco et al. 2007). Furthermore, *Globigerina bulloides* proved to be useful to estimate temperatures during the upwelling (dry) season, using both $\delta^{18}O$ and Mg/Ca ratios (Black et al. 2007; Tedesco et al. 2007).

Paleoenvironmental Evidence

Venezuela contains several sites for paleoenvironmental reconstruction. The Mérida Andes are well suited for paleoecological studies because of the abundant high-altitude lakes and bogs available for coring. Venezuelan paleoclimatology began in these mountains, after the pioneering work of C. Schubert, who was the first to date and characterize unambiguously the geomorphological expression of the Mérida Glaciation, which is correlated with the Würm/Wisconsin maximum (Schubert 1974). Since then, geomorphological, sedimentological, and palynological research has proliferated and provided essential clues for elucidating north-Andean paleoclimatology. Lake Valencia, located in the northern Coastal Range (plate 1), provided a wealth of paleoclimate data (Bradbury et al. 1981). Research to date has been limited to the period since the late glacial. However, the basin probably contains very old Quaternary sediments (Schubert 1980). At present, the most important area for study of Venezuelan paleoclimatology is the Gulf of Cariaco, located on the northern continental shelf. It contains a deep (1400 m), anoxic marine basin filled with laminated sediments deposited since the last glaciation. In addition to possessing the longest paleoclimate record for Venezuela obtained so far, these sediments have provided the basis for radiocarbon calibrations back to approximately 30,000 cal yr BP (Hughen et al. 1998). The Venezuelan Guayana has been significant for Holocene paleoecology and paleoclimatology, through the analysis of Gran Sabana lakes and peats, and high-tepui peats. After the pioneering work of Schubert and Fritz (1985), this region demonstrated its great promise, not only for paleoclimatological studies, but also for ecological and evolutionary inferences (Rull 2007a).

Paleoenvironmental research in other regions has had relatively less impact, but the potential is high. In the Orinoco Llanos, permanent lakes and morichales could provide suitable sediments for paleoclimate analysis. Morichales are lowland streams in savannas with riparian forest dominated by the moriche palm (*Mauritia flexuosa*). Caribbean coastal lagoons and mangrove sediments hold the potential for excellent records of past environments. Caves may also yield interesting records through the analysis of their speleothems and organic sediments. Tree rings have been documented, but have yet to be used for paleoclimate reconstruction.

Mérida Andes

Continuous paleorecords of the climate history of the Venezuelan Andes are largely based on pollen studies, which have yielded qualitative and quantitative estimates of past temperature and precipitation fluctuations (Salgado-Labouriau 1984; Salgado-Labouriau and Schubert 1976, 1977; Salgado-Labouriau, Schubert, and Valastro 1977; Salgado-Labouriau et al. 1988, 1992; Rull 1998b, 2005a; Rull et al. 1987, 2005). More recently, outcrop and lake-core studies based on sedimentology, geochemistry, and stable isotopes have improved temporal resolution and shed new light on the details of climate variability in the Andes during the late glacial and Holocene (Mahaney et al. 2001, 2004; Dirszowsky et al. 2005; Stansell, Polissar, and Abbott 2007; Stansell et al. 2005; Polissar et al. 2006a, 2006b).

Prior to the last glacial to interglacial transition, conditions were generally more arid and cold, but detailed paleoclimate analyses of this period are only now beginning to emerge. Schubert and Valastro (1980) dated a fluvioglacial terrace, probably deposited under arid conditions, between about 50 and 34 ^{14}C ka BP. Further pollen analysis indicated the existence of a gallery forest at the same site, which was suggested as a possible humid refuge within a generally cold and dry glacial period (Salgado-Labouriau 1984). A series of short (~2000-year duration), alternating stadials (coolings) and interstadials (warmings) were proposed between >60 ^{14}C ka BP and the LGM (Mahaney et al. 2001, 2004; Dirszowsky et al. 2005; Rull 2005a), which have been roughly correlated with the Dansgaard/Oeschger (D/O) cycles recorded in ice cores (Dansgaard et al. 1993). Chronological uncertainties still prevent a detailed correlation. The LGM occurred between around 23 and 20 cal ka BP (Stansell et al. 2005), and the first estimates, based on the elevation of representative moraines, suggested a decrease in average temperature of 7°C with respect to the present (Rull 1998b). Additional information can be gained by investigating the pattern and magnitude of glacier equilibrium-line altitude (ELA) lowering. Stansell, Polissar, and Abbott (2007) investigated nine paleoglaciers in the Venezuelan Andes using field observations, aerial photographs, satellite imagery, and high-resolution digital topographic data. Results indicate that during the LGM ELAs were ~850 to 1420 m lower than present. This corresponds to a temperature decrease of at least 8.8 ± 2°C relative to today. The paleoglacial data from the Venezuelan Andes support other published records that indicate the northern tropics experienced a greater ELA lowering and possibly a greater cooling than the southern hemisphere tropics during the LGM (Lachniet and Seltzer 2002).

Several glacier readvances and retreats have been identified during the late glacial, the period from the LGM to the beginning of the Holocene (Stansell et al. 2005). The existence, or not, of a cooling reversal synchronous with the Younger Dryas (YD) chron remains controversial, though it has been clearly documented in the Cariaco basin (see below). Some recent evidence seems to favor such cooling (Mahaney et al. 2008), but dating accuracy is still insufficient, as is the case for the Neotropics, in general (van't Veer, Islebe, and Hooghiemstra 2000). Lake studies in the Venezuelan Andes indicate subtle, but measurable, paleoclimatic variations during the Holocene (Bradley et al. 1985; Weingarten et al. 1990, 1991; Salgado-Labouriau et al. 1992; Rull et al. 2005; Stansell et al. 2005; Polissar et al. 2006a, 2006b). For example, earlier work by Weingarten et al. (1990) used analyses of extractable iron and clay mineralogy to identify periods of warm-wet and cold-dry conditions. These results showed that high lakes (páramo and superpáramo environments) have less climatically sensitive records than lakes at lower elevations.

Recent work using lake records from the Venezuelan Andes documented regional changes in the moisture balance during the Holocene. Polissar (2005) used lake-level reconstructions from a closed-basin lake situated below the glacial limit to identify and date changes in Holocene moisture balance. This study noted that the Andes were generally wetter during the earliest Holocene, although there were short but intense periods of aridity. The Middle Holocene was a time of low lake levels and generally reduced precipitation/evaporation ratio (P/E balance) while the Late Holocene was wetter, with the wettest period occurring during the Little Ice Age. Considerable climate variability has occurred during the last 2000 years in the Venezuelan Andes. For example, Polissar et al. (2006a) used a 1,500-year lake-core record from Laguna Mucubají to reconstruct the recent glacial history of this basin. Four glacial advances occurred between AD 1250 and 1810 and appear to coincide with solar-activity minima. Temperature declines of -3.2°C and precipitation increases of 22% are required to produce the observed glacial responses. It is likely that this mechanism may also serve to amplify the effects of warming trends, irrespective of their origin, which raises the concern that global warming will adversely affect high-altitude, tropical montane regions (Bradley, Keimig, and Diaz 2004).

Lake Valencia

Lake Valencia occupies a Tertiary tectonic graben between two mountain ridges separated by the Victoria fault: the Cordillera de la Costa (Coastal Range) to the north, and the Serranía del Interior (Interior Range) to the south (plate 1). The lake is the largest natural freshwater body of northern South America, with an area of ~360 km^2 and a maximum depth of ~40 m. Lake Valencia has an extensive sediment record that may date to the mid Tertiary. Results of acoustic reflection profiles showed the existence of three distinct units: Unit I is a Holocene lacustrine deposit, while Units II and III would correspond to a lacustrine sedimentary sequence deposited during warmer periods prior to the last glaciation. A fourth unit was recognized, but its thickness could not be determined (Schubert 1980). The available paleoecological and paleoclimatological records cover the last 13 ^{14}C ka BP (~15 cal ka BP) and include seismic profiles (Schubert 1980), diatoms (Bradbury 1979; Bradbury et al. 1981), invertebrates (Binford 1982), sediment geochemistry (Bradbury et al. 1981; Lewis and Weibezahn 1981), pollen analysis (Salgado-Labouriau 1980; Leyden 1985), δ^{18}O records (Curtis, Brenner, and Hodell 1999), and biomarkers (Xu and Jaffé 2007). Almost all dates available for Lake Valencia have been published as radiocarbon years and have been calibrated here for consistency.

According to Curtis, Brenner, and Hodell (1999), the paleoenvironmental history of Lake Valencia can be divided into four main phases, from the latest Pleistocene to the Late Holocene. At the end of the Pleistocene (12.6 to 10 ^{14}C ka BP, or 14.8 to 11.5 cal ka BP), the climate was generally semi-arid but intermittently wet (Salgado-Labouriau 1980; Bradbury et al. 1981). The present location of Lake Valencia was occupied by marshy zones and ephemeral pools (Bradbury et al. 1981; Lewis and Weibezahn 1981). Sediments corresponding to this phase are clay-rich (Curtis, Brenner, and Hodell 1999), and animal microfossils and diatoms are infrequent or absent (Bradbury 1979; Bradbury et al. 1981; Binford 1982). Tree pollen has been found in low quantity, indicating that sparse grasslands and saline marsh vegetation were growing around the lake (Salgado-Labouriau 1980; Leyden 1985). Lake productivity was relatively low (Xu and Jaffé 2007), and sediment organic matter was derived mainly from terrestrial plants.

The second phase corresponds to the earliest Holocene (10 to 8.2 ^{14}C ka BP, or 11.5 to 9.2 cal ka BP), when precipitation increased, making the water level rise. During this phase, the lake became permanent, though lake-level fluctuations still occurred (Bradbury et al. 1981; Curtis, Brenner, and Hodell 1999). The sediment composition changed dramatically to organic marls and silts with higher carbonate and organic matter concentrations, which suggests permanent submergence (Curtis, Brenner, and Hodell 1999; Xu and Jaffé 2007). The existence of laminated sediments indicates water column stratification and anoxic conditions in the hypolimnion (Bradbury 1979; Binford 1982). Fauna and flora tolerant of brackish waters dominated the lacustrine environment (Bradbury 1979; Binford 1982). Animals characterstic of deep, clear water also appeared (Binford 1982). Tree and grass pollen increased, suggesting the presence of savannas and dry lower montane forests around the lake. Saline swamp plants suffered a drastic reduction (Salgado-Labouriau 1980; Leyden 1985). The lake was hydrologically closed (Curtis, Brenner, and Hodell 1999).

During the Early to Middle Holocene (8.2 to 3 ^{14}C ka BP, or 9.2 to 3.2 cal ka BP), lake levels reached a maximum, causing the water to outflow, and the lake became an open basin (Curtis, Brenner, and Hodell 1999). Laminations disappeared, and C/N ratios and biomarker data suggest a significant increase in planktonic/microbial primary production during this period (Xu and Jaffé 2007). Stromatolites, diatoms, and pollen, however, indicate the existence of two short dry periods of lower lake level around 7 and 3.3 ^{14}C ka BP (7.8 and 3.5 cal ka BP) (Bradbury 1979; Leyden 1985; Curtis, Brenner, and Hodell 1999). Ostracoda reflected water freshening, and diatoms showed a transition to alkaline, eutrophic waters (Bradbury 1979; Binford 1982). Most arboreal pollen types declined, and savanna species increased, suggesting a vegetation type similar to present (Leyden 1985). Pollens from aquatic plants were uncommon, and *Botryococcus* appeared. Overall, changes to basically modern aquatic and terrestrial assemblages coincided with the termination of lake stratification (Leyden 1985; Xu and Jaffé 2007).

The last phase corresponds to the Late Holocene (3 ^{14}C ka BP, or 3.2 cal ka BP, to the present). Increased metal (Na, Fe, K, Mg) concentrations suggest recent desiccation of the lake and a drop in stage below the outflow level. The lake was a closed basin again, as it is today (Lewis and Weibezahn 1981; Binford 1982; Curtis, Brenner, and Hodell 1999). Faunal remains notably declined (Binford 1982). Planktonic assemblages indicated the beginning of such closed conditions about AD 1700. A significant decline in arboreal pollen and an increase in grass pollen during the last centuries suggests anthropogenic deforestation and savanna expansion around the lake. The disturbance of catchment vegetation and soils due to agriculture promoted the development of present eutrophic conditions in the lake (Bradbury et al. 1981, Xu and Jaffé 2007).

Guayana Region

Guayana is one of the most pristine areas of the world and, hence a place to understand the role of natural environmental changes that operate alone to shape the modern biota (Rull 2007a). A recent study shows that around half of the neotropical species whose origin has been dated appeared during the Quaternary, suggesting that glacial periods influenced biotic diversification in the tropics (Rull 2008). Several speciation modes linked to climate change have been proposed (Rull 2005b; Noonan and Gaucher 2005), but Quaternary paleoclimatology is still in its infancy in Guayana, due to its remoteness and the difficulty of obtaining fieldwork permits (Rull and Vegas-Vilarrúbia 2008; Rull et al. 2008).

Most of the Guayanan records correspond to the Holocene, and have been obtained from peat bogs from the Gran Sabana and the tepui summits. Initially, the apparent absence of Late Pleistocene sediments in this region led to the hypothesis of extended aridity in Guayana before the Holocene, both in the Gran Sabana and atop the tepuis (Schubert and Fritz 1985; Schubert, Briceño, and Fritz 1986). However, subsequent studies changed this view. In the Venezuelan Guayana, paleoecological records begin around the Pleistocene–Holocene boundary, but the Hill of Six Lakes, situated around 100 km southwest, in the Brazilian Amazon, extends the regional record back to the last glaciation. Multiproxy evidence from sediments of three lakes shows cyclic oscillations in precipitation, as reflected in lake-level oscillations, apparently correlated with precessional Milankovitch cycles. Intense lowering occurred between 35 and 27 cal ka BP. During the LGM, palynological evidence is consistent with a 4–5 °C cooling, as indicated by 1000–1100 m downward migration of montane forest trees such as *Podocarpus* (Bush et al. 2004). The Pleistocene–Holocene boundary is present in the Mapaurí section, from the Gran Sabana, where a warming of 2–3 °C was documented by a 400–500 m upward migration of cloud forests (Rull 2007b). Such warming coincides approximately with the end of the YD chron, but no evidence of this event has been found so far in the region. A new lake sequence, extending back to 13 cal ka BP, is now under study.

In the Gran Sabana, the Holocene is characterized by a succession of drier and wetter phases, as deduced from lake-level fluctuations. The onset of the Holocene was characterized by a decrease in available moisture together with the warming previously mentioned, favored the expansion of savanna vegetation (Rull 2007b). The record is interrupted from the earliest Holocene until the Middle Holocene, when a wetter climate existed until about 4 ^{14}C ka BP (~4.6 cal ka BP), followed by a drier period until around 3 ^{14}C ka BP (~3.5 cal ka BP), and the return of wetter conditions, which lasted until the present (Rull 1991, 1992). The possibility of two extended drought phases during the last millennium, centered around 500 and 200 ^{14}C yr BP, has been suggested (Rull 1999b), but the evidence remains limited. The picture atop the tepuis is more complex. The record is fairly continuous from around 8 cal ka BP, but the paleoclimatic insensitivity of most localities, together with the dominance of local over regional phenomena, make correlations difficult (Rull 2005c, 2005d). The most significant finding to date has been the altitudinal displacement of the meadow-shrubland ecotone, tentatively associated with temperature oscillations. In this way, a phase cooler than present has been proposed between 6.5 and 2.5 cal ka BP, followed by warming up to 1.5 cal ka BP, when present climate was established (Rull 2004b, 2004c).

Cariaco Basin

This basin is an excellent location for studying paleoclimatic changes on a broad range of time scales. The annually laminated, non-bioturbated, and almost continuous record of unparalleled temporal resolution constitutes a useful tropical counterpart to higher-latitude marine and ice cores for the reconstruction of climate variability during the last glacial period (Hughen et al. 1996, 1998, 2000, 2004b; Peterson et al. 2000a). A number of studies of Cariaco sediments have focused on marine proxies that provide information on paleotemperatures and paleoproductivity (Peterson et al. 1991, 2000a, 2000b; Hughen et al. 1996; Lin et al. 1997; Haug et al. 1998; Black et al. 1999; Dean, Piper, amd Peterson 1999; Werne et al. 2000; Lea et al. 2003; Tedesco and Thunell 2003; Piper and Dean 2002). Recent reconstructions based on the terrestrial fraction have provided a clearer history of the movements of the ITCZ and the hydrological conditions over the adjacent continent (Clayton, Pearce, and Peterson 1999; Peterson et al. 2000a; Yarincik, Murray, and Peterson 2000; Haug et al. 2001, 2003; Hughen et al. 2004a; Drenzek 2007; González et al. 2008a, b).

The Cariaco record begins in the last glaciation. High-resolution reflectance measurements of the interval 60–25 ka BP, corresponding to Marine Isotopic Stage 3 (MIS 3), have clearly documented the abrupt stadial-interstadial shifts that characterized the D/O cycles and Heinrich Events (HEs) described in north Atlantic marine cores and Greenland ice records (Hughen et al. 2004a). Interstadials (warmings) are characterized by enhanced marine productivity, and increased precipitation and river discharge (as deduced from the elevated Ti and Fe content), as well as expansion of semi-deciduous forests; while stadials (coolings) show the opposite trends (Peterson et al. 2000a, 2000b; Haug et al. 2001; Peterson and Haug 2006; González et al. 2008a). Furthermore, during stadials, the enhanced orographic precipitation probably caused by stronger upward winds promoted the expansion of montane forests (González et al. 2008a). Heinrich events are characterized by lighter sediments and lower terrigenous input, and are almost indistinguishable from stadials (Haug et al. 2001; Peterson and Haug 2006). However, HE vegetation is clearly different and characterized by abrupt expansion of coastal salt-marsh vegetation, coinciding with peaks of carbon isotopes measured in leaf waxes (Drenzek 2007; González et al. 2008b). This suggests even drier climates and lower sea levels than those corresponding to "normal" stadials.

During the LGM, sea level was ca. 80–120 m below present level (Lambeck and Chappell 2001), the sills surrounding the basin became shallower, and the basin was mostly isolated from sediments derived from the Amazon and Orinoco Rivers. During full LGM conditions, Cariaco Basin sea surface temperature (SST) reconstruction based on Mg/Ca surface-dwelling planktonic foraminifera indicates a cooling of

2–3°C (Lea et al. 2003). Simultaneously, oxic sediments with low TOC and low carbonate content have been interpreted as signals of reduced marine productivity (Lin et al. 1997; Haug et al. 1998). In spite of the evidence of stronger and perhaps even more zonal trade winds during the LGM (e.g., Bush and Philander 1998), lowered sea level might have reduced drastically the principal connection between the basin and the open Caribbean, thus having a strong effect on nutrient availability and productivity. Higher Ti inputs and presumably enhanced terrigenous delivery during LGM, compared to that of the Holocene (Peterson and Haug 2006), might also have been related to lowered sea level and the more proximal drainage of local rivers.

The YD has been documented in the Cariaco sediments as a distinct cool (SST 3–4 °C less than today) and dry interval (Haug et al. 2001; Lea et al. 2003; Hughen et al. 2004a), with increased wind-driven marine primary productivity (Peterson et al. 2000a; Werne et al. 2000). This was followed by a period of increased precipitation and riverine discharge that occurred during the Holocene thermal maximum (HTM, 10.5 to 5.4 cal ka BP), reflecting a more northerly mean annual position for the ITCZ (Haug et al. 2001). A sharp anomaly around 8.2 cal ka BP in the grayscale record reflects enhanced trade-wind intensities (Hughen et al. 1996; Haug et al. 2001). Since ~5.4 cal ka BP, a trend toward drier conditions is evident from the Ti and Fe data, and has been related to a reduction in the seasonality of Northern Hemisphere insolation. The high-amplitude fluctuations and the precipitation minima recorded between 3.8 and 2.8 cal ka BP, and during the Little Ice Age, are best explained by southward shifts in the mean latitude of the ITCZ and enhanced ENSO activity (Haug et al. 2001, 2003). Similar to cold stadial conditions, the relationship between cold temperatures at high northern latitudes and dry conditions recorded by Cariaco sediments also holds true for the Little Ice Age (LIA). Drier conditions are indicated by at least three intervals of decreased Ti contents (Peterson and Haug 2006), accompanied by a pronounced 1.5°C SST cooling (Black et al. 2007).

In addition to the remarkable body of paleoclimatic evidence described above, the annually laminated Cariaco sediments have provided an excellent basis for calibrating ^{14}C dates. The Cariaco layers have been correlated with other annual layers such as those from Greenland ice cores, speleothems, and fossil corals, thus extending the limits of reliable radiocarbon dating to the last 50 ka (Hughen et al. 2004b; 2006).

Orinoco Llanos

In contrast to their Colombian counterparts, the Venezuelan Orinoco Llanos are nearly unknown from a paleoenvironmental perspective (see Behling and Hooghiemstra 2001). Most paleoclimatic interpretations and correlations based on geomorphology are purely speculative, because of the absence of radiometric ages. The Orinoco Llanos are mostly developed on the extensive Mesa Formation that, according to the few thermoluminiscence (TL) dates available, is of Pleistocene age (0.5 to 2 Ma BP, Carbón, Schubert, and Vaz 1992). The other features with some dates are fossil dunes (locally called *médanos*) that have been related to assumed glacial and Early Holocene arid phases. So far, two pulses of dune formation have been documented on the basis of TL and ^{14}C dating: one around 36 ka BP, and the other between 12 and 11 ka BP (Roa 1979; Vaz and García-Miragaya 1989). According to Iriondo (1997), the southward displacement of the ITCZ during the Late Pleistocene (tentatively LGM) promoted the dominance of arid climates in the Orinoco Llanos, thus favoring the development of dunes by eolian erosion of superficial sand and silt from the Guayana Shield and the shelf exposed by the lowered sea level. During the Holocene, after a humid soil-forming interval, the Llanos underwent a second eolian episode, probably less intense (Iriondo 1997). The Orinoco lowlands of Venezuela are still unexplored for continuous records of the last glacial cycle. Lakes and the palm swamps, locally known as morichales, should contain sediments suitable for study, as is the case of the Colombian Llanos, which are part of the same sedimentary unit (e. g. Behling, Berrio, and Hooghiemstra 1999; Berrio et al. 2000).

Caribbean Coasts and the Orinoco Delta

Sampling localities of paleoecological interest located along the northern Venezuelan coasts were summarized and mapped by Rull (1998b). Most of these sites record single events of the Holocene sea-level rise, but no continual sediment sequence has been identified to date. A preliminary general eustatic curve for the last 12 cal ka BP was constructed by assembling the available dated mangrove sediments and corals, as indicators of paleo sea levels (Rull, Vegas-Vilarrúbia, and Espinoza 1999; Rull 2000). The curve is asymptotic, with its maximum slope (~15 m/ka) between 12 and 7–8 cal ka BP. The rates dramatically decreased to ~5 m/ka) during the Middle Holocene, and almost stabilized around 0.2 m/ka during the last four millennia. This trend was found to be consistent with other Caribbean reconstructions, and has been supported recently by strikingly similar curves from the nearby islands of Curaçao and Trinidad (Klosowska 2003; Ramcharan 2004).

Field geomorphological studies combined with radiocarbon dating of selected short-core sediments and remote sensing analyses have contributed to a better knowledge of the Holocene evolution of the Orinoco delta (Warne et al. 2002; Warne, Guevara, and Aslan 2002; Aslan et al. 2003). In spite of the number of dated sediment cores, no proxy analysis, nor consideration of paleoclimatological interest, has been attempted so far. Similarly, the only reference to sea-level change is the characterization of the Holocene as a highstand epoch. The Orinoco delta is relatively well known in terms of vegetation and modern pollen analogs (see above), and a broad palynological survey of Holocene sediments may provide new and interesting paleoenvironmental information. Offshore sediments from the Orinoco delta fan have also been studied recently using diverse methodologies including sedimentology, mineralogy, and stable isotopes (Gonthier et al. 2002; Medina et al. 2005; Alfonso et al. 2006). The main aim of these surveys has been to identify broadly the sediment sources and post-depositional processes leading to the present-day configuration of shelf deposits. The lack of radiometric dating and detailed paleoclimate interpretation prevents the inclusion of the results of such studies in this review, but they are mentioned as potential sources of paleoenvironmental information in the future.

Caves

Two dated paleoclimate studies from cave material in Venezuela are preliminary, but show the high potential of this approach. Both caves are located in the north of the country, along the Caribbean coasts. One is based on radiocarbon dating of accumulated bat excrement (guano), and spans from the Late Pleistocene (37–29 ^{14}C ka BP) to the present (Urbani 1998). A tentative paleoclimate interpretation was attempted based solely on estimated sedimentation rates. It was proposed that climate shifted from arid to humid around 34–32 ^{14}C ka BP, and from humid to arid between 13.4 and 11.5 ^{14}C ka BP. Unfortunately, these events have not been confirmed with additional proxy analysis. Another study is based on speleothems. Carbonate speleothems, specifically stalagmites, may present annual laminations useful for high-resolution paleoclimatic studies (Baker et al. 1998). The method has been used with success in caves from tropical and subtropical Brazil (Bertaux et al. 2002; Cruz et al. 2006). In Venezuela, the first attempt used U/Th dating and isotopic (δ^{18}O, δ^{13}C) analysis (González and Gómez 2002). Although the authors consider their data preliminary, they interpret a major shift to drier conditions around 11.5–10.0 ka BP and an increase in moisture from about 7 to 2 ka BP. The same paper reports a 53.3 to 27.3 ka BP opal stalactite from the Guayana Highlands. Analysis would be important for understanding the paleoecology of the region, as it is the only record yet found that captures evidence from the last glaciation (Rull 2004a). More investigations of this nature are in progress (F. Urbani, pers. comm. 2007).

Tree Rings

Dendrochronology and related methods are among the most powerful high-resolution techniques for paleoclimate study in the temperate zone (Briffa, Osborn, and Schweingruber 2004). As the main cause for the existence of tree rings is seasonal temperature differences, existence of these rhythmic growth marks in the tropics has been controversial. The existence of growth rings in tropical trees is now confirmed, and the major causes proposed are short drought periods, long flooding events, and El Niño anomalies (Worbes 2002). In Venezuela, the tree rings documented so far are from forests of the western Llanos and the lower Orinoco floodplain, and the more plausible environmental forcings are precipitation and flooding seasonality (Worbes 1999; Dezzeo et al. 2003). No attempt to extract paleoenvironmental information has been done so far on these interesting structures, which remain an open field for research.

Synthesis

Four time periods are considered to summarize the paleoeclimate history in Venezuela since the last glaciation: the last glaciation, the late glacial, the Holocene, and the last millennium. The first three are discussed at a millennial time scale, while the fourth is discussed at centennial time resolution.

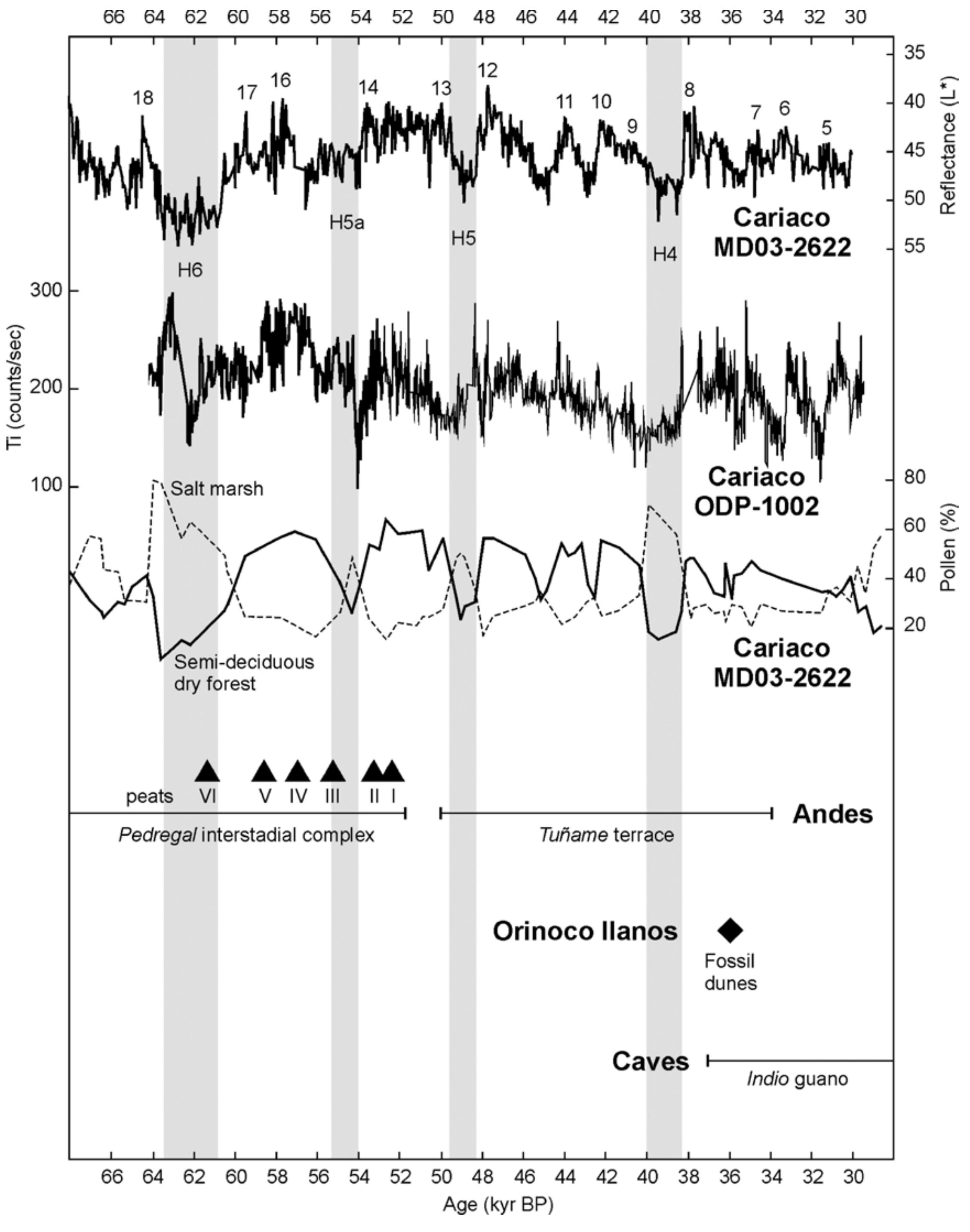
Fig. 4.1. *following page* Summary of paleoclimatic evidence for the last glaciation in Venezuelan sites. Cariaco basin reflectance and pollen records after González et al. (2008a). Titanium (Ti) data were taken from Peterson et al. (2000a), with ages recalibrated by González et al. (2008b) after Hughen et al. (2004b). S>Original data were downloaded from the World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/paleo.html (L. C. Peterson et al. 2001, Cariaco Basin ODP1002 Color Reflectance and Bulk Elemental [Fe, Ti, Ca] Data, IGBP PAGES/World Data Center A for Paleoclimatology Data Contribution Series #2001-020. NOAA/NGDC Paleoclimatology Program, Boulder, Colo., USA). For the Andes, the Pedregal interstadial complex was taken from Dirszowsky et al. (2005) and Rull (2005a), and the Tuñame terrace from Schubert and Valastro (1980). The fossil dunes in the Orinoco Llanos were dated by Vaz and García-Miragaya (1989), and the guano from El Indio cave by Urbani (1998). H4 to H6 (vertical gray bands) represent the Heinrich events 4 to 6 (González et al. 2008b).

The Last Glaciation

The Cariaco Basin record parallels the ice core records during the ~70–30 cal ka BP interval, as all the known Dansgaard/Oeschger cycles and Heinrich events are clearly shown in the reflectance curve (fig. 4.1). The strong relationship between these paleoclimate events and the salt marsh and semi-deciduous forest pollen curves is striking and merits further study, not only from a paleoclimatic perspective, but also from an ecological one. The availability of independent proxies of rapid response to climatic changes provides a unique opportunity to study the response of coastal and montane communities to environmental shifts, which may be used to forecast the potential response of similar ecosystems to future global warming and sea-level rise. The Andean evidence for this time interval suffers from dating uncertainty, and correlation at this stage is not possible. The lack of correlation between the peats assumed to be formed during the interstadial at Pedregal complex and the Cariaco D/O cycles is remarkable. The same is true for the fossil dunes from the Orinoco Llanos and the guano of Indio cave. They have been included in the correlation panel for the sake of completeness in a time period with very few records, and to show their relationship with the Cariaco curves in the present state of knowledge, in the hope that this will be useful for future research.

The Late Glacial

This time interval begins with the LGM, which has been documented in the Cariaco sea surface temperature (SST) reconstruction (fig. 4.2) and in the Mérida Andes, through glaciological studies. Estimates of LGM temperature depressions vary considerably, from 1 to 2°C in Cariaco, at sea level, to almost 9°C in the Andes, above 2900 m elevation. This implies a lapse rate notably steeper than at present, which has been tentatively


Cariaco MD03-2622
Reflectance (L*)
18
17
16
14
13
12
11
10
9
8
7
6
5
H6
H5a
H5
H4
Ti (counts/sec)
Cariaco ODP-1002
Salt marsh
Semi-deciduous dry forest
Pollen (%)
Cariaco MD03-2622
peats
VI
V
IV
III
II
I
Pedregal interstadial complex
Tuñame terrace
Andes
Orinoco llanos
Fossil dunes
Caves
Indio guano
Age (kyr BP)

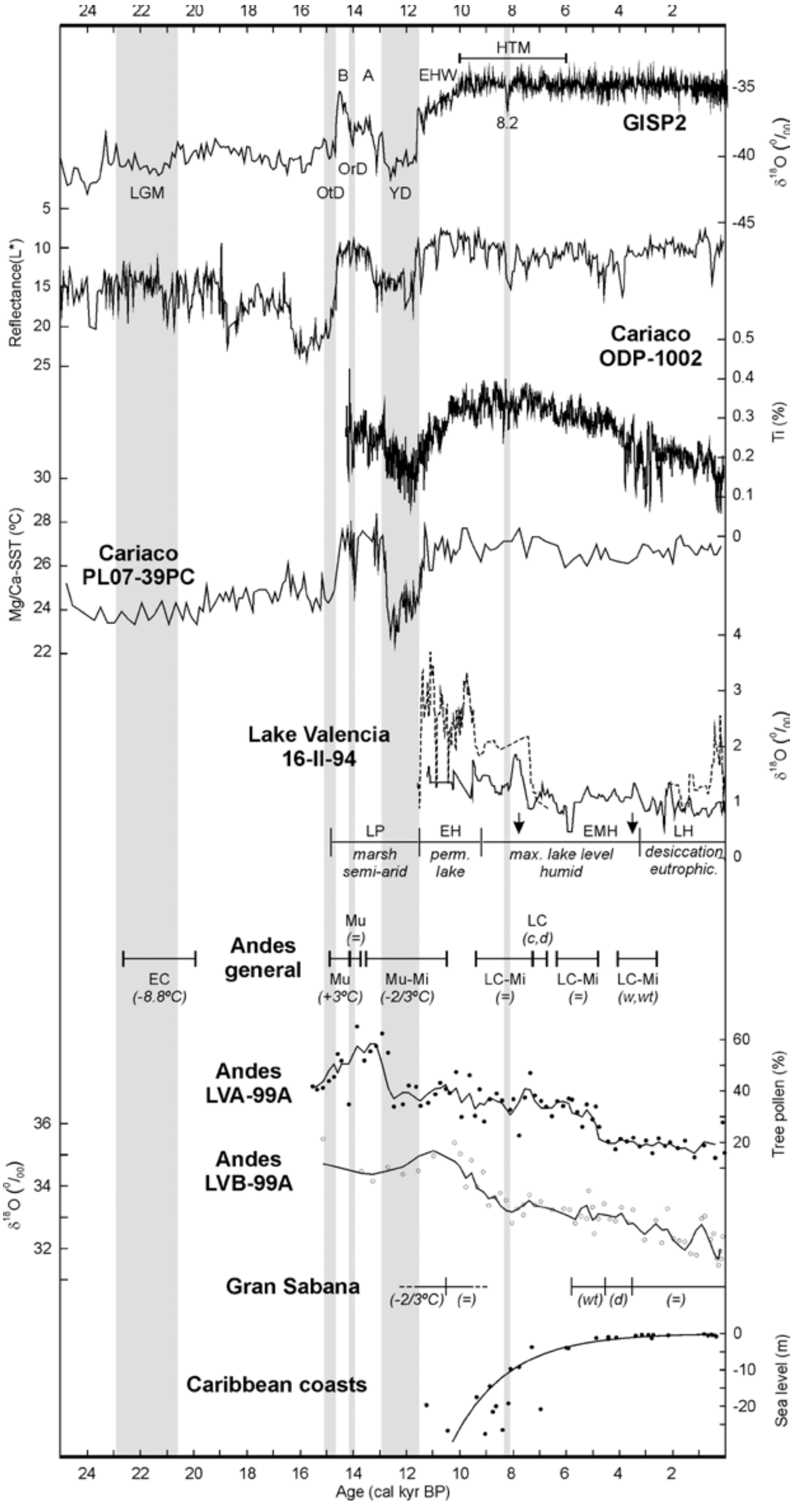


Figure 4.2. Summary of paleoclimate evidence since the LGM to the present, in Venezuelan sites. The oxygen-isotopic curve of the Greenland GISP2 ice core is shown for reference. *Downloaded from the World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/icecore/greenland/summit/document/gispisot.htm, file gispd18o.txt. Stadials and interstadials are from Stuiver, Grootes, and Braziunas (1995): B = Bølling, A = Allerød, OtD = Oldest Dryas, OrD = Older Dryas, YD = Younger Dryas. Early Holocene warming (EHW) and Holocene thermal maximum (HTM) according to Haug et al. (2001), Bjöcrk et al. (2002), Kaufman et al. (2004), and Kaplan and Wolfe (2006). The reflectance and Titanium (Ti) curves are from Haug et al. (2001), downloaded from the World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/paleo.html (G. H. Haug et al. 2001, Cariaco Basin Trace Metal Data, IGBP PAGES/World Data Center A for Paleoclimatology Data Contribution Series #2001–071. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA). The SST record is from Lea et al. (2003), downloaded from the same Web site (D. W. Leaet al. 2003, Cariaco Basin Foraminiferal Mg/Ca and SST Reconstruction, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2003-067. NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA). The oxygen isotopic record of Lake Valencia is from Curtis, Brenner, and Hodell (1999), downloaded from the World Data Center*

for Paleoclimatology (J. H. Curtis, M. Brenner, and D. A. Hodell, 2002, Lake Valencia, Venezuela Stable Isotope and Carbonate Data. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2001-063. NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA). The age scale has been modified from radiocarbon to calibrated years BP. Only two oxygen curves from ostracod species have been used. The four phases described by Curtis, Brenner, and Hodell (1999) are also represented: LP = Latest Pleistocene, EH = Early Holocene, EMH = Early-Middle Holocene, LH = Late Holocene. The Andes general phases and paleotemperature estimations are from Stansell, Polissar, and Abbott (2007) and Salgado-Labouriau (1989). EC = El Caballo, Mu = Mucubají, LC = La Culata, Mi = Páramo Miranda; w = warmer, wt = wetter, c = colder, d = drier; climate similar to present is represented by the symbol "=." Original radiocarbon dates have been calibrated to cal yr BP. The tree pollen curve from Andean core LVA-99A is from Rull et al. (2005), and has been smoothed using a 3-point moving average. The oxygen isotopic (opal) curve of core LVB-99A is from Polissar et al. (2006b), after raw data from Polissar (2005), and 3-point smoothing. The Gran Sabana phases and paleotemperature estimates have been taken from Rull (1991, 1992, 2007b), after calibration of radiocarbon dates. Symbols as in the Andes general phases. The sea level curve from the Caribbean coasts is from Rull (2000), using exponential fitting.

interpreted to reflect a drier atmosphere (Stansell, Polissar, and Abbott 2007). The YD cooling (reversal) is clearly visible in the Cariaco records, especially in the reflectance, Ti, and the SST curves, and is preceded by a warmer phase coinciding with the Bølling/Allerød warming. Surprisingly, the SST lowering during the YD is of the same magnitude as in the LGM. In the Andes, the tree pollen curve of Laguna Verde Alta (core LVA-99A) shows its maximum during the Bølling/Allerød, and a dramatic decline at the onset of the YD. The main proxy use to document these trends is *Podocarpus* (Rull et al. 2005). A recent study using non-pollen palynomorphs also suggests some YD signal in the same lake (Rull 2006). Recently, Mahaney et al. (2008) documented postglacial sediments and moraines containing several peat layers and wood fragments of ages ranging from 18.8 to 12.4 cal ka BP. Several Venezuelan records suggest a YD cooling, but moisture trends remain controversial. Indeed, the Cariaco Ti curve and the Lake Valencia record favor a drier climate, while other Andean records suggest that the YD occurred within the Mucubají cold and humid phase (Salgado-Labouriau 1989). The tentative interpretation of cave sediments also favors drier conditions. Further studies are needed to confirm this.

The Holocene

The Holocene begins with a warming trend (coinciding with the global Early Holocene warming), as recorded in the Cariaco SST curve and the Gran Sabana records, and lower sea level (20–25 m below the present), but with maximum rising rates (fig. 4.2). Inferences regarding moisture availability differ among the records. The Cariaco Ti curve and the Lake Valencia records (EH phase) indicate increasing precipitation, whereas the Gran Sabana records favor a shift toward drier and more seasonal climates (Rull 2007b). As the Gran Sabana is approximately 6° of latitude south of Cariaco and Lake Valencia, the position of the ITCZ would be important in this case (plate 1). During the Holocene thermal maximum, SST values stabilized, and precipitation attained maximum values in the Cariaco basin (Ti curve) and Lake Valencia. The 8.2 ka BP event is recorded in the Cariaco Ti curve, as a short drier event, and also in the Andean pollen and oxygen records, as small but consistent declines. Sea level attained a position similar to the present by the Middle Holocene, coinciding with the maximum levels of Lake Valencia and the Gran Sabana lakes. This contrasts with the decreasing tendency of the Andean oxygen curve, interpreted as a monotonous precipitation decrease throughout the Holocene (Polissar et al. 2006b), which coincides with the Cariaco Ti record from around 8 cal ka BP onward. The Holocene in South America has been recognized as paleoclimatically heterogeneous, especially with respect to moisture (Markgraf 2000; Markgraf and

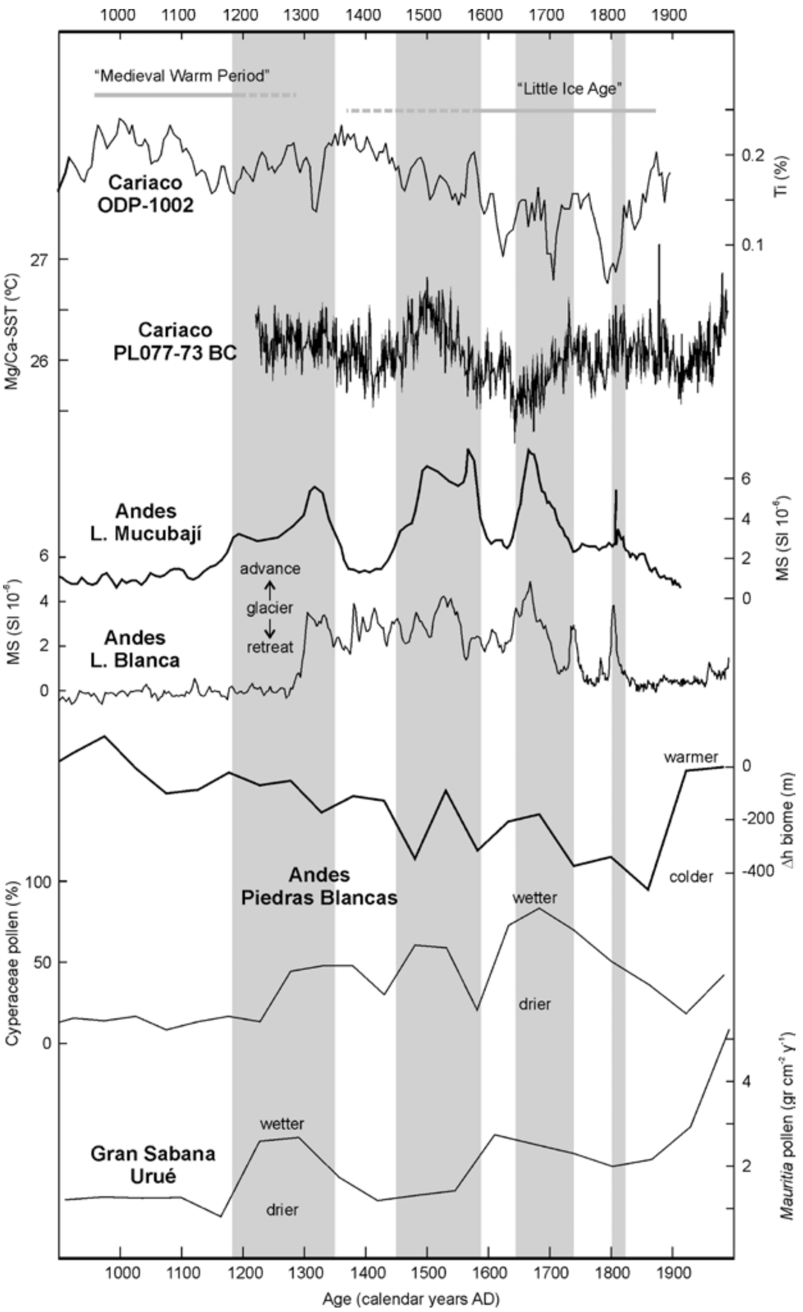


Fig. 4.3. Paleoclimate records for the last millennium in Venezuela. *The Cariaco Titanium (Ti) data source is the same as for figure 4.2; "Medieval Warm Period" and "Little Ice Age" according to Haug et al. (2001). The SST curve is from Black et al. (2007), as downloaded from the World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/paleo.html (D. E. Black et al. 2007. Cariaco Basin 800 Year Mg/Ca Sea Surface Temperature Reconstruction. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2007-097. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA). The L. Mucubají and L. Blanca magnetic susceptibility (MS), and the Piedras Blancas biome displacement records have been taken from Polissar et al. (2006a). The Piedras Blancas pollen data (Cyperaceae) are from Rull et al. (1987). The Gran Sabana record (Urué) corresponds to Rull (1999b) pollen data, after calibration of radiocarbon ages.*

Bradbury 1982). Such heterogeneity is thought to reflect spatial climatic heterogeneity similar to today, enhanced by the fact that paleoclimatic reconstructions are commonly based on isolated localities, where local phenomena may be highly influential and may obscure broader climate trends (Rull 1996). Continued study of Holocene records should help distinguish local from regional and global trends.

The Last Millennium

The most conspicuous features of the last millennium in the Venezuelan records are the multiple glacial readvances that occurred in the Andes during the last seven centuries, associated with the LIA. This is well documented in magnetic susceptibility records from Laguna Mucubají and Laguna Blanca (fig. 4.3), and most probably linked to cycles of solar activity (Polissar et al. 2006a). SST reconstructions from Cariaco records show generally warmer temperatures during the LIA, except at the time of the glacial advance centered at ca. AD 1700. These discrepancies cannot yet be fully explained, but moisture conditions, as well as temperature, must be taken into account to explain glacier dynamics. In the Andes, LIA glacier advances have been related to cold and wet climates, which is supported by pollen evidence (Polissar et al. 2006a). The Cariaco and the Gran Sabana records, however, are not consistent with this view. Once more, spatial heterogeneity appears and should be properly addressed. Such inconsistencies between inferred paleoclimate records may reflect spatial heterogeneity of past climate conditions, or an incomplete understanding of the proxies used to infer such records.

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