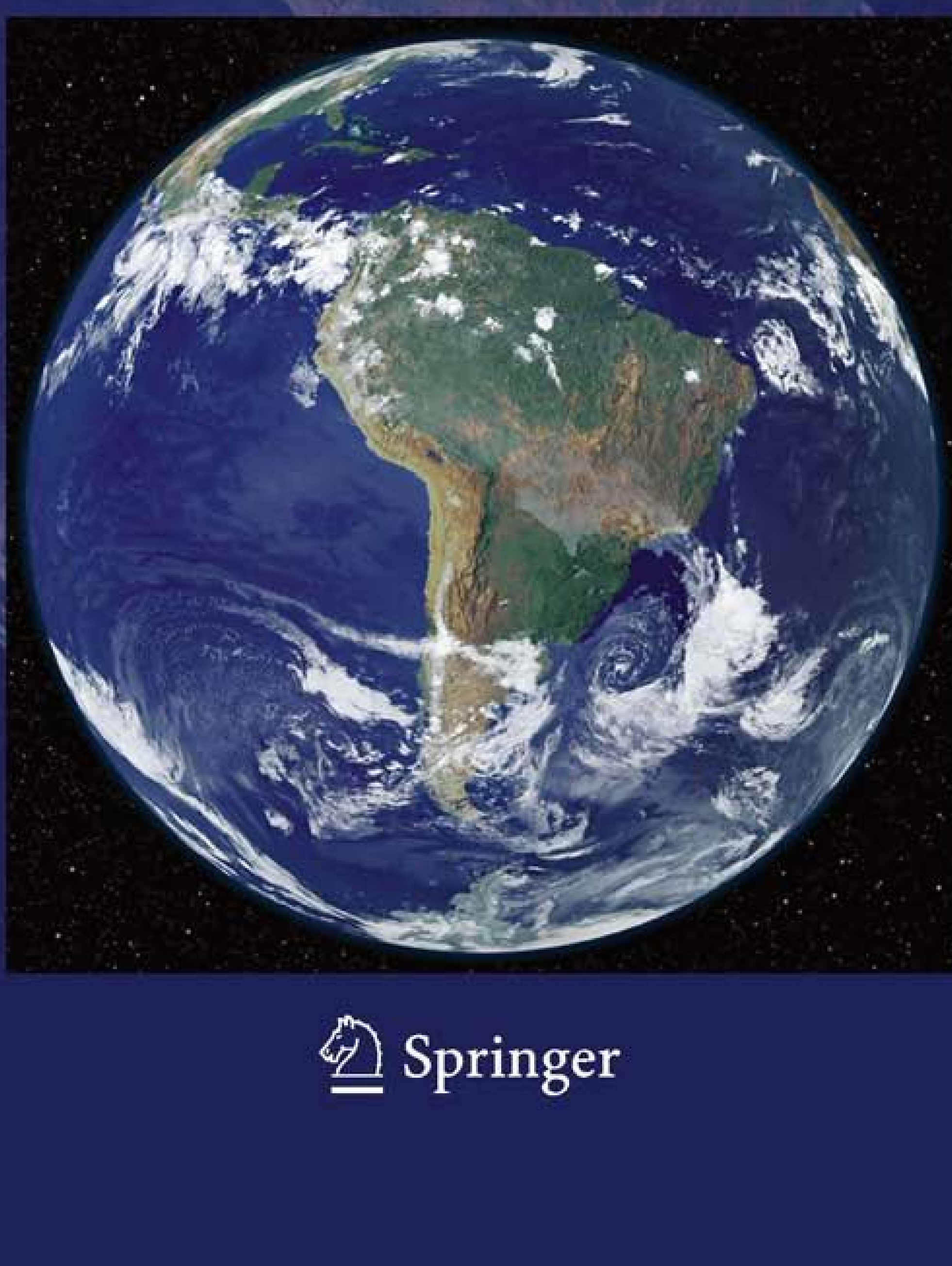
Past Climate Variability in South America and Surrounding Regions

From the Last Glacial Maximum to the Holocene

Volume 14

Edited by
FrançoiseVimeux, Florence Sylvestre
and Myriam Khodri



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Past Climate Variability in South America and Surrounding Regions

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Preface

South America is a unique place where a number of past climate archives are available from tropical to high latitude regions. It thus offers a unique opportunity to explore past climate variability along a latitudinal transect from the Equator to Polar regions and to study climate teleconnections. Most climate records from tropical and subtropical South America for the past 20,000 years have been interpreted as local responses to shift in the mean position and intensity of the InterTropical Convergence Zone due to tropical and extratropical forcings or to changes in the South American Summer Monsoon. Further South, the role of the Southern Hemisphere westerly winds on global climate has been highly investigated with both paleodata and coupled climate models. However the regional response over South America during the last 20,000 years is much more variable from place to place than previously thought. The factors that govern the spatial patterns of variability on millennial scale resolution are still to be understood.

The question of past natural rates and ranges of climate conditions over South America is therefore of special relevance in this context since today millions of people live under climates where any changes in monsoon rainfall can lead to catastrophic consequences.

We thus propose contributions that deal with tropical, temperate and high latitudes climate variability in South America with different type of archives and proxies on various timescales from the Last Glacial Maximum to the last thousand years. South America also offers a unique opportunity to examine climate fluctuations at various altitudes. The originality of this work is that it offers both observations and modelling works: we present contributions that aim at documenting paleoclimate histories and modelling studies are also included to help shed light on the relevant processes.

This book stems out from a 2006 Fall meeting American Geophysical Union (San Francisco, USA) session dealing with both overview and original researches on *Past climate variability from the last glacial maximum to the Holocene in South America and surrounding regions*. The 16 chapters in this volume are organized into three major parts. Part I, including 6 chapters, attempts at drawing a consistent picture for the Last Glacial Maximum in South America. Part II contains 4 chapters dealing with modern and past tropical and extra-tropical teleconnections with South America relying on both models and low to high latitudes ice core data comparison.

The third part of this book, containing the last 6 chapters, describes some aspects of the Holocene climate variability and specifically the southernmost part of South America which has been the subject of a growing attention during the recent years.

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Chapter 2
Orbital and Millennial-Scale Precipitation Changes in Brazil from Speleothem Records

Francisco W. Cruz, Xianfeng Wang, Augusto Auler, Mathias Vuille, Stephen J. Burns, Lawrence R. Edwards, Ivo Karmann, and Hai Cheng

Abstract Paleorainfall variability on orbital and millennial time scales is discussed for the last glacial period and the Holocene, based on a multi-proxy study of speleothem records from Brazil. Oxygen isotope ($\delta^{18}O$) records from Botuverá and Santana caves, precisely dated by U-series methods, indicate stronger summer monsoon circulation in subtropical Brazil during periods of high summer insolation in the southern hemisphere. In addition, variations in Mg/Ca and Sr/Ca ratios from speleothems confirm that this monsoon intensification led to an increase in the long-term mean rainfall during insolation maxima. However, they also suggest that glacial boundary conditions, especially ice volume buildup in the northern hemisphere, promoted an additional displacement of the monsoon system to the south, which produced rather wet conditions during the period from approximately 70 to 17 ka B.P., in particular at the height of the Last Glacial Maximum (LGM).

These $\delta^{18}O$ records, together with speleothem growth intervals from northeastern Brazil, have also revealed new insights into the influence of the northern hemisphere millennial-scale events on the tropical hydrological cycle in South America. This teleconnection pattern is expressed by an out-of-phase relationship between precipitation changes inferred from speleothem records in Brazil and China, particularly during Heinrich events and the Younger Dryas. We argue that the pronounced hemispheric asymmetry of moisture is a reflection of the impact of meridional overturning circulation conditions on the position and intensity of the intertropical convergence zone (ITCZ).

Keywords Speleothems · Brazil · Stable isotopes · Trace elements · South American monsoon · Insolation

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2.1 Introduction

Speleothems, secondary carbonate cave formations, have become key geological records for the reconstruction of regional to large-scale atmospheric circulation patterns associated with changes in precipitation regimes during the late Pleistocene and Holocene. Relatively long, high-resolution and well-dated oxygen isotope records from speleothems have provided important clues regarding the relationship between the hydrologic cycle of the (sub)tropical climate system and atmospheric/oceanic temperature variations recorded in northern hemisphere ice/marine cores during Dansgaard/Oeschger (D/O) and Heinrich (H) events (Dansgaard et al. 1993; Grootes and Stuiver 1997; NGRIP members 2004). These millennial-scale events occur as abrupt rainfall-related $\delta^{18}O$ changes, which interrupt the generally precession-driven tendency, as seen for example in speleothem records from China (Wang et al. 2001; Yuan et al. 2004). The same events are also responsible for most of the rainfall variability seen at full glacial times in the Indian/East African monsoon or in Eastern Mediterranean regions (Burns et al. 2003; Bar-Matthews et al. 2003).

Despite the increased knowledge about climate variations on millennial and orbital time-scales, the impacts of D/O, H-events and summer insolation on regional- and large-scale tropical atmospheric circulation patterns are not yet fully understood. Ti-Fe records off the coast of Venezuela (Peterson et al. 2000; Haug et al. 2001) and Brazil (Arz et al. 1998; Jennerjahn et al. 2004) provide some of the best evidence of how changes in sea surface temperature during D/O and H-events affected the tropical hydrological cycle in South America. For instance, an out of phase relationship, characterized by positive fluctuations in the tropical hydrological cycle of northern (southern) parts of South America, are observed in the former (latter) events, respectively. These observations have motivated paleoclimate simulations employing both coupled and atmospheric general circulation models (GCMs) (Chiang et al. 2003; Claussen et al. 2003; Chiang and Bitz 2005). Results from these experiments suggest that the expansion or contraction of land- and sea-ice during the Last Glacial Maximum (LGM) or during millennial events can lead to a displacement of the intertropical convergence zone (ITCZ) and produce precipitation asymmetries over tropical South America. However, Clement et al. (2004) argue that precessional forcing induces a stronger tropical hydrologic response than glacial boundary conditions.

Speleothems, together with other well-dated high-resolution paleoclimate records from low latitudes, especially from continental regions, can serve as a crucial test for these model experiments. In particular, models can help us understand how climate signals from high-latitude, millennial-scale events are transmitted through the tropical Atlantic to continental South America, ultimately affecting summer monsoon rainfall. Furthermore the high–low latitude phase-relationship and the exact timing of abrupt climate events in the southern hemisphere need to be assessed. Finally, it is also essential to document the relative geographic importance of the various forcings, as both summer insolation and millennial-scale events are thought to impact moisture transport and precipitation over the Amazon Basin and the tropical Andes (Seltzer et al. 2000; Baker et al. 2001a). Monsoon precipitation is antiphased between the two hemispheres on seasonal timescales, due to the seasonality of solar heating and related changes in the strength of the hemispheric Hadley cells (Dima and Wallace 2003; Biasutti et al. 2003). However, there is a need for further paleoclimate studies to reconstruct the precipitation patterns in South America and their related forcings.

Speleothem-based paleoclimate studies are a relatively late addition to the rapidly growing body of literature concerning past climates in South America. Carbonate (limestone, dolomite) areas – and thus caves suitable for speleothem growth – occur throughout South America, from $\sim$10° latitude north to $\sim$36° latitude south (Auler 2004), encompassing a wide range of climatic zones and all major biomes such as equatorial Amazon rainforest, semi-arid caatinga, central Brazilian savannas, Chaco swamplands, Atlantic rainforest, Andean grasslands and montane forests, and Patagonian pampas. South American speleothems have allowed new insights on regional precipitation and atmospheric circulation changes. They provide us with important archives for addressing paleoclimatic issues, such as the relative roles played by summer insolation and the glacial boundary conditions in shaping precipitation patterns (Fig. 2.1) within areas affected by the South American Summer Monsoon or the ITCZ (Wang et al. 2004, 2006, 2007a, b; Cruz et al. 2005a, 2006, 2007).

This chapter presents robust climate correlations of speleothem records in Brazil with contemporaneous records in South America and in the northern latitudes. The comparisons are based on independent chronologies as opposed to simply “wiggle matching”. This study is organized as follows: Section 2.2 reviews the spatiotemporal variability of stable isotopes in precipitation over South America and describes the results of modern calibration studies based on δ^{18}O and elemental ratios of cave drip waters. Section 2.3 presents Brazilian speleothem records and evaluates the most likely climate factors affecting their past δ^{18}O, Mg/Ca and Sr/Ca variations. Section 2.4 discusses precipitation variability in Brazil on millennial and longer time-scales from the last glacial period through the Holocene, summarizes possible climate forcings and shows how speleothem records reflect changes in regional to large-scale atmospheric circulation.

2.2 Climate Signals Recorded in Brazilian Speleothems

2.2.1 Climate Variability in South America Based on δ^{18}O in Precipitation

The stable isotopic composition of precipitation (δ^{18}O and δD) and its spatiotemporal variability over the South American continent have been the subject of a large number of observational, modeling and paleoclimatic studies. Early work focused on data made available through the network maintained by the International Atomic Energy Agency – Global Network of Isotopes in Precipitation (IAEA-GNIP). This database allowed for preliminary analyses of questions related to water recycling

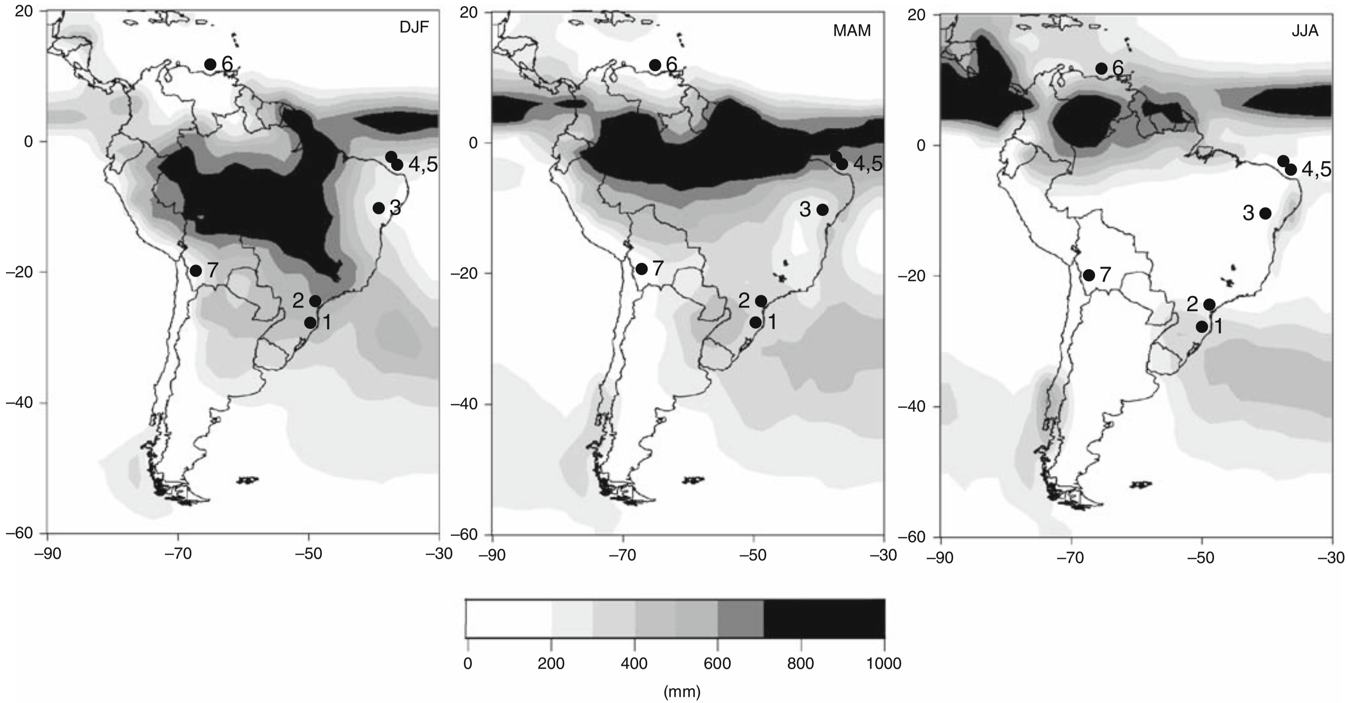

Fig. 2.1 Long-term mean (1979–2000) Climate Prediction Center Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) seasonal precipitation totals (in mm) for December-February (*left*), March-May (*middle*) and June-August (*right*). Precipitation over SE Brazil in DJF is related to the southward expansion and intensification of the South American summer monsoon, while in JJA precipitation is of extratropical nature and associated with midlatitude cyclonic activity over the South Atlantic. Precipitation in NE Brazil is mainly associated with the southern most position of the Intertropical convergence zone in MAM. Numbers in figure indicate locations mentioned in text: 1 – Botuverá Cave, 2 – Santana cave, 3 – Toca da Boa Vista cave, 4 – Marine cores GeoB 3104-1/GeoB 3911-3, 5 – Marine cores GeoB 3911-3, 6 – Cariaco Basin, 7 – Salar de Uyuni

and the evapotranspiration flux over the Amazon basin. It was observed that the isotopic depletion along an east–west trajectory was much lower than what one would expect based on a Rayleigh type law, despite intense rainout along the trajectory (Salati et al. 1979; Gat and Matsui 1991). This phenomenon can be explained by the intense water recycling taking place over the basin, largely accomplished through transpiration, which is a non-fractionating process, constantly recharging the atmosphere with relatively enriched water vapor. Only about 40% of the moisture flux returning to the atmosphere is isotopically light due to direct evaporation from lakes, rivers and forest canopy (Gat and Matsui 1991; Victoria et al. 1991). As a result the inland gradient of $\delta^{18}O$ in meteoric waters across the Amazon basin from the Atlantic coast to the Andes is much smaller than on other continents. Nonetheless, the long-range transport of moisture from the tropical Atlantic across the Amazon basin toward distant places such as the tropical Andes or subtropical South America leads to a clear depletion in heavy isotopes that can be traced to the degree of rainout upstream (Garcia et al. 1998; Vimeux et al. 2005; Vuille and Werner 2005). Once air masses reach the Andes, a much stronger depletion takes place with increasing altitude ("altitude effect"), due to progressive adiabatic cooling and condensation of atmospheric vapor as air masses are lifted along the Andean slopes (Gonfiantini et al. 2001).

The increasing number of stable isotopic paleorecords (ice cores, speleothems, records from lake and tree ring cellulose, etc.) emerging from South America have fueled the debate over the climatic controls on stable isotopes on interannual and longer time scales. Initially much of the attention was focused on ice core records from the tropical Andes, where the ancient composition of meteoric waters is directly preserved. Grootes et al. (1989) developed a simple transport model, trying to explain the inverse temperature-$\delta^{18}O$ seasonality observed on Quelccaya ice cap, Peru. Subsequent studies, however, showed that the more depleted $\delta^{18}O$ values during the austral summer are caused by an intensified hydrological cycle, where small-scale deep convection leads to the preferential removal of isotopically enriched molecules, thereby leaving the remaining water vapor increasingly lighter (Vuille et al. 2003a). The more intense the convective nature of an event, the higher the rainfall amount and the more depleted its isotopic composition. This process also leaves a significant imprint on interannual time scales, with a more enriched stable isotopic composition during dry years, and more depleted values when strong convective activity accompanies the monsoon season (Matsuyama et al. 2005; Vimeux et al. 2005). On average the interannual temporal slope of the $\delta^{18}O$- precipitation relationship ranges between –0.4 and –0.8‰/100 mm (Vuille et al. 2003a). Much of the spatial variability of this slope can be attributed to the different geographic locations, with high-elevation inland locations having much steeper slopes, while slopes at coastal lowland stations are weak.

This dependence of $\delta^{18}O$ on the precipitation amount has been exploited to use $\delta^{18}O$ from meteoric waters to study interannual climate variability over the South American domain, including the influence of El Niño-Southern Oscillation (ENSO) and the South American Summer Monsoon (SASM). Vuille et al. (2003a) performed a comprehensive study on the interannual variability of stable isotopes in precipitation over South America and its climatic controls, employing both General Circulation Models (GCMs) fitted with stable isotopic tracers as well as observational data from IAEA-GNIP. According to their results, later confirmed by similar studies (Vimeux et al. 2005; Sturm et al. 2007) stable isotopes record interannual variations of the hydrologic cycle, with a strong dependence on the precipitation amount ("amount effect") but are rather insensitive to temperature variability, at least north of $\sim 30°$S. In many regions where ENSO significantly influences the precipitation seasonal cycle, the stable isotopic variability therefore also shows a clear ENSO dependence. In most of tropical South America El Niño events are associated with below average precipitation, while precipitation is abundant during La Niña phases. Therefore El Niño years tend to be characterized by more enriched $\delta^{18}O$ values while they are more negative during La Niña (Vuille et al. 2003a). This is the case, for example, over the Amazon basin or at many Andean ice core locations (Henderson et al. 1999; Bradley et al. 2003; Hardy et al. 2003; Hoffmann et al. 2003; Vuille et al. 2003b). Similarly summers with an intense SASM season tend to show a more negative isotopic composition of monsoon precipitation than years where the SASM is weak. However, as shown by Vuille and Werner (2005), ENSO and the SASM are not independent of one another and, depending on the location, tend to either counterbalance or reinforce one another on interannual time scales. Therefore many regions of South America show a weakened relationship between $\delta^{18}O$ of precipitation and monsoon strength, once the SASM signal is decomposed into its ENSO- and non-ENSO-related variance. Southern Brazil is a notable exception to this rule as its isotopic variability appears to be little affected by ENSO and it therefore offers a great potential to study actual monsoon variability (Vuille and Werner 2005). These studies are fundamental for understanding short-term climate variability in high-resolution $\delta^{18}O$ speleothem records. Preliminary results from studies on speleothem layer counting revealed strong near-decadal variability that is correlated to the North Atlantic oscillation index, which imply in a possible oceanic forcing of monsoon rainfall (Soubies et al. 2005).

Southern Brazil is also an instructive example to demonstrate that the isotopic composition at subtropical regions can be significantly affected by atmospheric processes taking place in far away location upstream, within the tropics. Despite almost steady precipitation throughout the year, the isotopic composition of precipitation in southeastern Brazil is significantly more depleted during austral summer, when moisture is transported southward from tropical to subtropical latitudes by the Andean low-level jet (Fig. 2.1). This depletion is caused by the distant moisture source (recycled moisture from the Amazon basin and the tropical North Atlantic) of summer monsoon precipitation, when compared to the close proximity of the oceanic moisture source responsible for winter precipitation (Cruz et al. 2005b). In fact the tail end of depleted summer rainfall at $\sim 30°$S, where a sudden change to more depleted winter precipitation takes place, is a faithful recorder of the southernmost extent of the South American monsoon system (Rozanski and Araguás 1995). As suggested by Vuille et al. (2003a) and later confirmed by Cruz et al. (2005a) proxy records along this border are ideally located to investigate past variations in monsoon extent and intensity. The example from southern Brazil serves as an important reminder that caution should be exercised when interpreting the climatic controls on isotopic variability and that a simple conversion of isotopic values into "precipitation amount" may be misleading when upstream processes associated with deep convection and rainout or the varying influence of different moisture sources are ignored.

2.2.2 Factors Affecting the Isotopic Composition of Dripwaters and Modern Speleothems

Interpreting $\delta^{18}O$ of speleothems in terms of changes in isotopic composition of rainfall requires a good understanding of the hydrologic and geologic features that influence the response of $\delta^{18}O$ in the cave seepage waters to the rainfall recharge events.

This is particularly indispensable for relatively deep caves such as Santana and Botuverá (depth > 100 m), in southern/southeastern Brazil, because in this case the short-term $\delta^{18}O$ responses of dripwater feeding speleothems might be attenuated or even totally buffered due to the greater storage capacity and the resulting larger proportion of older reservoir water in the unsaturated karst aquifer right above the cave. Furthermore, speleothems with distinct $\delta^{18}O$ variations might be formed at different levels along the caves or at sites fed by drips with contrasting hydrologic characteristics, which might be produced by different rates of mixing between old and newly infiltrated waters. On the other hand, this problem is minimized in shallow caves in central Brazil, because of a smaller water reservoir in the aquifer above the cave and fast responses of drip waters discharge to rainfall events (Sondag et al. 2003).

A two-year monitoring program performed on soil and cave seepage waters from sampling sites with contrasting discharge values and located at 100 and 300 m below the surface in the Santana Cave System (Fig. 2.2) revealed important information on the temporal variation of the cave water $\delta^{18}O$ (Cruz et al. 2005b). First, a strong evaporative effect on the isotopic composition of soil and epikarstic waters can be ruled out because all the water infiltrating down to the cave conducts falls on the local meteoric water line. In addition, non-evaporative conditions can also be assumed for the cave environment given the approximate similarity of the observed mean cave temperatures of about 19°C in both Botuverá and Santana caves with the predicted values of temperatures obtained through the equation: $T_P = 16.9 - 4.2(\delta^{18}O_{calcite} - \delta^{18}O_{water}) + 0.13(\delta^{18}O_{calcite} - \delta^{18}O_{water})^2$(Craig 1965).

This suggests favorable conditions for deposition of speleothems close to isotopic equilibrium with their parental water; otherwise an evaporative enrichment of $\delta^{18}O$ in pool waters should be expected. Thus the oxygen isotopic composition of cave water can be primarily related to the rainfall, as evidenced by the similarity between the mean cave water $\delta^{18}O$ (5.34‰) and the annual weighted mean $\delta^{18}O$ of precipitation observed at IAEA stations along the Southern Atlantic coast (Vuille et al. 2003a).

Second, variations in groundwater $\delta^{18}O$ indicate that the climatic signal of recent rainfall events is rapidly transmitted through the relatively deep karst aquifer to

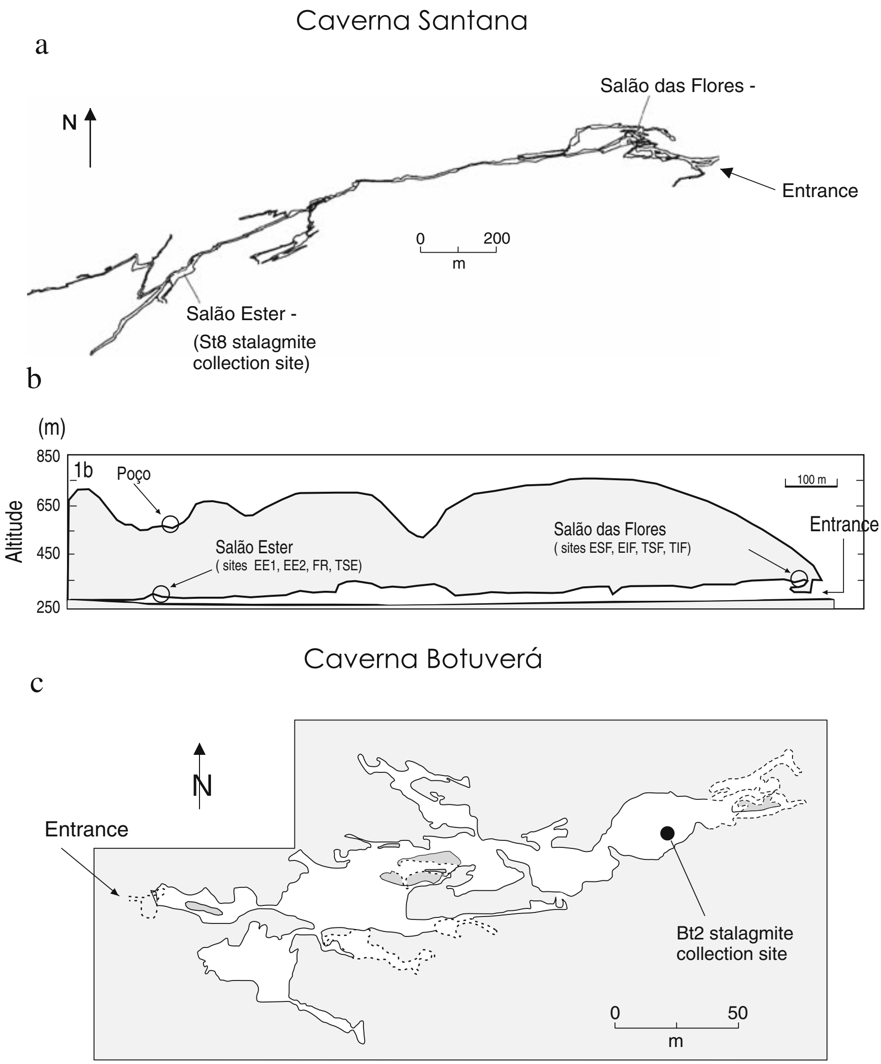

Fig. 2.2 (**a**) Plane view of Santana cave (modified from Viana Jr. 2002); (**b**) Cave longitudinal profile of Santana Cave showing the location of the drip-water monitored sites with depth and distance from entrance; (**c**) Plane view of Botuverá cave (modified from Zilli and Rabelo 2001)

the cave drip waters, regardless of cave location (Fig. 2.3). This is indicated by significant perturbations in the dripwater composition that occur approximately one month after periods of heavy rainfall at the Santana cave site (Cruz et al. 2005b). These δ^{18}O variations are possibly linked to more enriched rain waters from winter and early spring that are stored in soils and epikarst and later washed down at the peak of the summer rainy season. The lack of δ^{18}O variations seen in the second year of monitoring is associated with negative anomalies in winter precipitation (Cruz

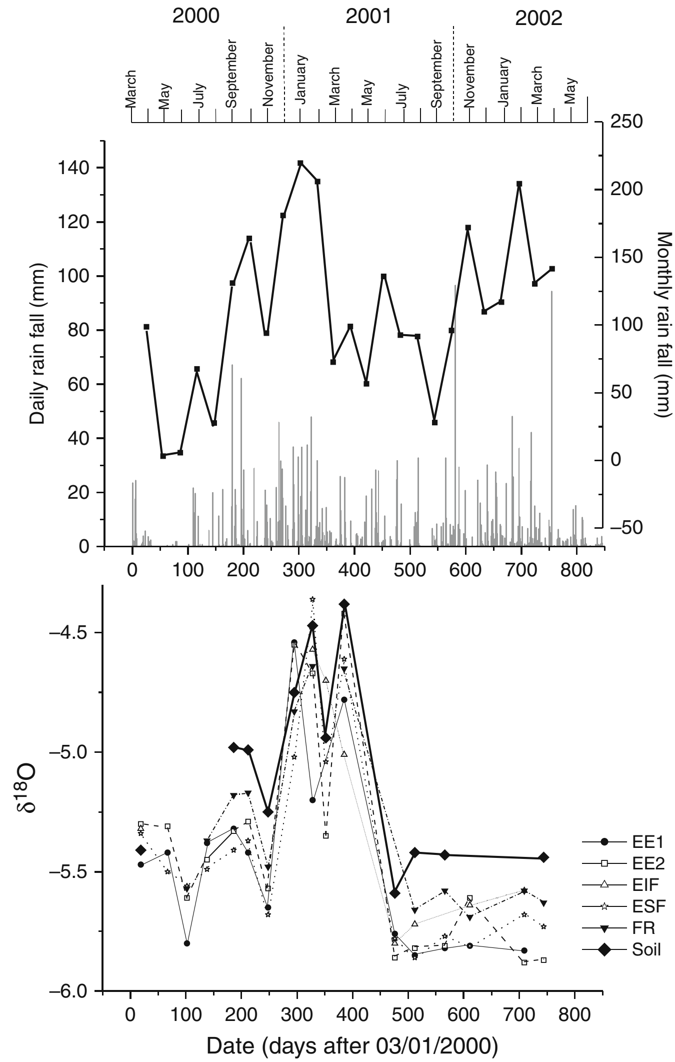

Fig. 2.3 *Top*: Daily and Monthly rainfall amount. *Bottom*: Time series of $\delta^{18}O$ for soil and drip waters at 300 m depth (EE1, EE2, and FR sites) and at 100 m depth (ESF and EIF sites) in Santana cave system

et al. 2005b). In addition, the simultaneous variations in $\delta^{18}O$ among sampling sites also suggest that effective mixing does not significantly influence the response of the drip-water composition to rainfall infiltration; otherwise different responses of infiltrated waters due to variations in aquifer thickness and time of residence should be expected between slow and fast drip flows, as reported in other studies (Ayalon et al. 1998).

These findings indicate that the isotopic composition of drip water is to a large extent influenced by the hydrological regime in which seepage flow occurs during periods of more effective recharge, when the storage capacity in the soil and epikarst zone is exceeded and the water accumulated in the upper parts reaches the whole karst profile in a short time interval. It also implies that CO_2 degassing in stalactite drips is unlikely to be a major factor affecting the isotopic composition of drip waters and consequently the calcite in Santana Cave stalagmites. Otherwise, different responses of infiltrated waters due to variations in time of residence and rate of degassing should be expected between slow and fast dripping speleothems. For example, a relative enrichment in both ^{18}O and ^{13}C caused by a rapid loss of CO_2 from solution has been observed in fast drip stalactites (Johnson et al. 2006; Wiedner et al. 2008).

Calibration studies in caves also provide important information on the relationship between regional climate and the $\delta^{18}O$ of waters forming speleothems. Comparison of cave waters and modern speleothems collected in Santana (24°31′S) and Botuverá (27°13′S) caves reveal a significant meridional gradient in the oxygen stable isotopic composition (Fig. 2.1). The $\delta^{18}O$ of both water and speleothems from Botuverá are more enriched than those from Santana cave by approximately 1‰. The mean $\delta^{18}O$ values in the latter cave are -5.34 ± 0.40‰ (SMOW) and -5.72 ± 0.31‰ (PDB), while in the former cave they are -4.28 ± 0.28‰ (SMOW) and -4.49 ± 0.42‰ (PDB), for drip water and modern speleothems, respectively. These differences in $\delta^{18}O$ have been attributed to changes in the regional rainfall composition as both caves present very close internal temperatures ($\approx$ 19°C) and there is no significant difference in the altitude of the rainfall recharge area. Results suggest that the more enriched values at Botuverá are due to a larger relative contribution of Atlantic moisture and less Amazonian moisture than at Santana. Botuverá has $\sim$20% more precipitation during winter to early spring (July–September, $\delta^{18}O$ mean $\approx$ –3‰) and $\sim$27% less during summer than Santana (December–February, $\delta^{18}O$ mean $\approx$ –7‰).

2.2.3 The Influence of Rainfall Amount on Mg/Ca and Sr/Ca Ratios in Speleothems

Present-day relationships between the Mg/Ca and Sr/Ca ratios of speleothems and climate were studied through a four-year monitoring program of water geochemistry and hydrology performed in the Pérolas-Santana cave system (Karmann et al. 2007). This study evaluated the significance of the commonly reported dissolution and precipitation processes and their possible relationships with changes in rainfall recharge by analysing hydrochemistry and hydrological parameters in different compartments of the cave system such as soil cover, cave drips and rimstone pools and rivers.

It was shown that the ratios of drip water above actively growing speleothems decrease at the height of the wet season, which is driven by the South American Summer Monsoon in the area (from November to February), while it was increasing during the dry season (from May to August). This relationship was found at drip water sites located in different depths of the cave and with contrasting drip discharges (Fig. 2.4). The most likely process controlling the Ca, Sr and Mg variability in drip waters is the prior calcite precipitation (PCP), which occurs in the unsaturated zone right above the cave (Fairchild et al. 2000; McDonald et al. 2004).

This process is more effective during the dry season when air circulation is enhanced in the upper portions of the karst system due to the low level of the aquifer, which favors the calcite precipitation. PCP increases the Mg/Ca and Sr/Ca ratios because Ca is preferentially incorporated in calcite crystals relative to Mg and Sr as the partitioning coefficients for both Sr ($D_{Sr} = (Sr/Ca)_{calcite}/(Sr/Ca)_{solution}$) and Mg ($D_{Mg} = (Mg/Ca)_{calcite}/(Mg/Ca)_{solution}$) are less than 1 in the low-ionic strength waters (Huang and Fairchild 2001). It affects all the waters in the cave system except the soil and runoff samples because dissolution processes prevail in the epikarstic or surface zone.

Other processes such as groundwater residence time and CO_2 degassing in drip solution are considered less important for the geochemical variations in Santana Cave. The latter has been reported as being an important mechanism, which increases the Mg/Ca and Sr/Ca ratios of the host stalagmite due to progressive removal of C and Ca from a saturated solution during carbonate precipitation in stalactite tips (Johnson et al. 2006). However, the epikarstic waters are always undersaturated with respect to calcite and their variations in Mg/Ca and Sr/Ca ratios differ substantially from those in dripwaters. In addition, simultaneous and relatively rapid variations in the Mg/Ca and Sr/Ca of stalactite drips (Karmann et al. 2007), also observed in $\delta^{18}O$ of water (Cruz et al. 2005b), rule out a major control on trace element ratios by CO_2 degassing (Fig. 2.4). Otherwise a different response of infiltrated water due to variations in time of residence and rate of degassing would be expected between slow and fast drip flow speleothems. Indeed, the elemental ratios are more consistent with variations in rainfall amount than drip discharge and, therefore, can be utilized as a proxy for the past variations of the South American Summer Monsoon. High Mg/Ca and Sr/Ca values are spatially associated with the secondary calcite precipitated in the vadose zone above the cave, which occurs during dry periods, characterized by aquifer low stands.

2.3 Paleoclimatic Changes from Speleothem Records

2.3.1 U/Th Chronology of Speleothems

A major strength of speleothem records is the potential for precise and accurate age control. Carbonate speleothems from tens of years to ~600,000 years are potentially datable by the ^{238}U-^{234}U-^{230}Th disequilibrium techniques (Richards and Dorale 2003). Because solubility of U in groundwater is extremely different from that of Th, a growing speleothem includes U into its crystal lattice but incorporates negligible ^{230}Th (Gascoyne 1992). If the crystal lattice remains a closed system with respect

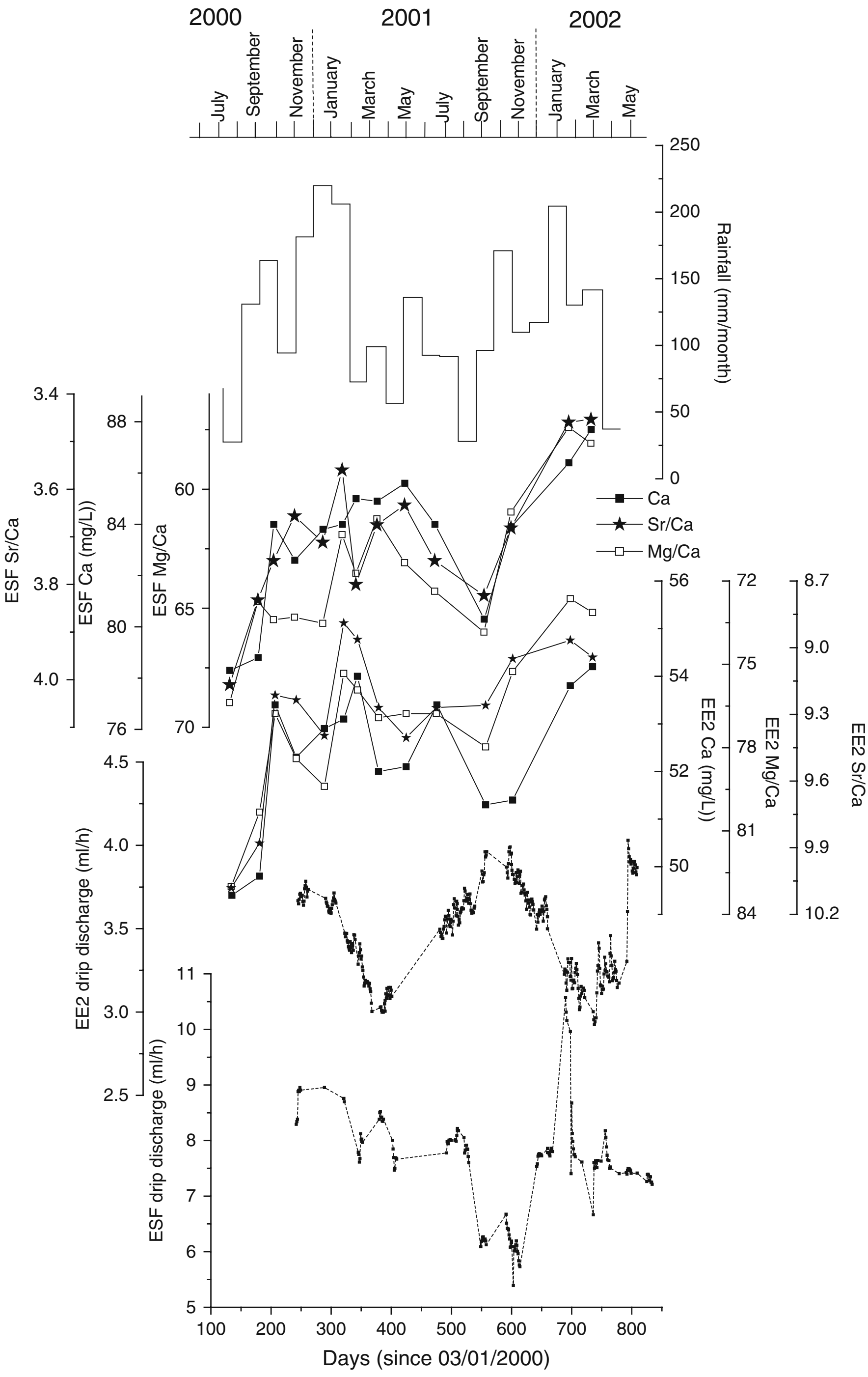

Fig. 2.4 Comparison between Ca, Sr/Ca, Mg/Ca and drip discharge variations at ESF and EE2 sites located 100 and 300 m below the surface in Santana cave, respectively

to the loss or gain of U and Th, the age of a speleothem can be calculated through measurement of radioactive production and decay of their isotopes in the system (Edwards et al. 1987).

Mass spectrometry has largely replaced traditional alpha counting methods for measuring U and Th isotopes on speleothem samples (Edwards et al. 1987; Li et al. 1989). Recently, technical improvements have resulted in a further shift from thermal ionisation mass spectrometry (TIMS) to inductively coupled plasma mass spectrometry (ICP-MS) (Shen et al. 2002; Goldstein and Stirling 2003). The ICP-MS method is preferred due to its distinct advantages, such as higher ionization efficiency and faster sample throughput. ICP-MS has particular interest to speleothem work, which benefits from analyzing small samples (e.g. ~100 mg if samples contain ~1.0 ppm U, Richards and Dorale 2003).

Speleothem samples are cut along the growth axis and sub-samples for dating can then be extracted by milling from flat, polished surfaces using a hand-held dental drill. Chemical separation of U and Th is done in a chemical clean room, following the basic procedure described in Edwards et al. (1987). Samples are totally dissolved with concentrated HNO_3 and then equilibrated with a mixed ^{229}Th-^{233}U-^{236}U spike of known concentration and isotopic composition. U and Th are co-precipitated with Fe and separated by an anion exchange column. Concentrated $HClO_4$ is recommended to use to destroy organics. Finally, the samples are either loaded onto rhenium filaments for TIMS or dissolved in weak nitric acid solution for ICP-MS analysis.

U-Th age errors are dominated by the precision of the analytical measurements and basically follow counting statistics. For typical speleothem samples with uranium concentrations of hundreds ppb to a few ppm, high-resolution dating can provide approximately calculated ages of 500±6 year, 10,000±40 year, 50,000±180 year, 120,000±500 year and 500,000±15,000 year (2σ analytical errors, Richards and Dorale 2003). Age accuracy is determined by the initial concentrations of ^{230}Th, which can be constrained by monitoring ^{232}Th and employing isochron techniques (Richards and Dorale 2003). However, initial ^{230}Th may vary in magnitudes even within the same sample (Shen et al. 2008). As a rule of a thumb, it is crucial to select high quality speleothem samples, i.e. high U content and low detrital contamination, for precise age control.

The uranium concentrations of Brazilian speleothem samples vary from tens of ppb to several ppm (Wang et al. 2004, 2006, 2007a; Cruz et al. 2005a, 2006). Most speleothem ages have 2σ analytical errors that correspond to 0.5–1% of the age. The U-Th ages are in correct stratigraphic order within quoted uncertainties and corrections for initial ^{230}Th are generally negligible. The samples' chronologies are further confirmed by the overall replication between the individual stable isotope profiles either in the same cave (Botuverá cave) or from different regions (i.e. Botuverá and Santana caves, Fig. 2.5). The BT2 age model was refined after Cruz et al. (2005a) by incorporating seven ages between 22,000 and 12,000 years ago and six ages between 42,000 and 62,000 years. With multiple samples, the Brazilian speleothem record now continuously covers the last 130,000 years, with a few episodic growths up to 210,000 years ago.

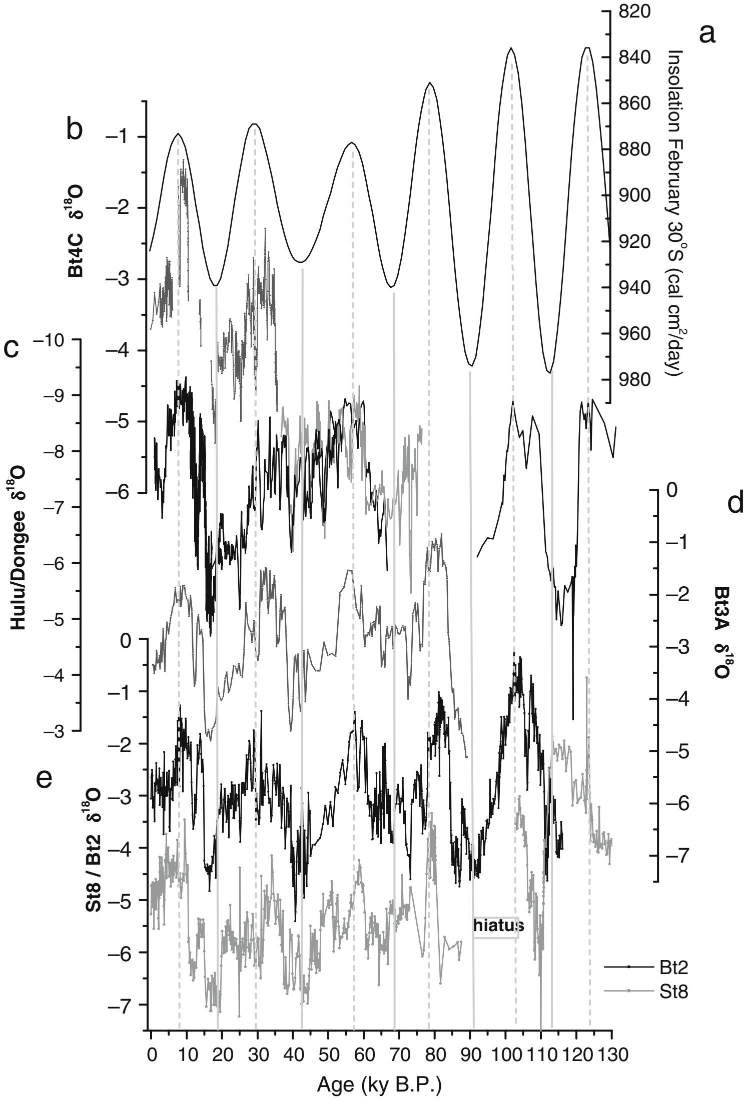

Fig. 2.5 Comparison between (**a**) February insolation at 30ºS (the insolation axis is reversed) and the oxygen isotope ratios of stalagmites; (**b**) BTV4C record from Butuverá cave (Wang et al. 2006); (**c**) Hulu and Dongee records from eastern China (the $\delta^{18}O$ axis is reversed, Wang et al. 2001; Yuan et al. 2004); (**d**) BT3A record from Botuverá cave (Wang et al. 2007a); (**e**) BT2 record and St8 records from Botuverá and Santana caves, respectively (Cruz et al. 2005a, 2006)

2.3.2 Stable Isotope Records

The speleothem isotope records in this study are from stalagmites collected in the Botuverá cave (Bt2, 27°13′24″S; 49°09′20″W) and in the Santana cave (St8, 24°31′51″S; 48°43′36″W), located 300 km apart in southeastern and southern

Brazil, respectively (Fig. 2.1). This set of records, consisting of five stalagmites from Botuverá cave and one from Santana cave, describes changes in the regional precipitation regime in subtropical Brazil over approximately the last 130,000 years (Fig. 2.5). The $\delta^{18}O$ in these records shows an amplitude of more than 4‰, with a mean resolution of 40–60 years for stalagmites Bt4a, Bt4c, Bt21a (Wang et al. 2006), ~150 years for Bt2 and St8 (Cruz et al. 2005a, 2006) and ~370 years for Bt3a (Wang et al. 2007a, b).

All the stalagmites appear to have been deposited in approximate isotopic equilibrium with cave drip water as indicated by the absence of significant correlations between $\delta^{18}O$ and $\delta^{13}C$ along their long axis according to the Hendy test (Mickler et al. 2006. Besides, the relatively large range of variation in $\delta^{18}O$ exclude a significant control by temperature, since the temperature-dependent fractionation between calcite and water is relatively small, –0.24‰/°C (Friedman and O'Neil 1977). The $\delta^{18}O$ variations are also inconsistent with the reported cooler and warmer periods during the last glacial and Holocene, respectively. Therefore, $\delta^{18}O$ variations of these speleothems are primarily related to changes in $\delta^{18}O$ of regional precipitation.

Figure 2.5 presents a comparison of the speleothem $\delta^{18}O$ time series with February insolation at 30°S (the scale for insolation is reversed). The calcite $\delta^{18}O$ shows a striking match with insolation throughout the last glacial period and is characterized by lower $\delta^{18}O$ values coinciding with maxima in insolation for each precessional cycle (periodicity of ~20 ka). However, this cyclicity is not as well defined in St8 as in Botuverá, in particular during the positive phases of summer insolation between 70 and 20 ka. Superimposed on the insolation-driven tendency are abrupt millennial-scale events, recognizable in all stalagmites as secondary fluctuations of 1.5–2‰. They are nearly coincident with one another and with variations seen in Northern Hemisphere paleoclimate records on the same timescale, especially during the so-called Heinrich events (NGRIP 2004). Despite the similarity of the records, the region presents a strong isotopic gradient, characterized by mean values, which are consistently about 2‰ higher at Bt2, when compared with St8.

Past changes in the oxygen isotope ratios are interpreted in terms of shifts in the seasonal balance of precipitation between winter-extratropical versus summer-monsoonal rainfall. This interpretation is supported by observations of the modern isotope climatology, as discussed above. Hence the $\delta^{18}O$ of Brazilian subtropical speleothems is thought to be primarily a function of the rainfall moisture source during the late Pleistocene, which in turn, is connected to the regional atmospheric circulation patterns (Cruz et al. 2005a). Lower values of $\delta^{18}O$ therefore reflect a greater proportion of more depleted SASM rainfall compared to the enriched extratropical rainfall and vice-versa.

2.3.3 Speleothem Growth Intervals

Speleothems can only grow if there is enough seepage water reaching the cave. These conditions are commonly not found in glaciated regions or in arid/semi-arid zones, such as northeastern Brazil (Site 3 in the Fig. 2.1). In these conditions, absence or occurrence of speleothems can be a reliable indicator of past climatic conditions. In semi-arid northeastern Brazil, home of South America's most extensive cave systems, profuse speleothem deposition occurred in the past. The present semi-arid climate, in which evapotranspiration (~1,400 mm/year) largely exceeds rainfall (~490 mm), does not allow for significant water infiltration and, consequently, speleothem generation. Thus, speleothem growth phases are a clear indicator of wetter conditions than at present at this site.

In addition to speleothems, abundant travertine deposits occur in the area. Travertines are also relict features in the present climate. Since they were generated by bicarbonate-rich shallow spring waters, which only flow when a net regional recharge to groundwater exists, they are also good indicators of past pluvial phases. It should be noted, however, that travertines tend to be a more sensitive paleopluvial feature than speleothems, since they were deposited in streams directly affected by rainfall events. In contrast, an infiltration threshold needs to be overcome in order to activate percolation routes responsible for drip waters forming speleothems. For this reason, travertines might be formed in periods that are not wet enough to promote speleothem growth.

The combined speleothem/travertine record shows a series of short-lived growth intervals (Fig. 2.6). The large majority of speleothems grew very quickly, during highly episodic wet phases as short as several hundred years, with some lasting up to a few thousand years. Last glacial pluvial phases, centered at around ~15.5 ka, 39 ka, 48 ka and additional growth phases between 60 and 74 ka correlate precisely with Heinrich Events recorded in the Northern Hemisphere as well as to high $\delta^{18}O$ recording low monsoon activity in Chinese speleothems (Wang et al. 2004) and to peaks of low $\delta^{18}O$ depicted in southeastern Brazil speleothems (Wang et al. 2006, 2007a) (Fig. 2.6). Pluvial periods in now semi-arid northeastern Brazil are associated with the displacement of the ITCZ, probably representing times when the ITCZ was located south of its present mean position.

2.3.4 Mg/Ca and Sr/Ca Ratios

Mg/Ca and Sr/Ca ratios measured in the Bt2 stalagmite record, presented here as anomalies (departure from total mean), are positively correlated with one another ($r^2 = 0.55$) and show a pattern that is coherent with southern hemisphere summer insolation and stable oxygen isotope ratios during the last 116 ka (Cruz et al. 2005a, Wang et al. 2007a). This pattern is characterized by a general increase in trace element ratios and $\delta^{18}O$ values during low insolation phases and vice-versa. However, there are some significant differences in the long-term variability of trace element ratios throughout the last glaciation (Fig. 2.7). For instance, the positive relationship between Mg/Ca, Sr/Ca and insolation is less clear during periods of lower amplitude insolation changes, such as from 70 to 17 ka or during the Marine Isotope Stages 4 to 2 (Abreu et al. 2003), similar to the $\delta^{18}O$ variations of St8 record (Cruz et al. 2006a).

Elemental ratios of Bt2 have been interpreted as a proxy for local hydrological changes based on evidence for a primary control of Mg/Ca and Sr/Ca ratios

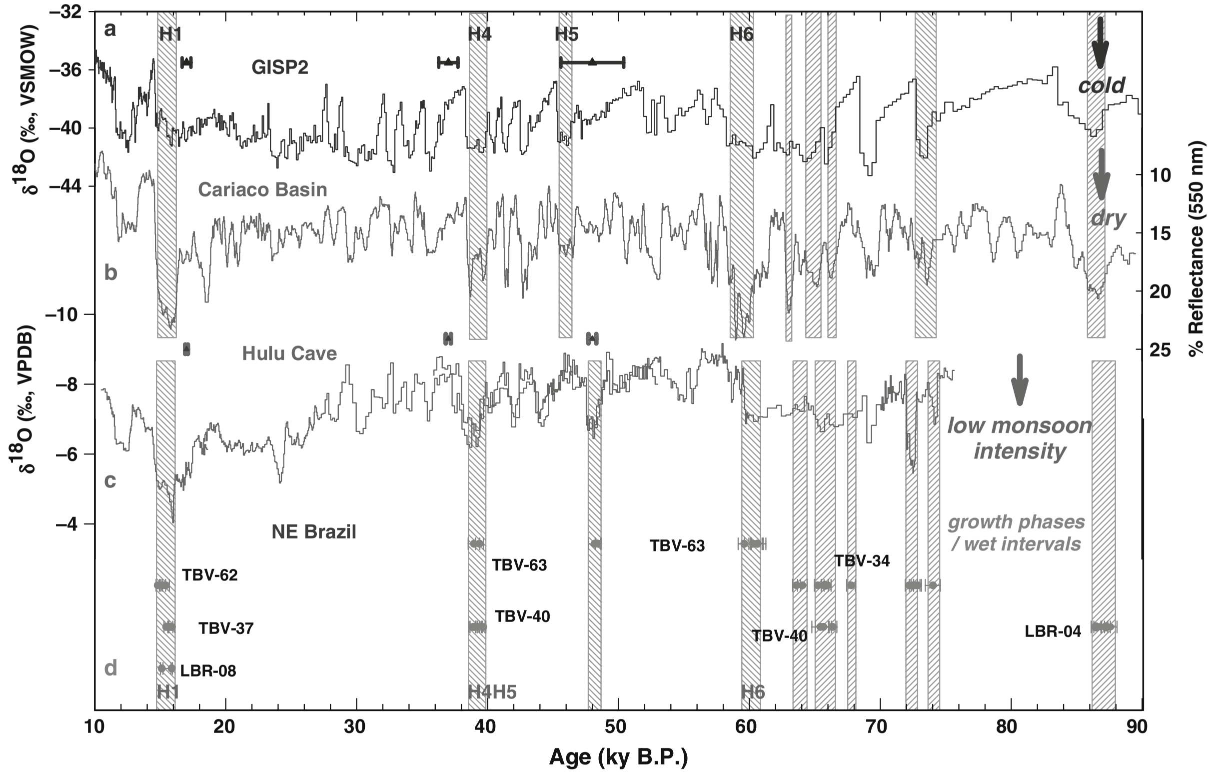

Fig. 2.6 Comparison of the growth patterns of speleothems from northeastern Brazil with events recorded in several Northern Hemisphere palaeoclimate archives; (**a**) $\delta^{18}O$ values of Greenland ice (Grootes and Stuiver 1997); (**b**) Light colour reflectance (*greyscale*) of the Cariaco basin sediments from ODP Hole 1002C5 (Peterson et al. 2000); (**c**) $\delta^{18}O$ values of Hulu cave stalagmites (Wang et al. 2001); (**d**) Speleothem growth patterns in northeastern Brazil. Growth intervals are shown by separated *gray dots* or connections between dots if they are within the same phase. 2σ dating errors (error bars) are typically 0.5–1%. *Gray hatched vertical bars* indicate possible correlations between four records. Also shown are dating errors for the GISP2 ice core 29 (*black horizontal bars*) and Hulu cave speleothems (*gray horizontal bars*). VSMOW, Vienna standard mean ocean water. VPDB, Vienna PeeDee Belemnite. H1, H4, H5, H6, Heinrich events

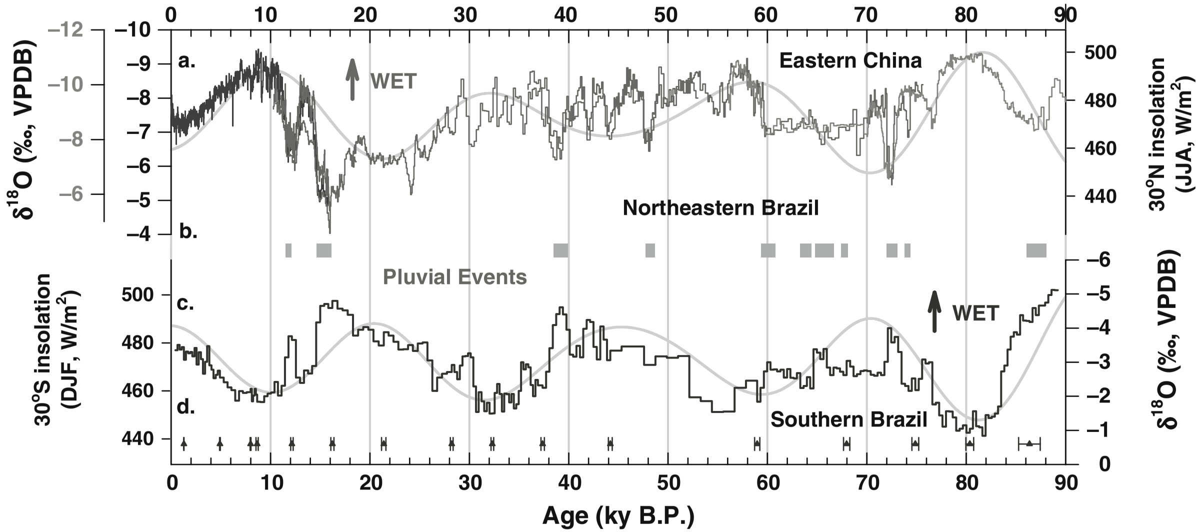

Fig. 2.7 Comparisons of speleothem records: (a) A combined profile of the eastern China $\delta^{18}O$ records (Dongge Cave, Yuan et al. 2004; Wang et al. 2005; Hulu Cave, Wang et al. 2001; and Shanbao Cave, Yongjin Wang and R.L. Edwards, unpublished data). Contemporaneous Dongge and Hulu stalagmites have virtually identical $\delta^{18}O$ values, while Shanbao values are offset by about –1‰, but with a similar pattern to Hulu (see replicated portions); (b) Northeastern Brazil growth periods (Wang et al. 2004); (c) BTV3A from Botuverá cave, Brazil $\delta^{18}O$ record (Caverna Botuverá, Wang et al. 2007a); (d) 2σ age error bars for the BTV3A record. Note scales for speleothem $\delta^{18}O$ are all reversed, increasing downwards. All three chronologies are established independently with uranium-thorium methods, with typical 2σ errors of about 0.5–1%. Also shown are 30°N and 30°S summer insolation (JJA and DJF, respectively, *gray curves*)

by prior calcite precipitation from the modern calibration study in Santana cave. These trace element ratios also show a coherent positive covariation during the last 116 ka and a consistent relationship with the $\delta^{18}O$ of the same stalagmite (Cruz et al. 2007). Furthermore, comparing these ratios with the Bt2 growth rates and $\delta^{13}C$ variations suggest that both growth rates and CO_2 degassing mechanisms are not a major control of the incorporation of Sr and Mg in the calcite (Huang and Fairchild 2001; Treble et al. 2003; Johnson et al. 2006). Thus, the regional climate variability inferred from these elemental ratios can be used as a proxy for mean rainfall amount, which in turn complements the reconstruction of the past activity of South American summer monsoon (SASM) and extratropical rainfall in subtropical Brazil, anchored in the speleothem $\delta^{18}O$ records (Cruz et al. 2005a; Wang et al. 2006; Cruz et al. 2006a; Wang et al. 2007a).

2.4 Discussion

Combined oxygen isotope and trace element records suggest that the past changes in southern Brazil rainfall were mostly led by the convective activity associated with the South American summer monsoon (Cruz et al. 2007; Fig. 2.7). Since the $\delta^{18}O$ of speleothems is directly affected by the isotopic composition of summer rainfall, it can be used to infer the mean location and intensity of the SASM and the South Atlantic convergence zone (SACZ). These features are closely linked to the intensity and location of convective precipitation over the Amazon basin and surrounding regions, because they influence the strengthening or weakening of moisture transport by the Andean low-level jet (ALLJ) from the southern Amazon to the subtropical Atlantic coast (Gan et al. 2004). On the other hand, the speleothem growth phases in northeastern Brazil suggest a direct coupling of regional climate to the mean latitudinal position of the ITCZ (Wang et al. 2004; Fig. 2.6).

To date, the Brazilian speleothem records suggest that past changes in tropical rainfall are associated with climate forcing mechanisms acting on both orbital and millennial time-scales, such as insolation precession and land- and sea-ice coverage in the northern hemisphere (Chiang et al. 2003; Claussen et al. 2003). These mechanisms impact the tropical rainfall distribution by influencing the moisture transport from the tropical Atlantic to the continent, thereby changing low-level moisture convergence and convective activity throughout much of tropical South America.

2.4.1 Long-Term Paleoclimatic Changes

Speleothem $\delta^{18}O$ records have revealed that the variations in the convective intensity within the area affected by SASM/SACZ are dominated by changes in precession-driven solar insolation (Cruz et al. 2005a; Wang et al. 2006, 2007a; Cruz 2006). Insolation determines the north-south displacement of continental convection over South America by favoring moisture convergence over the continent during periods of increased land-sea temperature contrasts at the solstices (Biasutti et al. 2003). In the past, periods of increased monsoon precipitation in subtropical Brazil occurred in response to enhanced summer solar radiation following the Milankovich ~23 ka precession cycle (Fig. 2.5). Similarly, the speleothem $\delta^{18}O$ records from Hulu and Dongee caves in eastern China (Fig. 2.5) also exhibit an insolation-driven control, which is out of phase with the Brazilian records (Wang et al. 2004; Yuan et al. 2004).

The SASM is reinforced at its southeastern border as the southern hemisphere Hadley cell is strengthened and displaced southward during high insolation phases, thereby increasing the relative contribution of summer monsoonal rainfall to the region. Further evidence for such a monsoon intensification comes from lake records in the Bolivian Altiplano, where similar wet conditions were observed during the last glacial period (Baker et al. 2001a). The comparison between SE Brazil and the Altiplano also holds during the Holocene, when the speleothem isotope records become progressively more negative after 4 ky, concurrent with an increase in summer rainfall on the Altiplano (Seltzer et al. 2000; Baker et al. 2001b; Moreno et al. 2007). At the same time a southward expansion of the Amazon rainforest is observed along its southwestern border (Mayle et al. 2000).

Although the insolation-driven paleo-rainfall, inferred from the Botuverá and Santana speleothem records, appears to be consistent with other available records from the region, it is still necessary to reconstruct each step of the monsoon evolution during the past, in order to elucidate the causal mechanism interconnecting the climate in southern Brazil with the center of deep convection over the Amazon region. To do this, some aspects of the moisture advection from the tropical Atlantic to the Amazon Basin need to be addressed in more detail for the last glacial period.

Unlike the present-day situation, it is difficult to link past low-frequency rainfall oscillations in South America with meridional sea surface temperature (SST) gradients in the tropical Atlantic or SST anomalies in the equatorial Pacific. It is reasonable to assume that the SASM may be intensified because of a more southerly position of the Atlantic Intertropical Convergence Zone (ITCZ) during periods of increased southern hemisphere insolation. However, except for the Holocene part of the Ti-Fe record from the Cariaco Basin (Haug et al. 2001), there is no clear match between summer insolation and hydrological (Arz et al. 1998; Peterson et al. 2000; Jennerjahn et al. 2004) or SST records (Arz et al. 1999, Lea et al. 2003; Weldeab et al. 2006) off the Venezuelan and Brazilian coast. Instead, both hydrological and SST variations in these records are dominated by millennial-scale events, such as Dansgaard-Oeschger- and Heinrich-events (see the discussion in the section below). Thus, it appears that the southeastward displacement of deep continental convection from the Amazon Basin to southeastern and southern Brazil is, at least partially, decoupled from oceanic conditions in the tropical Atlantic on orbital time-scales. Instead it appears as if changes in South American monsoon circulation during the last glacial and the Holocene were dominated by changes in sensible and latent heat transfer over land due to orbitally driven changes in solar radiation, rather than by changes in moisture influx from the Atlantic Ocean, associated with a southward displaced ITCZ (Haug et al. 2001). Indeed recent studies have shown that latent heat release over the Amazon basin is paramount for the development of the upper-level monsoon circulation, including the Bolivian High (Lenters and Cook 1997), which is associated with the southeastward extension of the SASM into the SACZ region (Zhou and Lau 1998; Gan et al. 2004).

One question, which cannot be answered by looking solely at speleothem $\delta^{18}O$ records, is to what extent an intensification of the SASM increases the long-term mean rainfall amount in southern Brazil. Since $\delta^{18}O$ variations in stalagmites from the Brazilian subtropics record not just monsoonal (60% of annual accumulation today), but also extratropical rainfall (40% of annual accumulation today), they cannot be used to directly infer mean rainfall variations. For example, an increase in the more isotopically depleted monsoon rainfall (today $\sim -7‰$) might be compensated by a decrease in more enriched extratropical rainfall ($\sim -3‰$) and thus create a more negative average $\delta^{18}O$ without any change in the total rainfall amount.

Instead changes in rainfall amount can be inferred by the use of Mg/Ca and Sr/Ca ratios, as reported by Cruz et al. (2007) for the last 116 ka based on the Bt2 stalagmite. The comparison with the $\delta^{18}O$ record suggests that increased local rainfall recharge occurred during periods of enhanced monsoon rainfall in the region coincident with high summer insolation phases, as manifested by lower values of both $\delta^{18}O$ and trace element ratios in Bt2 (Fig. 2.7). Conversely, relatively dry conditions, as indicated by higher trace element ratios during low insolation phases, must have been caused by a reduction in summer monsoon rainfall, since a decrease in the isotopically-enriched extratropical winter rainfall would have resulted in more negative $\delta^{18}O$ values in the Bt2 stalagmite. Therefore, this multi-proxy study confirms that the contribution of SASM precipitation is the dominant factor explaining precipitation variations in subtropical Brazil during the last glacial-deglacial period. In addition, the steep north–south gradient in $\delta^{18}O$ of speleothems throughout the region, characterized by more negative values of ST8 ($-2‰$) as compared to Bt2, indicate a higher relative contribution of SASM precipitation to the north at Santana cave. This gradient is also observed today in cave drip waters and modern speleothems (Cruz et al. 2005b).

There are, however, some significant fluctuations in the long-term variability of trace element ratios from 70 to 17 ka that cannot be explained by summer insolation forcing alone. These departures are characterized by a predominance of negative trace element anomalies despite low-insolation phases, which suggests that rather wet conditions persisted throughout most of the last glacial period due to longer and more intense summertime rainfall. This notion is supported by synchronous negative anomalies in both trace element ratios and $\delta^{18}O$ in Bt2 and St8 (Fig. 2.7). Hence, the weaker correspondence between trace element variations and insolation suggests that other factors must have contributed to the excess of monsoon rainfall during this time period.

Teleconnections from the high northern latitudes under glacial boundary conditions, dominated by extensive land- and sea-ice volume buildup, are a likely factor influencing the monsoon intensification observed in the region between 70 to 17 ka. According to simulations by Chiang et al. (2003) high-latitude glacial conditions are transmitted to the tropics through strengthened northeasterly trades over the North Atlantic, which increase the latent heat flux, in turn causing a progressive cooling of SSTs from the subtropical (Moreno et al. 2002; Abreu et al. 2003) to the tropical North Atlantic (Lea et al. 2003). As a consequence, this mechanism results in tropical Atlantic meridional SST gradients that favor a southerly displacement of the ITCZ. A more southerly position of the ITCZ, in turn will enhance the moisture flux into the Amazon Basin, ultimately triggering an intensification of the SASM in southern Brazil. This hypothesis is broadly supported by the coincidence of lower trace element ratios in Bt2 with lower SSTs in the subtropical North Atlantic (Abreu et al. 2003), as indicated by heavier $\delta^{18}O$ in planktonic foraminifera during Marine Isotope Stages 4 to 2 (Fig. 2.7). This interpretation is also in agreement with the wettest conditions recorded during the same period in Salar de Uyuni, an area in the Bolivian Altiplano where precipitation equally depends on SASM activity (Fritz et al. 2004).

2.4.2 Millennial-Scale Abrupt Changes in Climate

During the last glacial period, Greenland experienced millennial-scale abrupt climate changes (Dansgaard et al. 1993; Grootes et al. 1993; NGRIP members 2004). As observed in the polar ice cores, temperature could change 7–12°C in decades or less over Greenland, accompanied by dramatic fluctuations of atmospheric methane, sea-salt and dust concentrations (Mayewski et al. 1997; Severinghaus and Brook 1999; Blunier and Brook 2001). Since this discovery, similar events have been identified at many locations around the world (Voelker et al. 2002). Mechanisms of these abrupt climate events, however, are not yet resolved (Broecker 2003). A full understanding of the causes of these climate events requires our knowledge of the spatial and phase relationships between different paleoclimate records.

Recently, there is steadily increasing interest in obtaining records of millennial-scale climate events in speleothems from low-to-mid latitudes (Wang et al. 2001; Spötl and Mangini 2002; Bar-Matthews et al. 2003; Burns et al. 2003; Genty et al. 2003; Drysdale et al. 2007). With high-precision absolute-dated chronology, such studies on speleothems can not only test whether the abrupt climate events were a global phenomenon, but also help to reveal the mechanisms that were responsible for the events. Abrupt climate events have also been identified in different speleothem proxy records from tropical and subtropical Brazil. Indicated by speleothem short growth phases, current semi-arid northeastern Brazil has endured millennial-scale episodic wet periods in the past (Wang et al. 2004). In southeastern and southern Brazil, the speleothem $\delta^{18}O$ records also successfully capture millennial-scale events that are superimposed on the orbital-scale variations during the last glacial period (Cruz et al. 2005a, 2006; Wang et al. 2006, 2007a). The abrupt drop in $\delta^{18}O$ associated with these events is large, with up to 2‰ amplitude. Together with speleothem Mg/Ca and Sr/Ca ratios (Cruz et al. 2007), these suggest that SASM intensity and monsoonal rainfall has undergone abrupt changes in the region during the last glacial period.

Using their individual chronologies, the Brazilian speleothem records can be compared with the contemporaneous records from the northern hemisphere. Wet periods in northeastern Brazil are synchronous with periods of weak East Asian summer monsoons (Wang et al. 2001), cold periods in Greenland (Grootes and Stuiver 1997) and Europe (Genty et al. 2003); Heinrich events in the North Atlantic (Bond et al. 1993) and periods of decreased river runoff to the Cariaco basin (Peterson et al. 2000). The comparison between the Botuverá $\delta^{18}O$ records and the eastern China $\delta^{18}O$ profile also show, within their dating errors (a typical relative 2σ error in age of about 0.5–1%), a remarkable anti-correlation on both orbital and millennial timescales (Fig. 2.8). Throughout the whole profile, the lower Botuverá $\delta^{18}O$ coincides precisely with the higher $\delta^{18}O$ in the eastern China speleothems. However, the opposite is not so evident because no clear increase in the $\delta^{18}O$ of Brazilian speleothems is observed during the warm periods in the northern hemisphere that are coincident with the Daansgard-Oeschger events.

During the last glacial period, an abrupt reduction in the Atlantic overturning induces sea ice expansion in the North Atlantic and a subsequent southward displacement of the intertropical convergence zone (ITCZ) (Chiang et al. 2003; Chiang and Bitz 2005). This may cause an abrupt shift in the tropical hydrologic cycle, as seen in the Cariaco Basin (Peterson et al. 2000) and northeastern Brazil (Wang et al. 2004). Modeling efforts also indicate that weak ocean circulation may result in a positive SST anomaly in the South Atlantic and a weaker pole-to-Equator temperature gradient in the south (Crowley 1992) and the predictions are confirmed by studies of ocean sediment cores (Arz et al. 1998; Rühlemann et al. 1999). As observed today (Robertson and Mechoso 2000; Doyle and Barros 2002; Liebmann et al. 2004), a warm SST anomaly in the western subtropical South Atlantic (WSSA) may stimulate a persistent intense South American Summer Monsoon (SASM) and strong low-level jet (LLJ), which consequently supplies plenty of isotopically depleted precipitation into southern Brazil (Vuille and Werner 2005).

Moreover, analogous to modern seasonal observations in boreal winter (Lindzen and Hou 1988), southward ITCZ migration during millennial-scale stadial events may have caused a meridional asymmetry in the Hadley circulation. A southward shift of the zonal-mean Hadley cell would change meridional moisture transport through intense ascending air masses in the southern low latitudes and increased subsidence in the northern tropics and subtropics. Broadly, the northern low latitudes would be drier and the southern low latitudes wetter, which has been confirmed by recent model results (Clement et al. 2004; Chiang and Bitz 2005). The opposite scenario would have been true during glacial interstadial periods.

We can therefore define an index (speleothem $\Delta\delta^{18}O$) to monitor the displacement history of the mean ITCZ position and the associated strength of the past Hadley circulation. This index is given by the difference of calcite $\delta^{18}O$ values between samples from southern Brazil and eastern China (Table 2.1). As discussed above, low (high) calcite $\delta^{18}O$ values in southern Brazil correspond to high (low) calcite $\delta^{18}O$ values in eastern China. Thus, small (large) speleothem $\Delta\delta^{18}O$ values are linked to North Atlantic cold (warm) temperature, reduced (enhanced) ocean

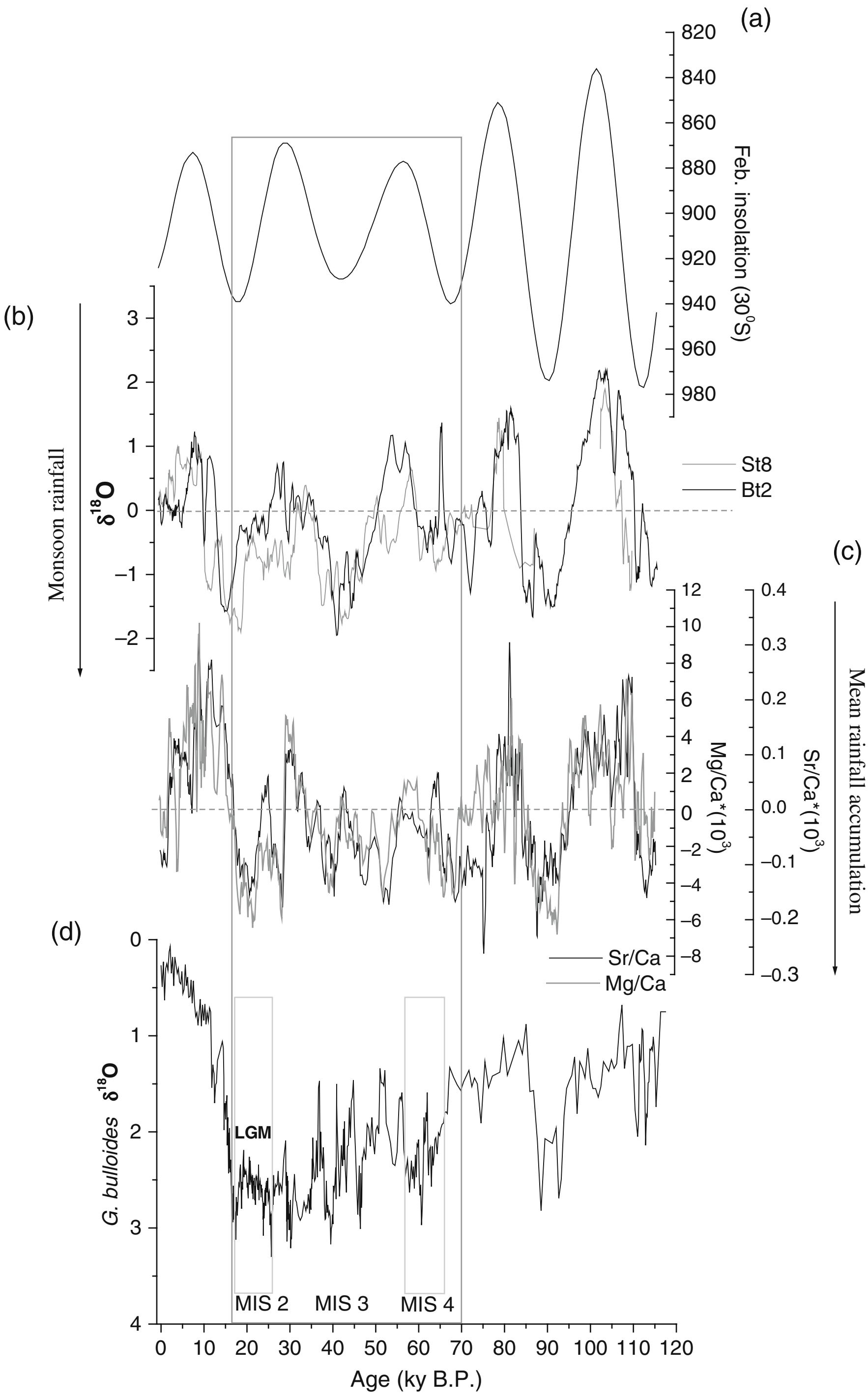

Fig. 2.8 (continued)

Table 2.1 Speleothem $\Delta\delta^{18}O$ index between Southern Brazil and Eastern China

Time window	Eastern China speleothem $\delta^{18}O$ (‰, VPDB)	Southern Brazil speleothem $\delta^{18}O$ (‰,VPDB)	$\Delta\delta^{18}O$ index (‰,VPDB)
Heinrich event 1	~ – 4.9	~ – 4.7	~ 0.2
Early Holocene	~ – 9.3	~ – 1.8	~ 7.5
Today	~ – 7.3	~ – 3.3	~ 4.0

circulation, and a southward (northward) shift of the ITCZ mean position. The North Atlantic circulation is nearly shut down during Heinrich Event 1 (H1) and is substantially strengthened during the early Holocene (McManus et al. 2004). Therefore, we select calcite $\Delta\delta^{18}O$ index values during H1 and the early Holocene as two end members that represent two extreme mean positions of the ITCZ and asymmetries of the Hadley circulation. Today's index value is around 4.0‰, which is close to the average between H1 and early Holocene values of about 0.2 and 7.5‰, respectively. This approach suggests an intermediate state of the mean ITCZ position and weak asymmetry of the Hadley circulation in the modern world.

It is still under extensive debate whether meridional overturning circulation (MOC) changes or tropical air-sea interactions, such as persistent El Niño-Southern Oscillation events (Super-ENSO), have triggered the millennial-scale climate events (Broecker 2003). Phase relationships of these events in Brazilian speleothem records may have implications on their mechanisms. The modern climate in both northeastern and southern Brazil is sensitive to the ENSO phenomenon. For example, modern El Niño events induce drought in northeastern Brazil and high precipitation in southern Brazil (Lau and Zhou 2003). If the modern ENSO behavior does not change substantially with time, the Super-ENSO scenarios may result in opposite rainfall patterns between the two regions. On the other hand, changes in the MOC would cause a latitudinal ITCZ migration and associated changes in the Hadley circulation (Chiang and Bitz 2005). This may cause in-phase precipitation changes in northeastern and southern Brazil on millennial timescales. With their robust chronologies, the Botuverá speleothem $\delta^{18}O$ record can be compared to the record of speleothem growth periods from northeastern Brazil (Wang et al. 2007b). Although the latter may not be a complete data set, a striking positive phase relationship stands out between the two records. For instance, northeastern Brazil speleothem resumes

Fig. 2.8 (continued) (**a**) February insolation at 30°S (the insolation axis is reversed); (**b**) $\delta^{18}O$ anomalies for Bt2 (Cruz et al. 2005a) and St8 (Cruz et al. 2006) stalagmites; (**c**) Mg/Ca and Sr/Ca anomalies for Bt2 stalagmite; (**d**) $\delta^{18}O$ of planktonic foraminifera in the core MD95-2040 from Iberian Margin in North Atlantic (Abreu et al. 2003). Note the predominance of low trace element and more positive values of $\delta^{18}O$ of planktonic foraminifera during the MIS4 to MIS2 (marked with *rectangles*) growth around 87 ka, 72 ka, 66 ka, 60 ka, 48 ka, 39 ka, 16 ka and 12 ka, when $\delta^{18}O$ values are relatively low in the southern Brazil sample. As both proxies represent regional rainfall changes, this correlation suggests that on millennial timescales, rainfall changes in the two regions are in phase. This relationship is consistent with shifts in the mean ITCZ position, linked to MOC changes, but not with the Super-ENSO mechanism.

2.4.3 Broader Significance of Precipitation Changes Based on Speleothem Records

The speleothem records suggest a new scenario for the paleoclimate in southern Brazil, featuring a predominantly wet last glacial period. These findings have important implications for the inferred paleoenvironmental changes from the pollen records and consequently for the "refugia" hypothesis (Haffer 1997). This is still a highly controversial matter because a considerable number of pollen records point to a complete dominance of grasslands over forests during the last glaciation in subtropical Brazil due to colder and drier conditions (Behling 2002), while other records suggest that an expansion of humid forests occurred during significant parts of this period in agreement with the precipitation changes inferred from speleothems (Ledru et al. 2005). Therefore, the existence of forests "refugia" as a consequence of a large-scale drying during the glacial period needs to be revised, once robust indications of wetter conditions have been found in several areas in South America. An alternative explanation for the changes in tropical biodiversity is the periodic exchange between distinct forests biomes during wet events, such as indicated by the study of paleobotanical remains preserved in travertines, which revealed a rapid expansion of humid forests over caatinga vegetation (dry savanna) in northeastern Brazil during the period coincident with H-events (Wang et al. 2004).

Substantial intensification of the tropical circulation system in subtropical South America at high insolation phases in the southern hemisphere and during cold periods in the Northern Hemisphere (H-events, MIS-4 to MIS-2) recorded in Brazilian speleothems is also important in an attempt to interpret the isotope records from Andean ice-cores and the events of moraine deposition in terms of temperature or precipitation changes (Ramirez et al. 2003; Zech et al. 2007), because an enhancement in the moisture flux and moisture convergence in southern Brazil is likely to affect precipitation in Andes in the same way during the South American summer monsoon season.

2.5 Conclusions

Combined time-series of $\delta^{18}O$ and elemental ratios of speleothems suggest that the long-term variations in mean precipitation in subtropical Brazil during the last glacial period and Holocene are in general modulated by changes in the southern hemisphere summer insolation. The South American monsoon is intensified at high insolation phases when the transport of low-level tropical moisture from the Amazon Basin to southeastern Brazil is enhanced; most likely due to a more favorable upper-level circulation, established by enhanced latent heat release over the tropics. However, the northern Hemisphere glacial boundary conditions probably played an important role by modulating moisture flux and convergence into the southern hemisphere tropics during austral summer. This impact is documented by the rainfall excess in the region from 70 to 17 ka and especially at the last glacial maximum, as indicated by rather negative anomalies of $\delta^{18}O$, Mg/Ca and Sr/Ca during this period.

Speleothem growth intervals and variations of $\delta^{18}O$ on millennial time-scales indicate significant increases in precipitation both in northeastern and southern Brazil, coincident with Heinrich events in the northern hemisphere. These changes are likely controlled by latitudinal ITCZ displacements, resulting in a hemispheric asymmetry of low-latitude precipitation, as exemplified by the anti-phased relationship between Brazilian and Chinese speleothem records. Furthermore, the similar precipitation response between NE and SE Brazil on millennial timescales implies that abrupt changes in precipitation within tropical South America are linked to climatic conditions in the North Atlantic, through changes in the AMOC and subsequent tropical air-sea feedbacks.

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