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Impact of the Holocene sea-level changes in coastal, eastern and Central Amazonia*

by

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Abstract

Pollen records from six sites are summarised and compared to provide insights in Holocene changes in the Amazon coastal and lowland regions of northern Brazil. The hydrology of Amazonian wetlands, especially those in the eastern part of the Basin, is strongly influenced by the Atlantic sea-level. Rapid sea-level rise in the early Holocene stabilized at near modern levels at ca. 7500 ^{14}C yr B.P. Mangroves first occur in coastal sequences of northeastern Pará State about 7500 ^{14}C yr B.P. The arrival of the mangroves in the pollen sequences is taken as an indication of sea-level. The retreat of mangroves after about 6700 ^{14}C yr B.P. reflects a lower relative sea-level. The modern mangroves developed mostly between 4000 and 3500 ^{14}C yr B.P. or somewhat later at the present-day coastline.

First impact of early Holocene sea-level rise in the Amazon Basin is found by the change of active to passive river systems between at ca. 8300 and 8000 ^{14}C yr B.P. Later, local *Mauritia* palm swamps developed along river margins in central and eastern Amazonia. The timing and length of this period differs and is probably related to the different location and topography of the rivers. It is suggested that the *Mauritia* palm swamp stage is a regional phenomenon for the whole low lying Amazon Basin. First várzea and igapó forests (seasonally inundated forests) developed at that time as well, but the area of this seasonally inundated forests was still small. The modern large extension of várzea and igapó forest areas is relatively young in age. In eastern Amazonia, marked increase of várzea/igapó forests is documented since 3120 ^{14}C yr B.P., especially since 2470 ^{14}C yr B.P., and in central Amazonia since 4070 ^{14}C yr B.P. and especially since 2080 ^{14}C yr B.P. The development of huge seasonally inundated areas must have had an important influence on the Amazonian water and carbon cycle and the regional climate in Amazonia.
Keywords: **Northern Brazil, palynology, palaeoecology, mangrove, Amazon rainforest, várzea, igapó, Holocene, sea-level.**

Resumo

Registros de polén de seis locais estão resumidos e comparados com as mudanças na Amazônia costeira e regiões de terras baixas do norte do Brasil. A hidrologia das terras alagadas da Amazônia, especialmente aquelas da parte leste da bacia, é fortemente influenciada pelo nível do mar atlântico. Com rápidos aumentos do nível do mar durante o Holoceno inferior, o nível atual foi atingido há cerca de 7500 ^{14}C anos A.P. Os primeiros manguezais ocorreram na costa nordeste do Estado do Pará por volta de 7500 ^{14}C anos

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A.P. A chegada dos manguezais na seqüência de polens é interpretada como um indicador do nível do mar. A retração dos manguezais depois de 6700 ^{14}C anos A.P. reflete um abaixamento no nível relativo do mar. Os manguezais modernos desenvolveram-se entre 4000 e 3500 ^{14}C anos A.P. ou um pouco mais tarde na atual linha de costa.

O primeiro impácto do aumento do nível do mar durante o Holoceno na bacia Amazônica é evidenciado pela mudança do sistema fluvial de ativo para passivo entre 8300 e 8000 ^{14}C anos A.P. Em seguida, palmeiras de *Mauritia* desenvolveram-se ao longo da margem dos rios na parte central e leste da Amazônia. O intervalo de tempo e extensão territorial deste período diferem e está provavelmente relacionado à topografia dos rios. Isto sugere que o estágio com pântanos de palmeira de *Mauritia* é um fenômeno regional para todas as zonas baixas da Bacia Amazônica. As primeiras florestas de várzeas e de igapó (florestas inundadas sazonalmente) desenvolveram-se neste momento, mas a área desta sazonalmente inundada floresta foi ainda pequena. A atual grande extensão das áreas de florestas de vázea e igapó é relativamente jovem. No leste da Amazônia, marcados aumentos das florestas de várzea/igapó é documentado desde 3120 ^{14}C anos A.P., especialmente desde 2470 ^{14}C anos A.P., e na Amazônia central desde 2080 ^{14}C anos A.P. O desenvolvimento de enormes sazonalmente inundadas florestas deve ter tido importante influência nas águas da Amazônia, no ciclo do carbono e no clima regional na Amazônia.

Introduction

The Amazon rivers occupies a 7,900,000 km^2 drainage area which is larger than Europe and a little smaller than the United States. Because of its huge area, Amazonia plays a significant role in the establishment of global climate, water and carbon budget (e.g. SAINT-PAUL et. al 1999).

Amazonia is mostly covered by rainforest and some savanna ecosystems. The Amazon Basin is low lying with >1,000,000 km^2 at <100 m elevation. For much of its course, the Amazon has a grade of 1 in 100,000. The water level in Manaus, which lies 1200 km inland is only 14 m a.s.l. (GRABERT 1991). As a consequence, in the eastern half of the basin the development of rivers and lakes is strongly influenced by Atlantic sea-level fluctuations. The amount of annual rainfall as well as the sea-level dynamics influence the occurrence of seasonally inundated forests, which form an area of up to 700,000 km^2 (PAVIA 1995). Also Amazonian coastal ecosystems such as mangroves and salt marshes are related to sea-level fluctuations.

In order to understand past environmental changes in Amazonia such as the natural amplitude of Amazonian ecosystem dynamics, including coastal ecosystems such as mangroves, as well as Amazonian river and climate changes, palaeoecological and palaeoenvironmental studies are important. Several lacustrine and mangrove sediment deposits have been studied by pollen analysis. The aim of this paper is to compare and summarise recent published pollen records and to give an overview of natural environmental changes in the coastal and Amazon Basin region, related to the impact of the Holocene sea-level changes.

Vegetation and climate

The Amazon coastal region includes areas of mangrove, salt marshes, restinga (coastal herb and shrub vegetation), and coastal savanna vegetation (e.g. BASTOS 1988; SANTOS & ROSÁRIO 1988). Major vegetation types of the Amazon Basin are unflooded upland forests, the so-called terra firme forests, and the seasonally inundated forests, the so-called várzea (white water) and igapó (black water) forests. Furthermore there are found smaller areas of floodplain herbaceous vegetation and floating meadows. Climatic savannas occur north and south of the Amazon rainforest, while edaphic savanna, (e.g.

white sand vegetation), are found within the Amazon rainforest region. General descriptions of the central Amazon vegetation are published by e.g. FERREIRA et. al (1997), HUECK (1966), JUNK (1970), JUNK & PIEDADE (1994), KLINGE (1973), KLINGE et al. (1995), LISBOA et al. (1997), PIRES & PRANCE (1985), and PRANCE (1990).

The atmospheric circulation of the Amazon region is controlled by the position of the Intertropical Convergence Zone (ITCZ), shifting from 7-9°N in July to 10-20°S in January. Consequently two main climate types are represented in Amazonia: a climate without dry season at equatorial latitudes, and a climate with a marked dry season north and south of the equatorial latitudes. South America north of the equator is influenced by the northeasterly trade winds blowing from the Caribbean, whereas the region south of the equator is influenced by the Atlantic southeasterlies, which originate from the subtropical high pressure cell over the south Atlantic Ocean. For most of the Amazon regions the annual precipitation ranges between 1750 and 3500 mm, and the average annual temperature is between 20 and 26 °C (NIMER 1989; SNOW 1976; WEISCHET 1996). The Amazon coastal region receives between 2000 and over 3250 mm precipitation per year. The climate station of Belém documents a mean annual precipitation of 2277 mm (WALTER & LIETH 1967). The average annual temperature is 25.9 °C. Measured maximum and minimum temperatures are 31.7 °C and 18.0 °C, respectively.

Sites used in the comparison

For the Amazon lowland regions only a few pollen records are available, reflecting the impact of Holocene sea-level changes (Fig. 1). For the coastal region of Amazonia there is Lagoa da Curuça (BEHLING 1996, 2001a, b), Lago Crispim (BEHLING & COSTA 2001), three records from the Braganca Peninsula and Lago Aquiri (BEHLING & COSTA 1997). For the Amazon Basin region there is Rio Curuá (BEHLING & COSTA 2000; COSTA et al. 1997), Lago Calado (BEHLING et al. 2001b).

Lagoa da Curuça (0°46'S, 47°51'W) is found in the coastal region of northeastern Pará State, about 100 km northeast of the city of Belém in northern Brazil (Fig. 1). The lake is circular shaped, covers an area of ca. 15 hectares and is mostly about 2 m deep. Lagoa da Curuça is isolated from rivers and lies in a relatively plain landscape at 35 m elevation, covered with almost secondary Amazon rainforest vegetation. The lake is about 15 km from the Atlantic Ocean, but mangrove vegetation grows along small rivers within about 1.5 km of the lake.

Lago Crispim (0°46'S, 47°51'W) also lies in the coastal region of northeastern Pará, about 130 km northeast of Belém (Fig. 1). The lake is located near the village Crispim, at the west side of the Baiá do Maruda, which is formed by the Rio Marapanim. The isolated lake is 1-2 m above sea-level and only 500 m from the modern shore of the bay. The more or less circular lake has a diameter of about 100 m and a water depth of about 1 m. The lake seems to be part of a former inter-dune valley or channel in a relatively flat coastal area. Modern vegetation near the lake includes coastal vegetation (mangrove, restinga) and, further inland, strongly disturbed Amazon rainforest and edaphic white sand vegetation.

Bragança Peninsula is located between the mouth of the rivers Maiaú and Caeté in the coastal region of northeastern Pará (Fig. 1). The area is near Bragança City, lying 200 km east of Belém. The 30 km long and up to 15 km wide peninsula is mostly covered by mangroves. Pollen records are available from three different areas. The first site, "Bosque de Avicennia" (00°55'65"S, 46°40'09"W, 2.4 m a.s.l), is located on the relatively high central southern part of the peninsula. Only *Avicennia* trees form the mangrove forest. The second site, "Campo Salgado" (00°54'46"S, 46°40'63"W, 2.7 m a.s.l), is in Cyperaceae-dominated open salt marsh of the central part of the peninsula. The third site, "Furo do Chato" (00°52'25"S, 46°39'00"W, 1.9 m a.s.l), is in the northern part of the study area at a lower elevation than the two other sites. Here *Rhizophora* trees dominate the mangrove, but *Avicennia* trees occur close to the site.

Lago do Aquiri (3°10'S, 44°59'W, 10 m a.s.l.) is located 3 km north from the village Viana, about 120 km southwest of São Luis, capital of Maranhão State, and 450 km southeast of Belém (Fig. 1). The lake lies in a soft rolling landscape with elevated areas between 20-40 m a.s.l. and flood plain areas between 3-10 m a.s.l.. To the west, the study area is influenced by the river systems of the Rio Mearim. The shortest distance between Lago do Aquiri and Rio Mearim is 20 km, but sometimes a connection forms during the rainy season, when huge areas of the western study area are flooded. During the wet season the fresh water lake is about 11 km long by 1-3 km wide, while the water depth is 3 m. During the dry season the lake contracts to a small basin 1-2 km in diameter. The present-day vegetation to the west of the lake is anthropogenic palm forest/savanna. The eastern part is covered with periodically inundated swamp savanna. Only small remnants of rainforest, probably now secondary forest exist. Mangroves were not observed in the Lago do Aquiri region.

Rio Curuá (1°44'07"S, 51°27'47"W) is an inactive river, within the Caxiuanã National Forest Reserve, located 350 km west of Belém (Pará State) in eastern Amazonia (Fig. 1). The surrounding area is relatively flat, only a few meters above sea-level, and covered with Amazonian rainforest. Rio Curuá is connected to the Baía de Caxiuanã which is about 40 km long and 8-15 km wide. Water of the inland bay flows about 400 km via Baía de Portel, Baía de Melgaço, and Rio Pará to the Atlantic Ocean. Baía de Caxiuanã is mostly shallow, with water depths between 2 and 5 m. The water level is <3 m above sea-level. Therefore the Rio Curuá is a low energy river, controlled by the Baía de Caxiuanã. At the coring site the inactive river is about 40 m wide and about 5 m deep. Fluctuations between high and low water levels at the Caxiuanã station, as recorded by HIDA et al. (1997), average 33 cm (Dec. 1995-April 1996). At this location, there is still a tidal influence, the range between low and high tides is approximately 17-21 cm.

Lago Calado (3'16'S, 60'35'W, 23 m a.s.l.) is located on the northern bank of the Rio Solimões near the village Manacapuru, about 80 km upstream from the confluence of the Rio Negro and the Rio Solimões (Fig. 1). The terra firme lake has an outflow to the Rio Solimões that connects the water bodies during times of high water levels. A network of small rainforest streams from the Amazon terra firme forest flow into the lake. Controlled by the Solimões water level, the water depth of the lake fluctuates on an annual cycle between about 1-2 m in November and roughly 12 m in June. During the same period the lake surface area changes from 2 to 8 km^2. Today várzea/igapó forests cover about 5-10 % of the total forest area of the Lago Calado region.

Holocene environmental changes

Coastal region of Amazonia

Vegetational changes which reflect sea-level fluctuations are evident in pollen records from the coastal region of northern Brazil. In the **Lagoa da Curuça** sediment core,

Rhizophora pollen grains were already present during the Lateglacial/Holocene transition. These pollen grains were probably transported by wind over some distance into the lake. Mangrove apparently developed along the rivers near the lake between 7250 and 5600 ^{14}C yr B.P. The subsequent retreat of mangroves from these rivers reflects lower relative sea-level stands between ca. 5600 and 3100 ^{14}C yr B.P. Mangrove was replaced by successional stages of palms, first *Mauritia*, then Arecaceae II and *Mauritiella*, suggesting a somewhat lower ground water table in the Lagoa da Curuça area. Mangrove expanded again along the rivers near the lake after 3130 ^{14}C yr B.P., indicating the return of relatively high relative sea-levels.

Based on the **Lago do Crispim** record, mangroves first developed along the river close to the core site between 7550 and 6620 ^{14}C yr B.P. There is evidence that areas, originally covered by dense, tall coastal Amazon rainforest, were partly replaced by mangrove and some restinga vegetation during the early Holocene. Decreasing *Rhizophora* pollen abundances document a retreat of mangroves, reflecting sea-level regression starting at around 7000 ^{14}C yr B.P. The marked reduction of mangroves near the lake indicates a lower relative sea-level between around 6620 and 3630 ^{14}C yr B.P. During this period a local *Mauritia/Mauritiella* palm swamp formed. That palm trees are sensitive to the local ground table changes is well known (HENDERSON 1995). Marked coastal environmental changes occurred at around 3630 ^{14}C yr B.P. driven by sea-level transgression. Mangroves expanded again close to the site. The local palm swamp was replaced by a Cyperaceae swamp. Rainforest and restinga vegetation adjacent to the swamp were replaced by salt marshes as sea-level rose. The Atlantic Ocean was close to the core site, but the site, which is only 1-2 m above modern sea-level, was apparently never affected by marine incursions during the Holocene. Reduced mangrove vegetation since ca. 1840 ^{14}C yr B.P., may be due to a slightly lower relative sea-level or to human impact.

The **Lago Aquiri** record, far inland from the modern ocean, shows the formation of mangrove between 7450 and 6700 ^{14}C yr B.P. Due to a sedimentary gap, only the last century is recorded. For this period pollen data indicate the present-day environment, seasonally inundated swamp savanna and secondary forests on somewhat higher elevated areas. Mangroves were not found.

Sea-level changes also play an important role in the development and dynamic of mangrove ecosystems on the **Bragança Peninsula**. The radiocarbon dates indicate that the development of mangroves started at the three sites at different times: Campo Salgado at around 5120 ^{14}C yr B.P., Bosque de Avicennia at 2170 ^{14}C yr B.P. and Furo do Chato at 1440 ^{14}C yr B.P. The development of mangrove during the early Holocene, as documented from the other sites, is so far not registered on the peninsula.

The presence of mangrove at Campo Salgado, the highest elevated site on the peninsula which is today a salt marsh, suggests relatively high sea-levels since the mid Holocene. The highest amount of non-mangrove shrub and tree pollen in the basal samples, suggests that mangroves here also replaced an earlier coastal forest ecosystem prior to 5120 ^{14}C yr B.P. Compared with other sites from northern Brazil, it is suggested that the relative sea-level during the mid Holocene was only slightly higher than today. Results from the site Lago do Crispim, which is located next to the modern coastline and only 1-2 m a.s.l., indicate that it was never flooded during the Holocene (BEHLING & COSTA 2001). Poor pollen preservation between 750 and 420 ^{14}C yr B.P., indicate that mangrove deposits were exposed and the area of the Campo Salgado site was relatively dry. The frequency of inundation must have been lower in response to lower sea-levels. Pollen assemblages indicate that an open Poaceae-dominated salt marsh with *Avicennia* shrubs developed after 420 ^{14}C yr B.P. The change from a Poaceae-dominated to a Cyperaceae-dominated modern salt marsh during the last 200 ^{14}C yr B.P., may be related to a lower relative sea-level. The high *Avicennia* pollen concentrations in the sediments from Bosque de Avicennia during the last 180 ^{14}C yr B.P., also suggest a regression of sea-level. Studies by COHEN et al. (2003), show that there is a recent relative sea-level rise on the Bragança Peninsula during the last three decades.

Eastern and central region of Amazon lowland

Sedimentological data from the **Rio Curuá** core in the Caxiuanã region of eastern Amazonia show that the relatively high-energy river changed to a low energy river at ca. 8000 ^{14}C yr B.P. The period prior to 7030 ^{14}C yr B.P. was characterised by the transition to a passive fluvial system. A well-drained highly diverse terra firme Amazon rainforest was found at that time. Later, a *Mauritia* palm-swamp developed along the margins of the river between 7030 and 5970 ^{14}C yr B.P. The area of inundated várzea and igapó forest along rivers were at that time relatively small. Subsequently, the river changed to shallow lake-like conditions. Abundant terra firme rainforest still occupied the well-drained areas. At 3120 ^{14}C yr B.P., the increase of *Virola* (probably *Virola surinamensis*), *Euterpe/Geonoma*-type (probably the palm *Euterpe oleracea),* and *Macrolobium*, trees which are common in inundated forests (FERREIRA et al. 1997), suggest a first expansion of inundated várzea and igapó forest area. After about 2470 ^{14}C yr B.P., the pollen data reflect the largest extension of seasonally inundated forests and Rio Curuá reached a water level similar to that of present.

Sedimentological data indicate that the deposits of the core base from **Lago Calado** in central Amazonia correspond to a fluviatile palaeoenvironment in the Lago Calado valley prior to 8280 ^{14}C yr B.P. Pollen analytical results show the formation of a local *Mauritia* palm-swamp along the river margin between 8280 and 7700 ^{14}C yr B.P. At that time, highly diverse terra firme Amazon rainforest and poorly developed várzea/-igapó forests along the river characterised the vegetation of the study region. The small expansion of várzea/igapó forests and a strong presence of aquatic plants started at 7700 ^{14}C yr B.P., reflecting the increase of the Amazonian water level and the formation of the Lago Calado. The occurrence of abundant Poaceae and Cyperaceae pollen in the lake sediments since 7700 ^{14}C yr B.P., suggest both the local colonisation of unflooded mud banks around the lake margin and the formation of flooding meadows. Open exposed unflooded mud areas, periodically colonised by herbs, are related to cyclic annual Amazonian high and low water stands. In respect to the abundance of Poaceae pollen during the early and mid Holocene, these open areas were large, suggesting short annual high and long annual low Amazonian water stands. After 4070 ^{14}C yr B.P. the area of várzea/igapó forests increased. Herbs were less frequent, probably due to the smaller area of unflooded mud banks. The Amazonian water levels must have been higher than before and the period of the annual high water stands was probably longer. Since 2080 ^{14}C yr B.P., the largest proportion of várzea/igapo forests is recorded, reflecting the highest Amazonian water level. Herbs were rare, suggesting that open unflooded mud areas around the lake were relatively small. This may perhaps also indicate that the cyclic annual period of the Amazonian high water level was the longest since 2080 ^{14}C yr B.P.

Discussion and conclusions

During the Last Glacial Maximum (around 18,000 ^{14}C yr B.P), the Atlantic sea-level was around 120 m lower than today (e.g. SHACKLETON & OPDYKE 1973). During the Lateglacial/early Holocene sea-level rise, huge areas of the exposed coastal shelf were inundated by the Atlantic Ocean. The exposed area along the north Brazilian coast was a belt mostly about 150-200 km wide. Nothing is known about these former ecosystems, but this zone could have been partly covered by Amazon rainforest, savanna, mangrove and other coastal vegetation types.

The compared and summarised pollen record from the Amazon coastal and Basin region document remarkable vegetational and environmental changes, related to the Atlantic sea-level rise during the Holocene (Fig. 2, Table 1). The coastline shifted inland during the Lateglacial/early Holocene sea-level rise. Ancient low elevated coastal ecosystems were destroyed and new ecosystems, such as mangroves developed on intertidal, now higher elevated areas, replacing the former Amazon rain forest. First occurrence of mangrove pollen (*Rhizophora*) in the sediment deposits reflects the early Holocene sea-level rise close to the modern sea-level. Mangrove developed near Lagoa da Curuça between at 7250 and 5600 ^{14}C yr B.P., at Lago do Aquiri between 7450 and 6700 ^{14}C yr B.P. and near Lago Crispim between 7550 and 6620 ^{14}C yr B.P. The occurrence of some *Rhizophora* pollen grains in the Lagoa da Curuça record, already at the beginning of the Holocene at 9430 ^{14}C yr B.P. or earlier), is probably related to wind transported pollen over somewhat longer distances. Evidence of a mangrove environment in the Aquiri region, about 120 km inland from the modern coastline, suggests a significant early Holocene transgression near the Rio Mearim.

Due to the very low elevational gradient of the central and eastern Amazonian rivers, the levels of the Amazonian water depend also on Atlantic sea-level. During last glacial low sea-level stages, when the sea-level was over 100 m lower than today, the gradient was steeper resulting in erosional processes in the Amazon Basin. The Amazon and its tributaries incised and the riverbeds were several tens of meters deeper than today (SIOLI 1957; IRION 1982, 1984; IRION et al. 1995, 1997). With the post-glacial rise of the Atlantic sea-level, the waters in the Amazon Basin rose as well.

The influence of the early Holocene sea-level rise in the Amazon Basin is found by the change of active to a passive river system of the Rio Curuá record in eastern Amazonia and of the Lago Calado record in central Amazonia at ca. 8000 ^{14}C yr B.P. and at 8280 ^{14}C yr B.P., respectively. These events occurred about 500-1000 years earlier, than the first mangrove formation near the modern coastline. In both records is found a local *Mauritia* palm swamp stage, in Rio Curuá in eastern Amazonia between 7030 and 5970 ^{14}C yr B.P. and in Lago Calado in central Amazonia between 8280 and 7700 ^{14}C yr B.P. The timing and length of this successional period differs, which may be relating to the different location and topography of the two rivers. These palm swamp stages occurred before or during the period of the mangrove development in coastal Amazonia. It is supposed that the *Mauritia* palm-swamp stage is a regional phenomenon for low-lying areas in the Amazon Basin, related to the sea-level rise during the early Holocene. First várzea and igapó forests developed at that time as well, but the area of seasonally inundated forests was small.

In the coastal region is found a retread of the mangroves, reflecting a lower relative sea-level: in Aquiri since 6700 ^{14}C yr B.P., in Lago Crispim between 6620 and 3630 ^{14}C yr B.P. and in Lagoa da Curuça between about 5600 and 3950 ^{14}C yr B.P. The interpolated age of 5600 ^{14}C yr B.P for the Lagoa record can be older, due to the poor radiocarbon dating of the core. During this mid Holocene sea-level transgression, in lowland Amazonia are recorded shallower water levels than today, between 5970 and 3120 ^{14}C yr B.P. in Rio Curuá and between 7700 and 4070 ^{14}C yr B.P. in Lago Calado.

The second major period of mangrove formation at the modern coastline occurred during the late Holocene, at the Lagoa da Curuça record since around 3950 ^{14}C yr B.P. and at the Lago Crispim record since 3620 ^{14}C yr B.P., reflecting the highest Holocene sea-level stands. The first development of mangroves on the Bragança Peninsula is found in the Campo Salgado area at around 5120 ^{14}C yr B.P. It is suggested that the radiocarbon date form the Campo Salgado core base is too old in comparison with events of the Lago do Crispim, Lagoa da Curuça and the two Amazon Basin record. The beginning of the mangrove development at the Campo Salgado site is probably not older than 4000 ^{14}C yr B.P. The formation of mangroves at the Bosque de Avicennia site started at around 2170 ^{14}C yr B.P. and at the Furo do Chato since around 1440 ^{14}C yr B.P.

In the eastern Amazon Basin a marked increase of várzea/igapó forests is documented in the Rio Curuá record since 3120 ^{14}C yr B.P. and especially since 2470 ^{14}C yr B.P. In the central Amazonia a marked increase of seasonally inundated forest is found since 4070 ^{14}C yr B.P. and especially since 2080 ^{14}C yr B.P. The marked increase of inundated areas of várzea/igapó forests is apparently related to the late Holocene sea-level rise and almost the complete low lying Amazon Basin seem to have experienced this change. Huge areas of terra firme Amazon rainforest were replaced by várzea and igapó forests during the late Holocene. The development of large seasonally inundated areas must have an important influence on the Amazonian water and carbon cycle and the regional climate in Amazonia.

The development and the modern extension of mangrove forests in the Amazon coastal region and the large extended areas of modern seasonally inundated várzea/igapó forests in the lower Amazon Basin, consequently are relatively young in age.

The Atlantic sea-level rise was probably the major factor in palaeoenvironmental changes, but high water stands might also partly related to climate change, that means greater annual rainfall rates in Amazonia. There is evidence of Amazon rain forest expansion, both north and south of the equator, reflecting a change to wetter climatic conditions (higher precipitation rates and longer wet periods) since mid and especially during the late Holocene (BEHLING & HOOGHIEMSTRA 2001). In the northwestern Amazon rainforest/savanna transition zone, (Llanos Orientales in Colombia), rainforest expansion is documented since 6000 ^{14}C yr B.P. and was further intensified after 3000 ^{14}C yr B.P. (BEHLING & HOOGHIEMSTRA 2000). In southwestern Amazonia, there is evidence of Amazon rain forest expansion (Laguna Bella Vista and Chaplin, Bolivia) during the late Holocene at least since 3000 ^{14}C yr B.P. (MAYLE et al. 2000). The expansion of the Amazon rain forest after 5460 ^{14}C yr B.P. is also reported for the southeastern Amazon region (BEHLING 2002).

In western Amazonia (Colombia) the lower terrace of Rio Caquetá was poorly drained after 4000 ^{14}C yr B.P., as a result of higher river levels, probably due to higher precipitation rates (BEHLING et al. 1999). In this context in the Lago Calado record, possibly relatively short annual high water levels during the early Holocene and relatively long annual high water levels since 4070 and especially after 2080 ^{14}C yr B.P., can be interpreted as signal of climate change to wetter late Holocene periods (BEHLING

et al. 2001a).

However, the Atlantic sea-level rise was probably the major factor in palaeoenvironmental changes, but high water stands might also be due to greater annual rainfall during the late Holocene in western, central and eastern Amazonia.

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References

BASTOS, M. DE N. DO C. (1988): Levantamento florístico em restinga arenosa litoranea na Ilha de Maiandeua-Pará. - Bol. Mus. Para. Emílio Goeldi, sér. Bot. **4**(1): 159-173.

BEHLING, H. (1996): First report on new evidence for the occurrence of *Podocarpus* and possible human presence at the mouth of the Amazon during the Late-glacial. - Veg. Hist. Archaeobot. **5**(3): 241-246.

BEHLING, H. (2001a): Der Amazonas-Regenwald im Wandel der Zeit. - Naturw. Rdsch. **54(3):** 140-144.

BEHLING, H. (2001b): Late Quaternary environmental changes in the Lagoa da Curuca region (eastern Amazonia) and evidence of *Podocarpus* in the Amazon lowland. - Vegetation History and Archaeobotany **10**: 175-183.

BEHLING, H. (2002): Late Quaternary vegetation and climate dynamics in southeastern Amazonia interfered from Lagoa da Confusão in Tocantins State, northern Brazil. - Amazoniana **17**(1/2): 27-39.

BEHLING, H. & M.L. COSTA (1997): Studies on Holocene tropical vegetation, mangrove and coast environments in the state of Maranhão, NE Brazil. - Quaternary of South America and Antarctic Peninsula **10(7):** 93-118.

BEHLING, H. & M.L. COSTA (2000): Holocene environmental changes from the Rio Curuá record in the Caxiuanã region, eastern Amazon Basin. - Quat. Res. **53**: 369-377.

BEHLING, H. & M.L. COSTA (2001): Holocene vegetational and coastal environmental changes from the Lago Crispim record in northeastern Pará State, eastern Amazonia. - Rev. Palaeobot. Palynol. **114**: 145-155.

BEHLING, H. & H. HOOGHIEMSTRA (2000): Holocene Amazon rain forest - savanna dynamics and climatic implications: high resolution pollen record Laguna Loma Linda in eastern Colombia. - J. Quat. Science **15**: 687-695.

BEHLING, H. & H. HOOGHIEMSTRA (2001): Neotropical savanna environments in space and time: Late Quaternary interhemispheric comparisons. - In: MARKGRAF, V. (ed.): Interhemispheric Climate Linkages: 307-323. Academic Press, London.

BEHLING, H., BERRIO, J.C. & H. HOOGHIEMSTRA (1999): Late Quaternary pollen records from the middle Caquetá river basin in central Colombian Amazon. - Palaeogeog., Palaeocl., Palaeoecol. **145**: 193-213.

BEHLING, H., COHEN, M.C.L. & R.J. LARA (2001): Studies on Holocene mangrove ecosystem dynamics of the Bragança Peninsula in northeastern Pará, Brazil. - Palaeogeog., Palaeocl., Palaeoecol. **167**: 225-242.

BEHLING, H., KEIM, G., IRION, G., JUNK, W.J. & J. NUNES DE MELLO (2001): Holocene environmental changes inferred from Lago Calado in the Central Amazon Basin (Brazil). - Palaeogeo., Palaeocl., Palaeoecol. **173**: 87-101.

COHEN, M.C.L, SOUZA FILHO, P.W., LARA, R.J. & H. BEHLING (2003): Model on Holocene mangrove development and relative sea-level changes on Bragança Peninsula (North Brazil). - Wetland Ecology and Management: in press.

COSTA, M.L., MORAES, E.L., BEHLING, H., MELO, J.C.V. & N.V.M. SIQUERIA (1997): Os sedimentos de fundo da Baía de Caxiuanã. - In: LISBOA, P.L.B. (ed.): Caxiuanã: 121-137. Museu Paraense Emílio Goeldi, Belém.

FERREIRA, L.V., ALMEIDA, S.S. & C.S. ROSÀRIO (1997): As áreas de inundação. - In: LISBOA, P.L.B. (ed.): Caxiuanã: 195-211. Museu Paraense Emílio Goeldi, Belém.

GRABERT, H. (1991): Der Amazonas. - Springer, Berlin.

HENDERSON, A. (1995): The palms of the Amazon. - Oxford University Press, New York.

HIDA, N., MAIA, J.G., HIRAOKA, M., SHIMMI, O. & N. MIZUTANI (1997): Notes on annual and daily water level changes at Breves and Caxiuanã, Amazon estuary. - In: LISBOA, P.L.B. (ed.): Caxiuanã: 97-107. Museu Paraense Emílio Goeldi, Belém.

HUECK, K. (1966): Die Wälder Südamerikas. - Fischer, Stuttgart.

IRION, G. (1982): Mineralogical and geochemical contribution to climatic history in Central Amazonia during Quaternary times. - Trop. Ecol. **323**: 76-85.

IRION, G. (1984): Clay minerals of Amazonian soils. - In: SIOLI, H. (ed.): The Amazon. Limnology and landscape of a mighty tropical river and its basins: 537-579. Junk, Dordrecht.

IRION, G., JUNK, W.J. & J. NUNES DE MELLO (1997): The large Central Amazonian River floodplains near Manaus: geological, climatological, hydrological and geomorphological aspects. - In: JUNK, W.J. (ed.): The Central Amazon Floodplain: 23-46. Springer, Berlin.

IRION, G., MÜLLER, J., MELLO, J.N. DE & W.J. JUNK (1995): Quaternary geology of the Amazonian lowland. - Geo-Marine Letters **15**: 172-178.

JUNK, W.J. (1970): Investigations on the ecology and production-biology of the "Floating Meadows" (Paspalo-Echinochloetum) on the Middle Amazon). - Amazoniana **2**(4): 449-495.

JUNK, W.J. & M.T.F. PIEDADE (1994): Species diversity and distribution of herbaceous plants in the floodplain of the middle Amazon. - Verh. Internat. Verein. Limnol. **25**: 1862-1865.

KLINGE, H. (1973): Struktur und Artenreichtum des zentralamazonischen Regenwaldes. - Amazoniana **4**(3): 283-292.

KLINGE, H., ADIS, J. & M. WORBES (1995): The vegetation of a seasonal várzea forest in the lower Solimões River, Brazilian Amazonia. - Acta Amazonica **25**: 201-220.

LISBOA, P.L.B., SILVA, A.S.L., & S.S. ALMEIDA (1997): Florística e estrutura dos Ambientes. - In: LISBOA, P.L.B. (ed.): Caxiuanã: 163-193. Museu Paraense Emílio Goeldi, Belém.

MAYLE, F., BURBRIBDGE, R. & T.J. KILLEEN (2000): Millennial-scale dynamics of southern Amazonian rain forests. - Science **290**: 2291-2294.

NIMER, E. (1989): Climatologia do Brasil. - Fundação Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro.

PAVIA, F. (1995): Der Amazonas. - Eco, Köln.

PIRES, J.M. & G.T. PRANCE, (1985): The vegetation types of the Brazilian Amazon. - In: PRANCE G.T. & T.E. LOVEJOY (eds.): Key Environments Amazonia: 109-145. Pergamon Press, Oxford.

PRANCE, G.T. (1990): The floristic compositon of the Forests of Central Amazonian Brazil. - In: GENTRY, A.H. (ed.): Four Neotropical rainforests: 112-140. Yale University Press, New Haven.

SAINT-PAUL, U., SCHLÜTER, U.-B. & H. SCHMIDT (1999): The significance of Amazonian rain forest deforestation for regional and global climate change - a review. - Ecotropica **5**: 87-114.

SANTOS, J.V.M. DOS & C. DA S. ROSÁRIO (1988): Levantamento da vegetação fixadora das dunas de Algodoal-PA. - Bol. Mus. Para. Emílio Goeldi, sér. Bot. **4**(1): 133-154.

SHACKLETON, N.J. & N.D. OPDYKE (1973): Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. - Quat. Res. **3**: 39-55.

SIOLI, H. (1957): Sedimentation im Amazonasgebiet. - Geologische Rundschau **45**: 608-633.

SNOW, J.W. (1976): The climate of northern South America. - In: SCHWERDTFEGER, W. (ed.): World Survey of Climatology, 12, Climates of Central and South America: 295-403. Elsevier, Amsterdam.

WALTER, H. & H. LIETH (1967): Klimadiagramm-Weltatlas. - Fischer, Jena.

WEISCHET, W. (1996): Regionale Klimatologie, 1. Die Neue Welt. - Teubner, Stuttgart.

Table 1: List of the summarised and compared pollen records, showing the timing of two major events of environmental changes. The table includes also data on the modern elevation (m about mean modern sea-level) of the coring site, and at the time of the environmental changes.

First event/ Site	Modern elevation	Vegetational change to	Past elevation (m a.s.l)	Period (^{14}C yr B.P.)	Length (^{14}C yr)
Lagoa da Curuça	35 m	Mangrove	32 m	7250–5600(?)	1650(?)
Lago Crispim	1-2 m	Mangrove	-6 m	7550-6620	930
Lago do Aquiri	ca. 10 m	Mangrove	ca. 1.5–7 m	7450–6700	750
Rio Curuá	<3 m	*Mauritia*-swamp	-11 m	7030-5970	1060
Lago Calado	23 m	*Mauritia*-swamp	ca. 5 m	8280-7700	580
Second event/Site					
Lagoa da Curuça	35 m	Mangrove	32.5 m	c. 3950-0	3950
Lago Crispim	1-2 m	Mangrove	-1- -0.75 m	3630-1840	3630
Bragança Peninsula					
Campo Salgado	2.7 m	Mangrove	1.35 m	5120(?)-750	4370(?)
Bosque d. Avicennia	2.4 m	Mangrove	-4.0 m	2170-0	2170
Furo do Chato	1.9 m	Mangrove	0.1 m	1440-0	1440
Rio Curuá	<3 m	>Várzea/Igapó	(-5 m)–4.5m	3120/2470-0	3120
Lago Calado	23 m	>Várzea/Igapó	ca. 10/12.5m	4070/2080-0	4070

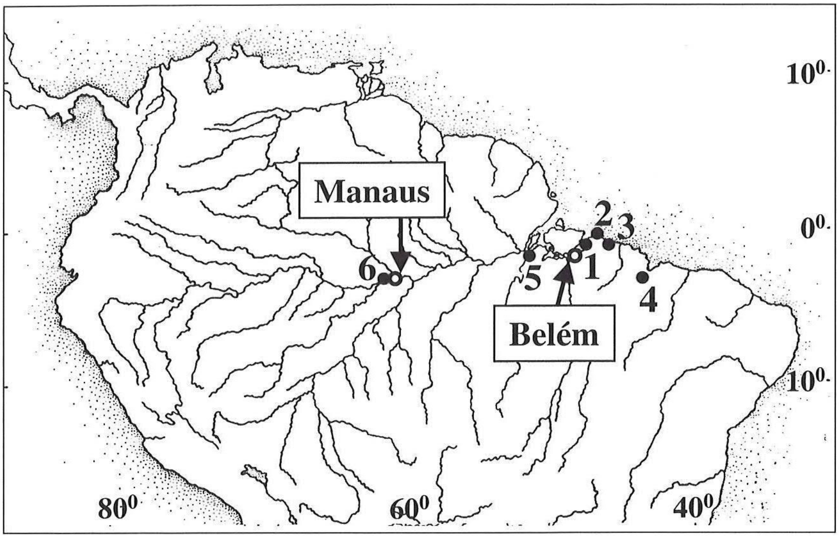

Fig. 1:
Map showing the Amazon river system and the location of the site for the coastal region of Amazonia: (**1**) Lagoa da Curuça; (**2**) Lago Crispim, three records from the (**3**) Braganca Peninsula; (**4**) Lago Aquiri, and for the Amazon Basin region: (**5**) Rio Curuá and (**6**) Lago Calado.

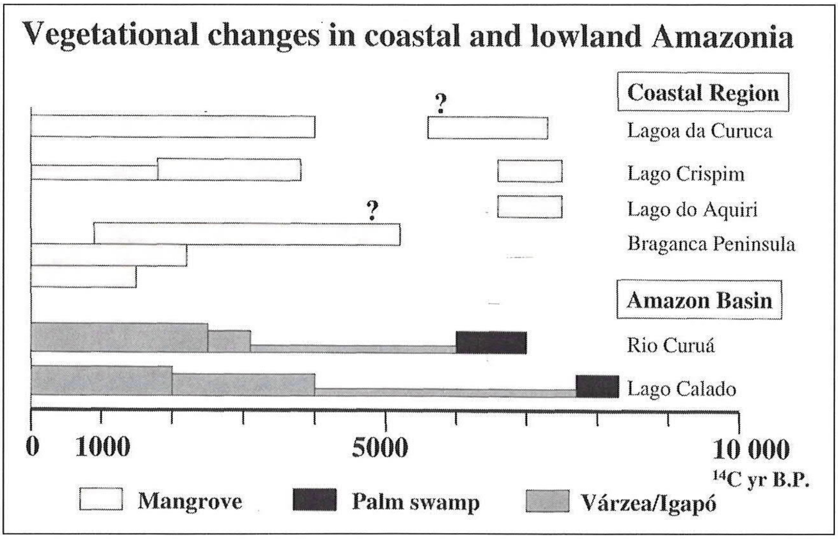

Fig. 2:
Graph summarising the vegetational changes in the coastal and Amazon lowland region related to Holocene sea-level changes.