Chapter 11
Mid-Holocene Climate of Tropical South America: A Model-Data Approach

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Abstract Most of the Early and mid-Holocene paleoclimate studies in tropical South America indicate a drier climate in Amazon and Southeast Brazil and a wetter climate in Venezuela. This pattern has been interpreted as a northward migration of the Intertropical Convergence Zone (ITCZ) due to insolation changes explained by Milancovitch cycles. We show how model simulations and model-data comparisons can help to investigate further the reason of these changes by considering the mid-Holocene period (6 ka). The insolation effect and the vegetation interaction on the seasonal cycle are explored with emphasis on the regional impact on precipitation and on the atmospheric circulation. A major feature of the mean mid-Holocene simulated climate is indeed the decrease of the rainfall in the South Atlantic Convergence Zone (SACZ) region compared to present day, which is confirmed by the proxy data. However, the ITCZ migrates southward during the Southern Hemisphere summer thus enhancing the precipitation in Northeast Brazil. The SACZ and ITCZ displacements are enhanced by the vegetation feedback. The analysis of the transient meridional heat transport and of the baroclinicity of the model climate suggests more intense winter and early spring cold outbreaks in the central region of South America, which seems in agreement with paleoclimate proxies.

Keywords Holocene · Inter tropical convergence zone · Ocean atmosphere general circulation model · South-America · South Atlantic convergence zone

11.1 Introduction

Several Holocene paleoclimate studies in tropical South America indicate a drier climate during Early and mid-Holocene (Absy et al. 1991, Salgado-Labouriau et al. 1997, Ledru et al. 1998, Behling and Hooghiemstra 2000, Freitas et al. 2001,

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Sifeddine et al. 2001, Turcq et al. 2002, Abbott et al. 2003, Cordeiro et al. 2008). This drier paleoclimate has been interpreted as being due to a northward shift of the position of the Inter Tropical Convergence Zone (ITCZ) during the early and mid-Holocene in response to a lower summer insolation in the Southern Hemisphere at that time (Martin et al. 1997, Mayle et al. 2000, Marchant et al. 2001). The ITCZ would have then withdrawn progressively to the south during the last 7000 years (Koutavas and Lynch-Stieglitz 2004).

In the northernmost region of South America a wetter climate and higher riverine discharge has been evidenced by the geochemical composition of Cariaco basin sediments (Haug et al. 2001). A trend toward drier conditions is evident in the data since 5400 years BP. This regional climate changes are also explained by a northern position of the ITCZ during Early to mid-Holocene (Haug et al. 2001), in agreement with the preceding data. This hypothesis clearly links the Monsoon intensity to ITCZ position. This strong link which indeed is observed for present and Holocene climate in North Africa (Braconnot et al. 2000a) is not so clear in South America. Although a relationship exists between the location of the ITCZ and rainfall over Northeast Brazil (Nobre and Shukla 1996) as well as a relationship between inter-hemispheric SST gradients in the Atlantic Ocean, which controls ITCZ position, and past rainfalls in the Andes (Moura and Shukla 1981, Baker et al. 2001), the precipitations in Amazon and Southeast Brazil during summer are linked to the strong convective activities in Amazon Basin and along the South Atlantic Convergence Zone (SACZ). The SACZ is a low level confluence zone, oriented in the NW/SE direction, which provides a major contribution to the total precipitation in the tropical sector of South America and significantly contributes to the north/south energy exchange in the atmosphere (Kodama 1992, Satyamurti et al. 1998). Although the ITCZ and the SACZ are two different climatic features (Garreaud et al. 2008), their variability are related to each other and to remote forcing (Grimm and Silva Dias 1995). Another indication from Holocene paleoclimate studies is the interpreted changes in cold outbreaks dynamics in Central Brazil (Ledru 1993) and on the central Atlantic coast of Espirito Santo (Martin et al. 1993)

Here we show how climate simulations and the comparisons of the simulated climate with proxy indicators can help to better understand the behaviour of some essential characteristics of the South American paleoclimate. We consider the mid-Holocene climate at 6000 years cal BP (6 ka), which is a period of reference for the Paleoclimate Modeling Intercomparison Project (Joussaume et al. 1999, Braconnot et al. 2007a)

Solar radiation at the top of the atmosphere at 6 ka was significantly different from today due to orbital changes. At 6 ka, during the Northern Hemisphere summer the Earth was closer to the Sun than today. As a result, more (less) energy was available in Northern Hemisphere during summer (winter), which strengthens the temperature contrast between ocean and land. Several studies have been realized during the first phase of the PMIP project considering successively simulations with atmosphere alone model, simulations with coupled ocean-atmosphere model and coupled ocean-atmosphere-vegetation models (Braconnot et al. 2004). Most of the studies focused on Northern Hemisphere where the seasonal cycle is amplified.

Significant changes have been reported in Asia and Africa where the monsoon system was reinforced by an increase of the land-ocean temperature gradient and the resulting increase of the low level convergence in the monsoonal low pressure area (Harrison et al. 1998, Joussaume et al. 1999, Braconnot et al. 1999). The enhanced monsoon contributed to the global energy redistribution at 6 ka (Braconnot et al. 2000a). Although these results are qualitatively in agreement with paleoclimate proxies, the magnitude of the monsoon increase on North Africa is underestimated by all atmosphere alone simulations (Joussaume et al. 1999).

The influence of ocean-atmosphere coupled processes has been first analysed by Kutzbach and Liu (1997) and more recently by Zhao et al. (2005) from several coupled simulations. All the coupled simulations show that the intensity of the hydrological cycle is enhanced at 6 ka and the African summer monsoon is intensified and expanded northward toward the Sahara (Braconnot et al. 2004). The SST responds to insolation forcing with a 2–3 months delay affecting the duration of the monsoonal period which initiates about one month earlier in the coupled simulation while the retreat is slower as compared to the present-day simulation. Another important characteristic of the 6 ka coupled simulation is an amplification of the meridional displacement of the ITCZ (Zhao et al. 2005).

Besides the ocean feedbacks, interactions associated with vegetation changes have been identified in the coupled system (Ganopolski et al. 1998, Braconnot et al. 1999, Diffenbaugh and Sloan 2002). In some regions the vegetation control appeared as important as the insolation effect (Braconnot et al. 1999). The coupling of atmosphere, ocean and vegetation lead to the intensification and enhancement of the northward displacement of the African monsoon thus in better agreement with the paleoclimate data (Braconnot et al. 2004).

Few model studies deal with the South American mid-Holocene climate. Valdes (2000), comparing 19 PMIP atmosphere alone simulations, observed decrease of the amplitude of the temperature seasonal cycle over the continent and weakening of the seasonal precipitation cycle. In most of the continent, during the mid-Holocene, drier conditions were simulated by the mean of the 19 models. The continental mean sea level pressure indicates a small positive anomaly during summer which is consistent with reduced ascent that leads to relatively drier and cooler conditions. Melo and Marengo (2008), using the Atmosphere General Circulation Model from "Centro de Previsão do Tempo e Estudos Climáticos", evidenced, at 6 ka, a weakening of low-level convergence over the Amazon, a decrease of southward moisture transport North of 20°S and an increase of the northerly flow east of the Andes South of 20°S.

In this study, we go one step further and analyse the results of the simulations presented in Braconnot et al. (1999) over South America. Comparison with proxy also allows us to evaluate the simulated changes, and provides new interpretations on the causes of the observed changes in different regions. These simulations consider the coupling between atmosphere and ocean, as well as changes in the vegetation cover. Even though more recent simulations performed as part of the second phase of PMIP consider interactive changes in vegetation, it is not possible from the PMIP2 database to analyse the vegetation feedback because simulations with interactive vegetation and simulations with ocean-atmosphere models do not share the same control simulation (see Braconnot et al. 2007b for details). A short description of the design and characteristics of the model experiments is provided in Section 11.2. The comparison between the model simulation with the present climate is available in Section 11.3 where we also discuss the main climate differences associated to the insolation changes and the impact of the vegetation changes. Comparison of the model results for the mid-Holocene with paleoclimate proxies are presented in Section 11.4.

11.2 Methodology

The atmospheric model used in this study is the coupled ocean-atmosphere climate model of the Institute Pierre et Simon Laplace – IPSL CM1 (Braconnot et al. 2000b). The atmosphere model resolution is 3.6° in latitude and 5.6° in longitude (50×64 grid points) with 11 sigma levels in the vertical. The oceanic component resolution has a 2.4° latitude and 3.9° longitude resolution (76×92 grid points) with 31 vertical levels including 10 layers in the upper 100 m. The atmosphere models include a land surface scheme (Noblet-Ducoudre et al. 2000) to compute the water and energy exchanges between land and atmosphere depending on the vegetation type and soil moisture. Changes in the vegetation were accounted for by asynchronously coupling the climate model with BIOME1 (Prentice et al. 1992), which provides the vegetation type as a function of the simulated climate. A complete description of the model and of the experimental design are provided by Braconnot et al. (1999) and Braconnot et al. (2000b). In the present study, all analyses are based on a mean seasonal cycle averaged over at least 50 years of simulation. In the control simulation the vegetation is fixed to the observed modern climatology. This experiment is referred to as CTL. Two mid-Holocene simulations will be explored. The first one only considers the changes in the Earth's orbital parameters prescribed as provided in the Paleoclimate Modeling Intercomparison Project (Joussaume et al. 1999) and includes the biome distribution for present day conditions (referred herein as H1). The second one (H2) also includes changes in vegetation taken from interactive application of BIOME1 vegetation model to the simulated 6 ka climate until equilibrium is reached between vegetation and climate. The present-day and 6 ka BIOME1 vegetation computed for H2 are shown in Fig. 11.1.

11.3 Results

11.3.1 Present Tropical South America Climate as Simulated by IPSL Model (CTL)

Some of the feature of the mid-Holocene climate may be affected by systematic model biases. Therefore it is important to know how the model reproduce the modern climatology before discussing the differences between the past climate and present. The IPSL coupled model has a well-defined precipitation annual cycle

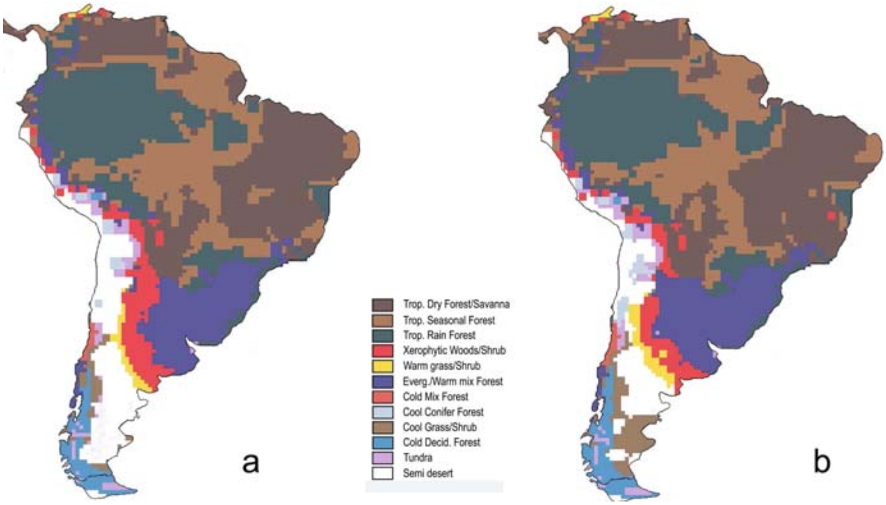

Fig. 11.1 (**a**) Vegetation produced by BIOME1 model with current climate (**b**) Vegetation produced by BIOME1 model with 6 ka simulated climate. This last one is used in H2 simulation

with the development of a very strong SACZ from October to March. This feature well illustrated on Fig. 11.2, which shows the difference between the observed precipitation (*Global Precipitation Climatology Project* /GPCP, Alder et al. 2003) and the CTL mean precipitation for December, January, February (DJF) and June, July, August (JJA). Some of the model drawbacks are commonly found in climate simulations. They concern: (a) excessively dry Amazon region, (b) too much precipitation in the SACZ, (c) excessive precipitation along the eastern slopes of the Andes and over the Bolivian Altiplano, (d) North East (NE) Brazil precipitation above observed values and (e) relatively weak Atlantic ITCZ. The CTL simulation captures the major features of the winter circulation (Fig. 11.2) in South America such as the northward displacement of the ITCZ and the high precipitation associated to the baroclinic zone in the southern portion of South America, along the Andes. However, the model overestimates the precipitation along the eastern slopes of the Andes and the intensity of the ITCZ in the Atlantic Ocean. The simulation properly captures the relative maximum of precipitation along the coast of NE Brazil but fails in reproducing the high levels of precipitation in Central America, particularly over Panama. As a result of the overestimation of the intensity of the precipitation in the Atlantic ITCZ, the trade winds are stronger from the SE in the western Atlantic in the simulated JJA climate (not shown). During winter, the model underestimates the precipitation in northern Argentina, Uruguay and SE Brazil. This is probably related to the lack of sufficiently strong cyclones which typically form in this region from autumn to spring (Gan and Rao 1991). The observed precipitation pattern in the northern portion of the continent is reasonably well reproduced except for some details along the Andes in Colombia.

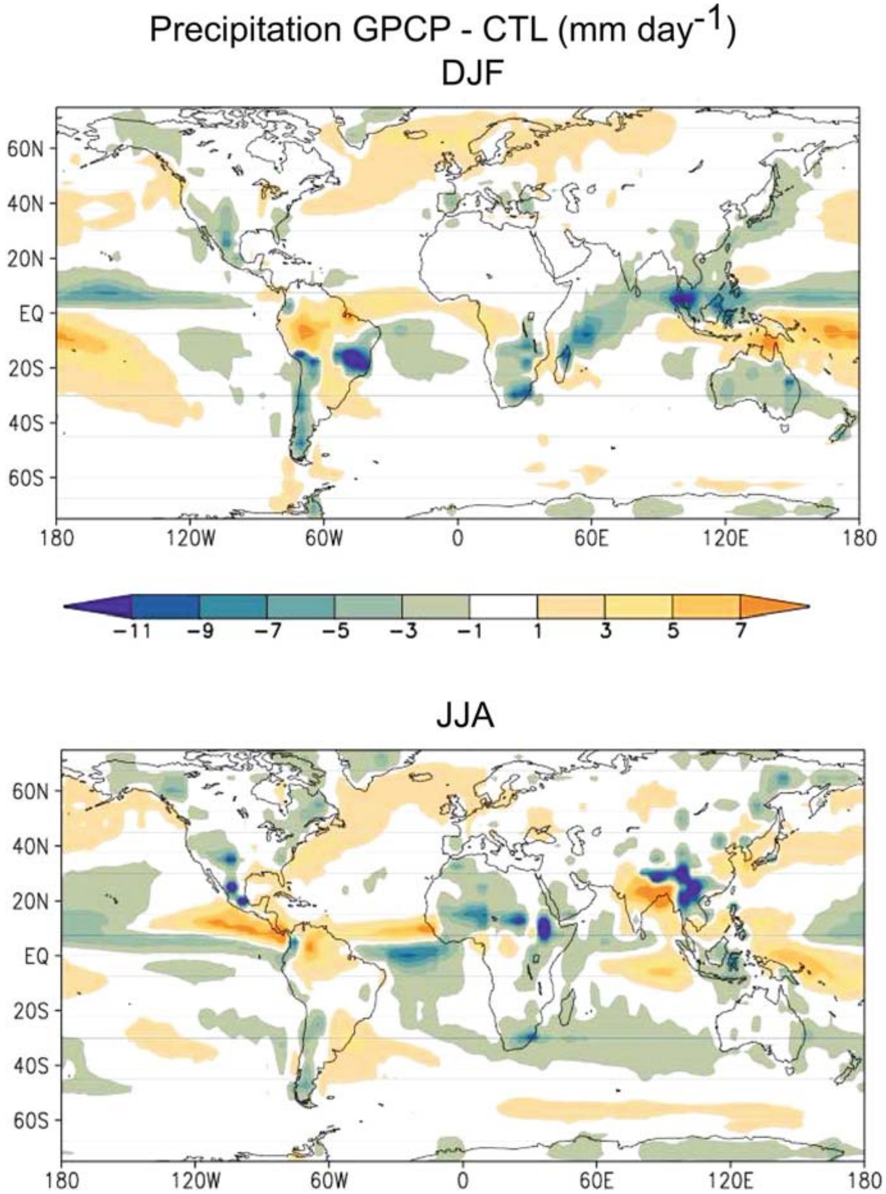

Fig. 11.2 Difference between the observed precipitation (*Global Precipitation Climatology Project*/GPCP, Alder et al. 2003) and the CTL simulation for December-January-February and June-July-August periods

The model summer climate is wetter in the SACZ than observations by a factor of 2–2.5 and drier in the Amazon and Southern Brazil (Gandu and Silva Dias 1998). If the convective scheme does not produce sufficient deep clouds, the tropical atmospheric column is moistened and the so called large-scale precipitation scheme takes over, producing stratiform precipitation. Thus, the model tends to heat the atmosphere mainly at lower levels, creating a rather persistent low pressure system near the surface which enhances the moisture convergence and in turn, feedback into the stratiform precipitation. This hypothesis is corroborated by the relatively weak upper tropospheric anticyclonic anomaly to the SW of the maximum precipitation in the SACZ region (figure not shown). In the following, we will keep in mind these differences with observations and mainly discuss robust large-scale features.

11.3.2 ITCZ and ZCAS at the Mid-Holocene

The difference between the climatology of H1 and CTL is first discussed in this section. The amplitude of the seasonal temperature cycle is significantly decreased over most of the South American continent (Fig. 11.3). The mean temperature in DJF (JJA) and MAM (SON) in H1 is colder (warmer) compared to CTL. Cooling in H1 is particularly strong in MAM period over the northern and southern sectors of the continent and relatively small in the central region where the SACZ is located during the summer. The cooling in northern Argentina in summer and autumn is particularly strong. The winter and spring warming is stronger along the coast and the Andean region in the spring. There is a slight cooling (approximately 0.2°C) in the annual mean in H1 (mean temperature over the continent of the order of 17.2°C in CTL), which is consistent with the reduction of annual mean insolation within the tropics.

Precipitation differences (Fig. 11.4) between H1 and CTL are also significant. The H1 spring is wetter in central Brazil and the ITCZ precipitation is lower. The SACZ becomes less active in the summer in H1 and displaced to the north while the ITCZ is displaced to the south producing enhanced precipitation in the NE region of Brazil. The ITCZ and the SACZ seem to merge in NE Brazil thus enhancing the precipitation. This phenomenon indicates that the displacement of ITCZ and ZCAS do not follow necessarily the same direction. The autumn climate is also drier in the SACZ region and wetter in the eastern portion of NE Brazil. In the Andes, the Altiplano and eastern slopes are also significantly drier in the present simulation (CTL) than in the 6 ka case (H1). In Southern Hemisphere winter the ITCZ is displaced to the north. The southward (northward) displacement of the ITCZ in summer (winter) is the prevailing feature in the equatorial region. Very small differences in the precipitation regime are found in Southern Brazil, Uruguay, Northern Argentina and Paraguay (just slightly more humid, mainly in the winter period).

These results are in agreement with Valdes (2000) who also observed a dryer climate all over Brazil. This feature is thus a primary climate response to insolation change. Valdes (2000) used PMIP1 atmosphere alone model. The coupled ocean atmosphere model we studied here enhances ITCZ displacements. Most of PMIP2 models, which are also coupled Ocean-Atmosphere models, indicate the same widening of ITCZ range of displacement, suggesting that the feedback from the ocean strongly modulates the location and the size of the ITCZ.

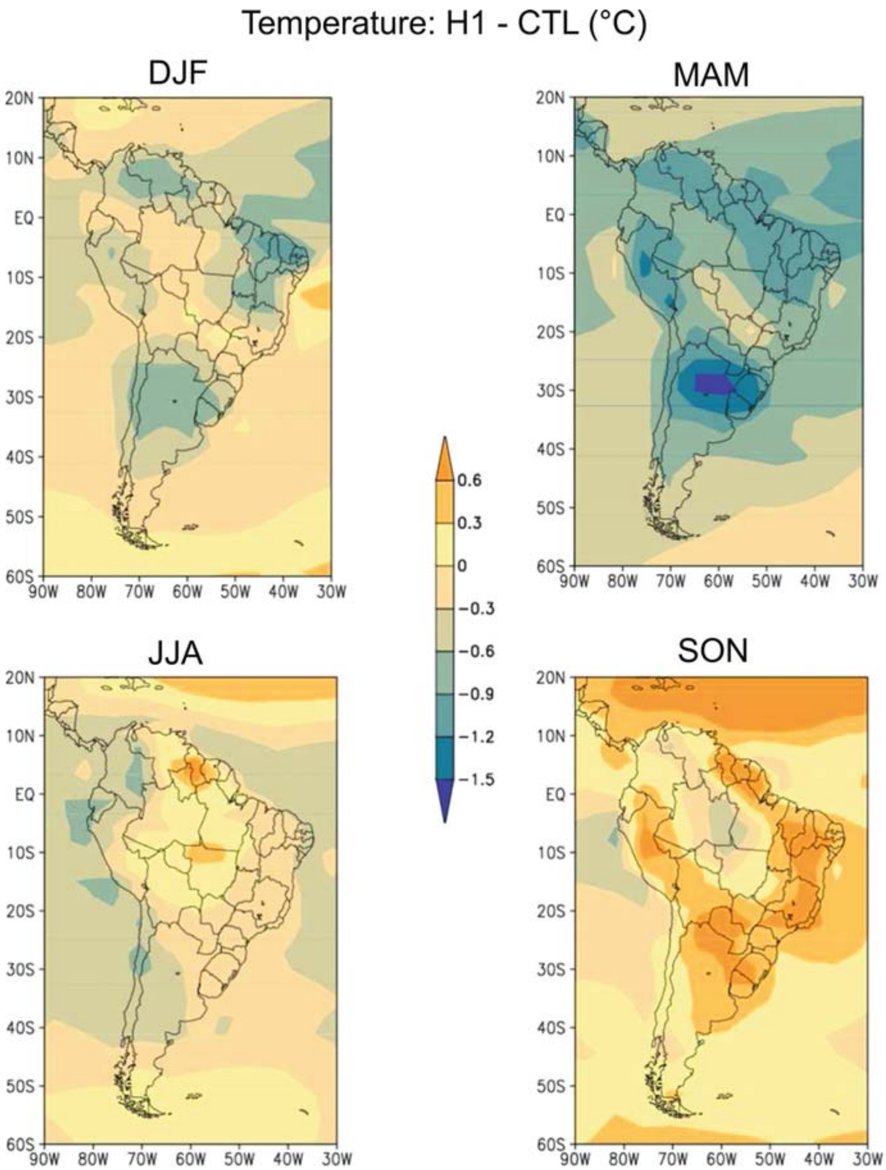

Fig. 11.3 Temperature (°C) difference between CTL and H1 for December-January-February, March-April-May, June-July-August and September-October-November periods

The impact of the vegetation change in H2 provokes an enhancement of the northward displacement of the SACZ and southward migration of the ITCZ during summer compare to H1 (Fig. 11.5). This effect is well depicted by the difference between H2 and H1. The vegetation effect is sufficiently strong in the SACZ to lead

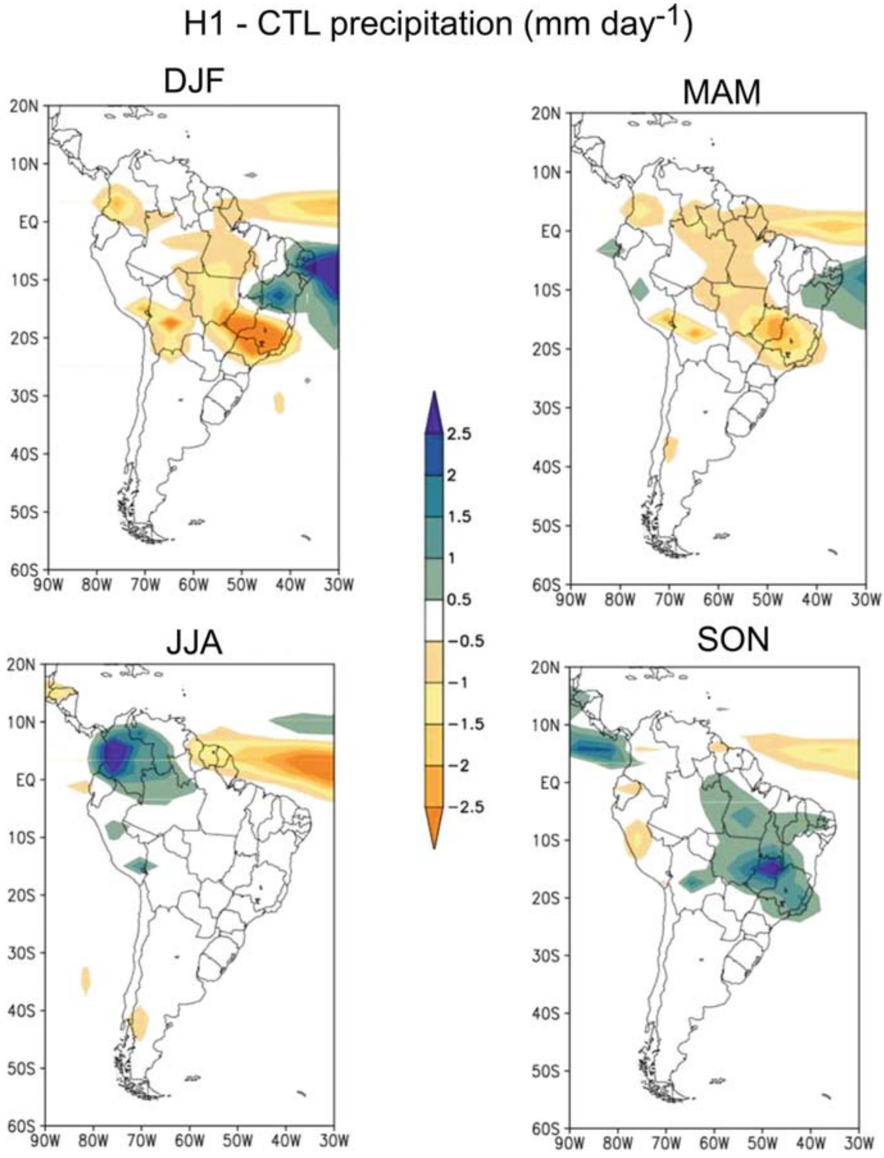

Fig. 11.4 Precipitation difference between H1 and CTL December-January-February, March-April-May, June-July-August and September-October-November periods

to a significant decrease in the summer precipitation. The precipitation regime in NE Brazil is significant in autumn and winter, with relatively more precipitation in JJA in H2 with respect to H1. More precipitation is observed in Central South America during SON, indicating a possible earlier start of the rainy season (Fig. 11.5).

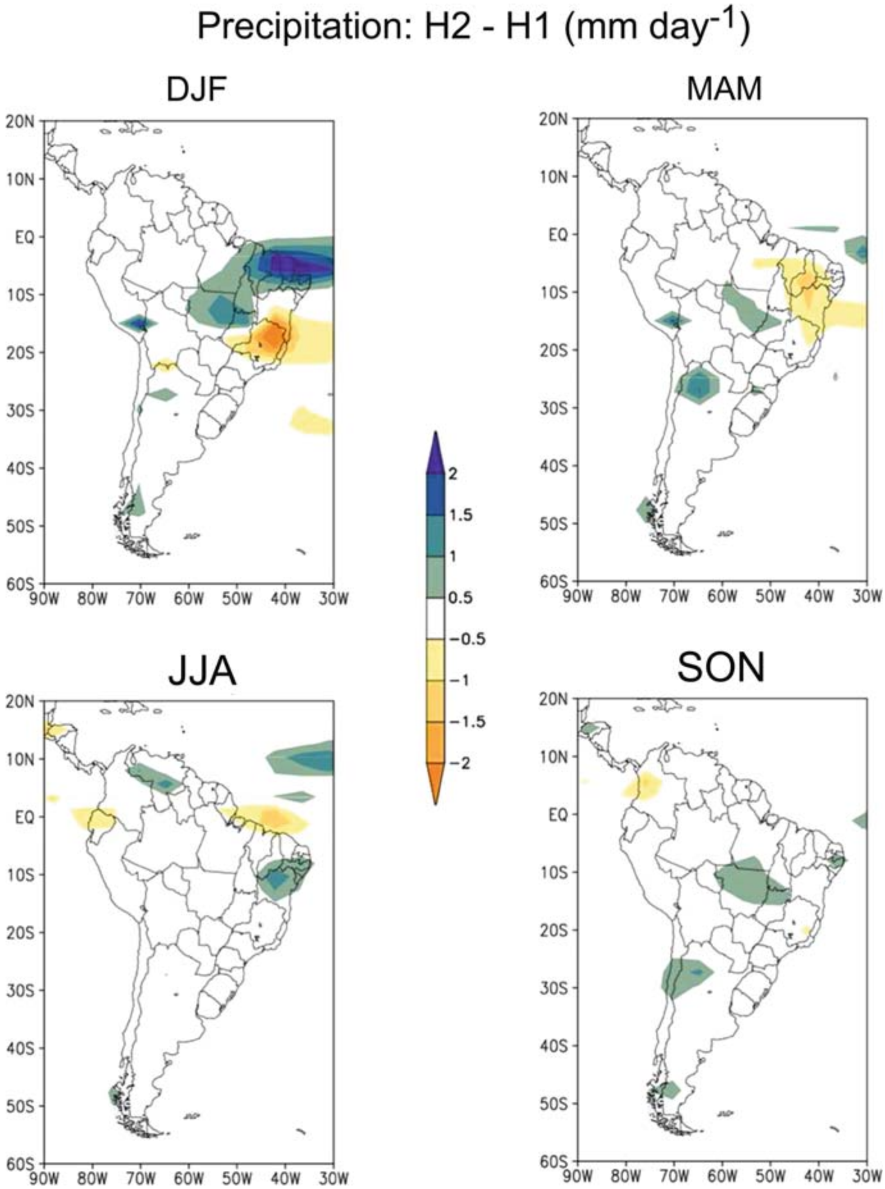

Fig. 11.5 Precipitation difference (mm/day) between H2 and H1 in December-January-February, March-April-May, June-July-August and September-October-November

The vegetation effect leads to increased precipitation in northern Argentina almost throughout the year (small impact in the winter).

Regional vegetation feedbacks due to changes, for example, in albedo, roughness length, and soil moisture are important in paleo-climate simulations, because they affect both the heat and the water exchanges between the surface and the atmosphere (Dutton and Barron 1996). In the case of the SACZ region (from Southwest Amazon to Southeast Brazil) the observed rainfall reduction cannot be a direct effect of vegetation since there are no changes in the BIOME1 Model (the simulated climate changes are not sufficient to provoke a vegetation change). Thus the observed climate changes are due to a remote effect of the global vegetation change. The weakening of the monsoon circulation associated with the northward displacement of the SACZ is related to an anticyclonic wind anomaly at 850 hPa during the summer and early autumn (Fig. 11.6) and to a more intense westerly flow in H2 than in H1 south to about 40°S. This weakening of the tropical circulation, associated with the precipitation decrease in the SACZ, is probably due to the vegetation changes produced by the model in west Africa and their impact on the Tropical Atlantic SST and the associated strengthening of the SST gradient across 5°N in the Atlantic ocean (Braconnot et al. 2004). In the same manner, the weakening of the trade winds in JJA (Fig. 11.6) is due to the intensification of the African monsoon by the development of vegetation in West Africa arid regions (Braconnot et al. 2004). In Northern Argentina and Northeast Brazil small differences in vegetation are observed (Fig. 11.1). Sensitivity tests would be needed to determine the relative influence of these local vegetation changes.

11.3.3 Atmospheric Mean and Transient Circulation

The reduction of 850 hPa flow intensity over the continent during the mid-Holocene is also and mainly due to the decrease in the seasonal variation of insolation in the Southern Hemisphere producing smaller temperature gradients. Significant changes can be observed at the tropospheric low-level circulation such as the decrease of the intensity of the northwesterly South American Low Level Jet – SALLJ (Marengo et al. 2002) east of the Andes (in DJF and MAM, Fig. 11.7) and of easterly flow in the equatorial region (SON and DJF). The spring and summer main feature in the wind field is the decrease in the intensity of the circulation associated with the subtropical Atlantic High which is associated with the southward displacement of the ITCZ. The decrease in the intensity of the SALLJ has a significant impact in the moisture transport from the Amazon Basin to the northern part of the Plata Basin. The winter low level circulation is characterized by the intensification of the westerly flow towards the northern Andes which provides the moisture explaining the enhanced precipitation in Colombia. We will see later that this increase does not appear in the proxy data, probably because it is, in reality, located more on the North.

However, the transient eddies heat transport shows significant differences between the present and the 6 ka model climate simulations. Figure 11.8 shows the transient meridional heat transport at 20°S 62°W just to the east of the Andes and 20°S 40°W (off the coast of State of Espirito Santo in Brazil). Although the changes in the mean meridional wind (figure not shown) are small, the transient

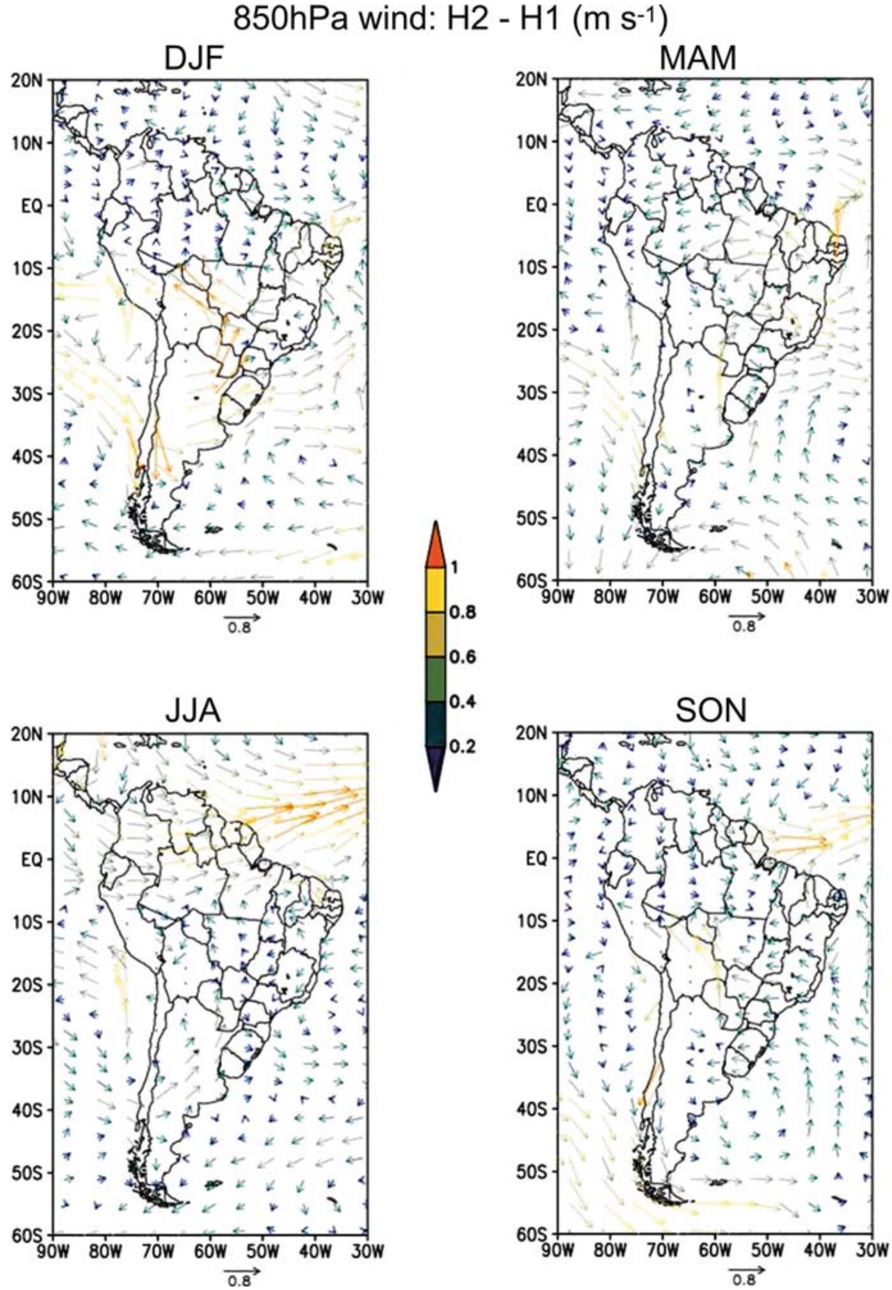

Fig. 11.6 850 hPa wind difference (m.s^{-1}) between H2 and H1 in December-January-February, March-April-May, June-July-August and September-October-November

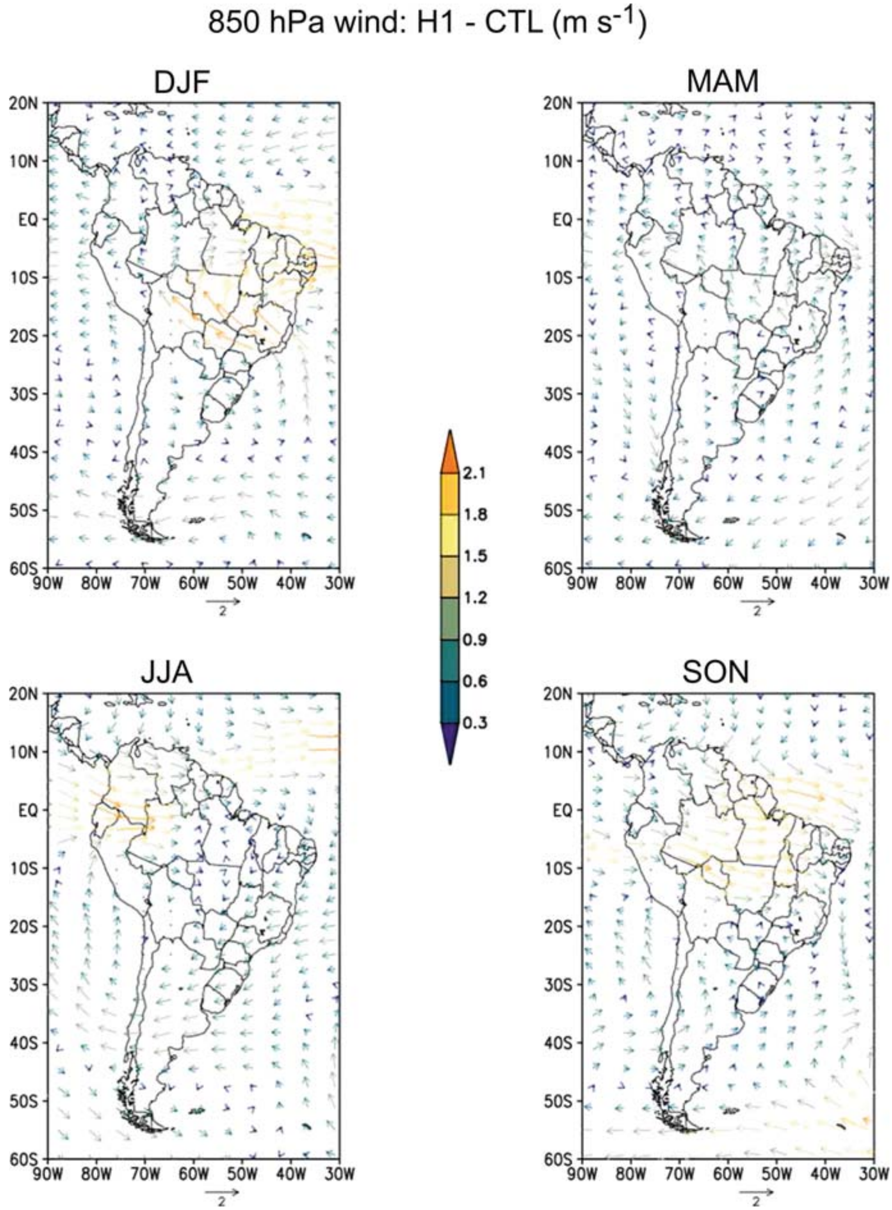

Fig. 11.7 850 hPa wind difference (m.s^{-1}) between H1 and CTL in December-January-February, March-April-May, June-July-August and September-October-November periods

southward (negative in Fig. 11.8) heat transport is significantly lower in H1 off the coast of the State of Espirito Santo during the winter, indicating weaker baroclinic perturbations affecting eastern Brazil in this region. Inversely, the transient meridional heat flux along the Andes in spring (mainly September and October)

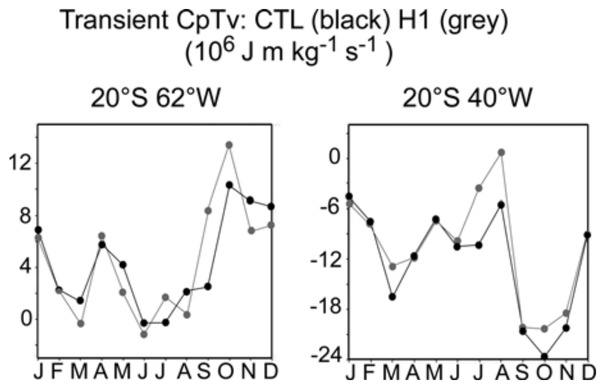

Fig. 11.8 Transient heat transport at 20°S 62°W and 20°S 40°W plotted as a function of months for CTL (*black circles*) and H1 (*grey circles*)

is larger in H1, indicating stronger activity associated with weather systems, suggesting that the cold air outbreaks in Central Brazil could be more intense at the end of the winter/early spring. The zonal flow at 500 hPa is stronger in a broad band between 20 and 35°S in September (Fig. 11.9), supporting enhanced baroclinic

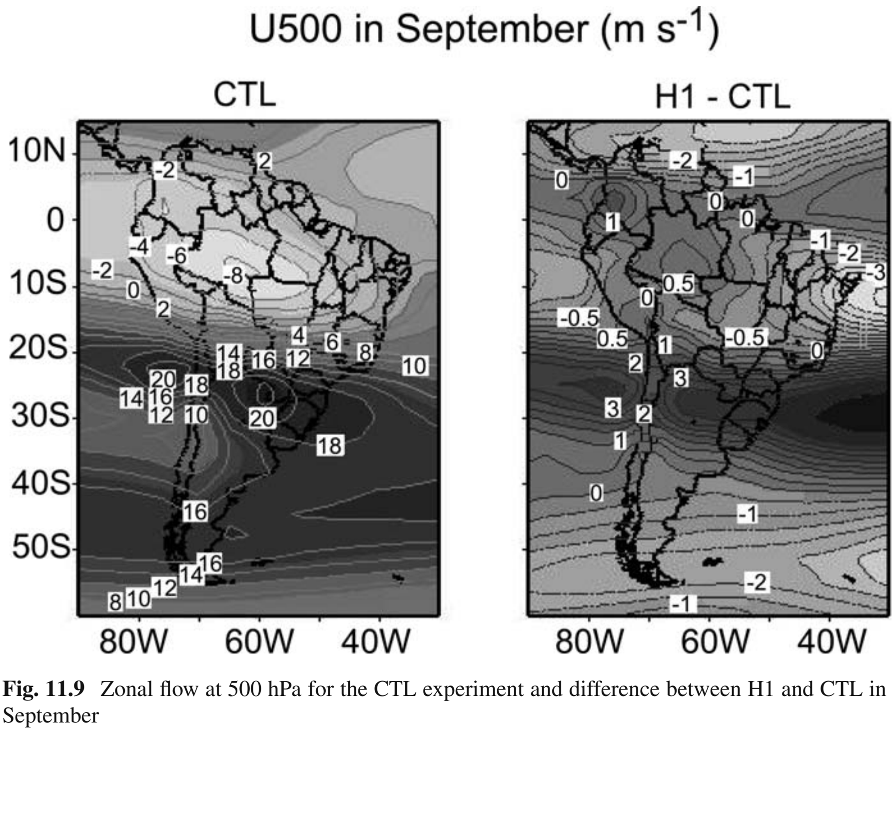

Fig. 11.9 Zonal flow at 500 hPa for the CTL experiment and difference between H1 and CTL in September

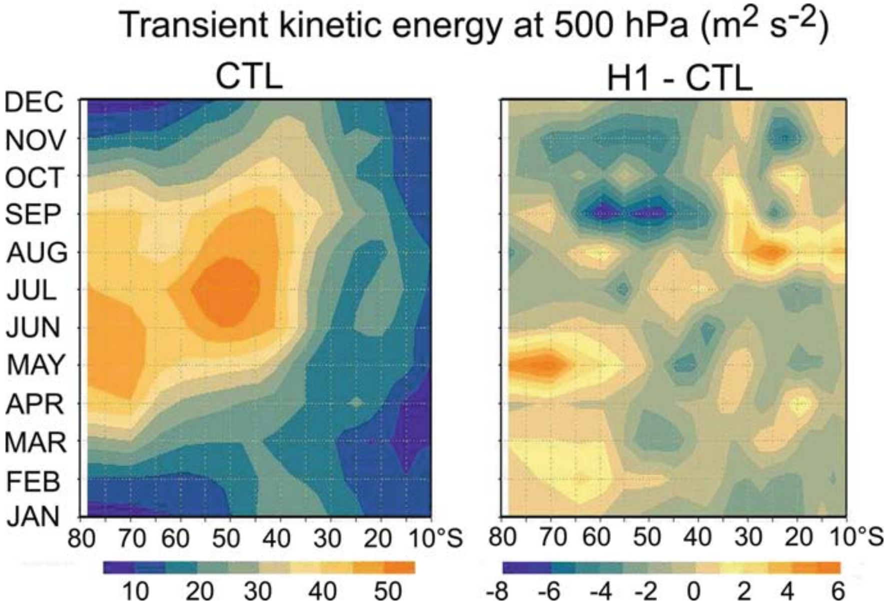

Fig. 11.10 Hovmoller diagram of the transient kinetic energy at the 500 hPa level at 60°W (unit $m^2.s^{-2}$) for the mean CTL annual cycle and the difference between H1 and CTL

instability in this region, which favors the development of low level cyclogenesis. The associated cyclones enhance the northward penetration of cold air masses in the continent.

Another interesting evidence of changes in the transient structure of the weather systems in South America is shown in Fig. 11.10 (transient kinetic energy at the 500 hPa level). The mean CTL annual cycle clearly indicates that the maximum activity occurs from June to November at 35°S and that the tropical intrusion of upper level transients from the south occurs in early spring. The H1 experiment shows significant enhancement of the transient kinetic energy activity in the late winter/early spring and small increase in the autumn. Further south, there is a significant decrease in the transient activity in the spring. Thus, the simulated changes at 6 ka are also significant in the transient activity and therefore in the weather patterns.

A vegetation feedback is identified in the transient meridional heat transport during the winter (Fig. 11.11). A large increase in the magnitude of the heat transport is observed at 20°S and 60°W, near Paraguay and eastern Bolivia. The vegetation feedback in the atmospheric circulation is such that the enhanced upper level flow facilitates the development of transient baroclinic modes which are associated to stronger cyclogenesis and more intense cold outbreaks in the central portion of the continent.

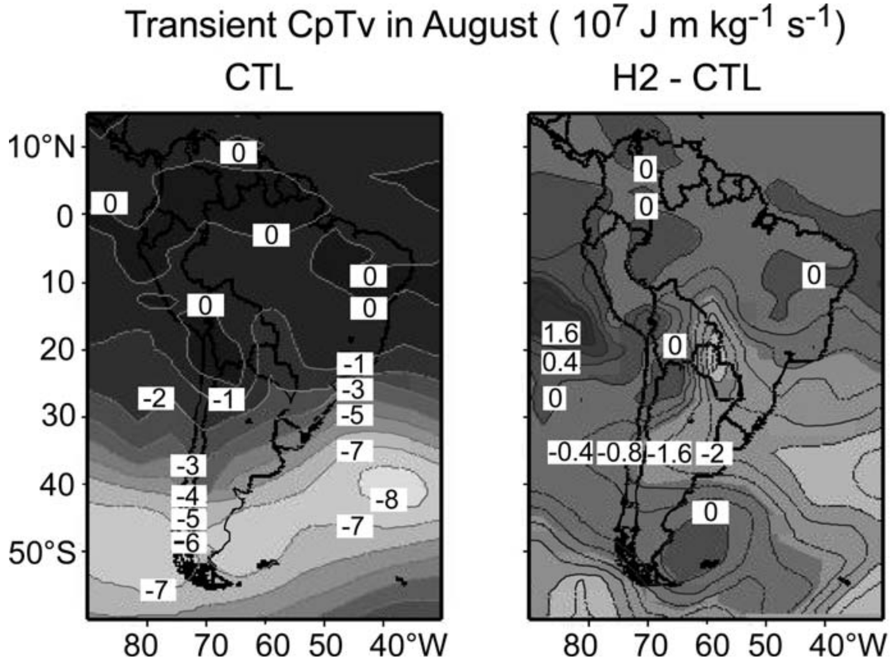

Fig. 11.11 Transient meridional heat transport (units 10^7 J.m.kg^{-1}.s^{-1}) in CTL and difference between H2 and CTL in August

11.4 Comparison with Paleoclimate Data

11.4.1 Precipitation

A major feature of the mean climate change between the CTL and the H1 experiments is the decrease of the rainfall in the SACZ region in the mid-Holocene. This dryness is confirmed by the proxy data (Fig. 11.12). The lakes Dom Helvecio (19°41′S, 42°35′W) and Preta de Baixo (18°25′S, 41°50′W) had water levels lower than present during the mid-Holocene (Turcq et al. 2002). The same is observed at Lagoa Santa (19°38′S, 43°54′W) according to Parizzi et al. (1998). The vegetation reconstructed from palynological studies was more open at Lagoa dos Olhos (19°38′S, 43°54′W – De Oliveira 1992), Morro de Itapeva (22°47′S, 45°28′W – Behling 1997) and Lago do Pires (17°57′S, 42°13′W – Behling 1995a), indicating a dryer climate at 6 ka. It is worth noting that Behling (1995a) interpreted the vegetation change as a result of a longer dry season (approximately 5 months during the mid-Holocene and closer to 4 months at present). The IPSL model indicates a decrease of the summer precipitation in this region but there are no significant indications of a change in the dry season length due to the early start of the rainy season. Another important point is that the vegetation reconstructed by the model (Fig. 11.1) is not significantly changed in this region, i.e. the simulated climate

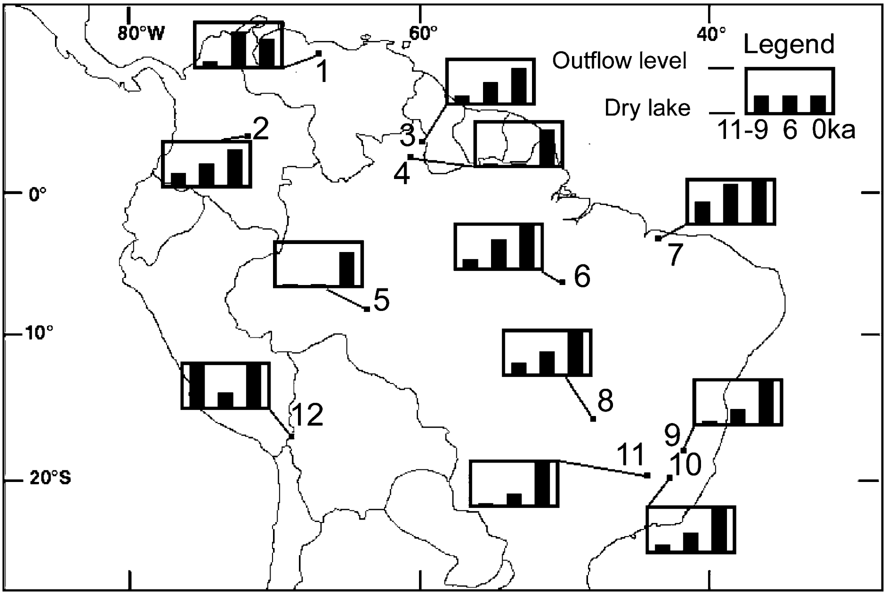

Fig. 11.12 Lake level changes in tropical South America at the beginning of Holocene (11–9 ka), at Middle Holocene (6 ka) and at present. Ages have been calibrated according to Stuiver et al (1998). (*1*) Lake Valencia (Bradbury et al. 1981, Curtis et al. 1999), (*2*) Lake Loma Linda (Behling and Hooghiemstra 2000), (*3*) Lake Caracaranã (Turcq et al. 2002), (*4*) Boa Vista lakes (Simões Filho et al. 1997), (*5*) Humaita lakes (Cordeiro et al unpublished), (*6*) Carajás lake N3 (Cordeiro et al.1997), (*7*) Lake Caçó, (*8*) Aguas Emendadas, (*9*) Lake Agua Preta de Baixo (Turcq et al. 2002), (*10*) Lake Dom Helvecio (Turcq et al. 2002), (*11*) Lake Santa (Parizzi et al. 1998), (*12*) Lake Huinaimarca (Wirrmann and Mourguiart 1995)

change is not strong enough to modify the vegetation classification provided by the BIOME model. However, the proxy data confirms that the tropical rainforest had regressed and thus some cautions must be taken in interpreting the H2 results in that region.

In Northeast Brazil the palynological record of Saquinho (10°24′S, 43°13′W) reveals more developed gallery forests during the mid-Holocene (De Oliveira et al. 1999) indicating a wetter climate, which is also reconstructed by the H1 simulation. It is difficult to assess the results of the changes in vegetation produced in H2 because this region is located in the transition between the wetter and drier areas. More proxy data are necessary in order to evaluate the magnitude and impact of the vegetation change in NE Brazil.

The lake record of Lagoa Feia (47°18′S, 15°34′W – Turcq et al. 2002) as well as the palynological records of Aguas Emendadas (15°S, 47°35′W – Barberi et al. 2000) and Crominia (17°15′S, 42°13′W – Salgado-Labouriau et al. 1997) in the Central region of Brazil (Fig. 11.12) indicates dryer climate conditions during the mid-Holocene. The H1 model shows reduced rainfalls from December to April and slightly increased precipitation from September to November (Fig. 11.4). These changes are less marked in H2.

In the Southern region of Brazil, where the model indicates a slightly wetter past climate mainly in the H2 experiment (Fig. 11.5), the palynological records show, on the contrary, a reduced forest extension (Behling 1995b) with exception of Serra da Boa Vista (27°42′S, 49°52′W) where a well developed forest was present. This divergence may be related to the mountainous relief of this coastal region. Southward, the Aparados da Serra record (29°13′S, 50°W – Roth 1990) does not evidence any forest change since the mid-Holocene. In the pampas of Argentina (37–38°S, 58–62°W) the pollen indicates a more humid climate during the mid-Holocene (Prieto 1996).

In the northern part of Amazon, in the Roraima state, the Caracaranã Lake (3°51′N, 59°47′W) level was low (Turcq et al. 2002) and the lakes in the Boa Vista region (2°55′N, 50°40′W) have dried (Simões Filho et al. 1997). This is in agreement with the H1 model results (Fig. 11.4). H2 does not significantly change the results in this region. Westward, in the llanos of Colombia (3–5°N, 69–73°W) the forests and arboreal savannas were less developed than present indicating a dryer climate or a longer dry season (Behling and Hooghiemstra 2001). The CTL model indicates less precipitation during the dry season and at the beginning of the rainy season but an increase at the end of the wet period. H2 enhances the effect at the end of the rainy season but has no significant effect in the remaining periods. This result does not seem compatible with the proxy data. In the north, in Venezuela, the paleodata from lake Valencia (Bradbury et al. 1981, Curtis et al. 1999), as well as the marine Cariaco Basin study (Haug et al. 2001) indicate a mid-Holocene wetter climate. The model doesn't reproduce such feature although the Northern position of ITCZ during North Hemisphere summer explains the recorded change. The rainfall increase does not seem to be located at the right place in the model.

11.4.2 Temperature and Cold Outbreaks

The palynological study from Salitre (19°S, 46°46′W) suggests a well-developed forest with cold taxa between 10200 and 7400 cal BP (Ledru 1993). It has been interpreted as a stronger intensity of cold outbreaks during the Holocene. Between 7400 and 6300 cal BP, this forest was replaced by a semi-deciduous forest. Such change in vegetation type may still indicate a cold outbreak influence, since those systems provoke rainfall during the dry season. A higher cold outbreak influence than today, in central Brazil is also reproduced by the model, although the mid-Holocene simulation does not show higher precipitations. In the H2 simulation the transient meridional heat transport indicates an additional increase in cold front intensity in a central South-American region centered in Paraguay and northern Argentina, extending into central Brazil (Fig. 11.11). The reason for this increased penetration of cold air may be partially related to change in vegetation in the Chaco region (Fig. 11.1).

On the central Brazilian coast, the transient meridional heat transport shows, on the contrary, a decrease in cold front influence (Fig. 11.6). This feature seems in a good agreement with the coastal geomorphologic data. Today, in this region, the residual long shore sand transport is always northward due to the southwestern storms generated by the cold outbreaks. During the mid-Holocene several events of erosion due to southward long shore sand transport related to trade winds have been observed (Martin et al. 1993), in agreement with a weaker intensity of transients simulated at 6 ka on Espirito Santo coast (Fig. 11.8).

11.5 Conclusions

The model results of the simulation for the present climate and the mid-Holocene indicate a significant reduction in the seasonal cycle, which is coherent with the orbital forcing. A basic impact of the insolation forcing is the change in the ITCZ location, which is influenced by the coupled ocean-atmosphere system and by the vegetation change. In summary, the following features were observed in the IPSL model simulation for the present and 6 ka climates:

- The simulation of modern precipitation is much larger than observed in the SACZ region and underestimated over the Amazon region;
- At mid-Holocene, the northward displacement of the SACZ and southward migration of the ITCZ during Southern Hemisphere summer is such that the two systems merge, increasing the precipitation in the NE area of Brazil;
- There is a northward migration of ITCZ during mid-Holocene Northern Hemisphere summer.
- The vegetation feedback enhances the impact on the SACZ and ITCZ;
- As a consequence of the ITCZ migration to the south, NE Brazil tends to be cooler in the 6 ka simulation;
- Southern Brazil, Uruguay and NE Argentina are slightly wetter and cooler (mainly in the summer) in the 6 ka simulation;

The northward migration of the SACZ leads to drier condition in SE Brazil that is consistent with paleoclimate proxies, as discussed in Section 11.4. There are observational evidences suggesting a wetter NE Brazil. Thus, the basic model features associated with the northward displacement of the SACZ and southward migration of the ITCZ are consistent with observations. Weakening of the monsoonal circulation in the model is associated with a reduction of the intensity of the upper tropospheric anticyclonic circulation (the Bolivian High).

The largest temperature changes (Fig. 11.3) in the 6 ka simulation are observed in the Atlantic tropical basin. The 6 ka North Atlantic is particularly warmer than in the present simulation and colder to the south, in agreement with other studies (Braconnot et al. 1999, Otto-Bliesner 1999). The warming in the South Atlantic and cooling the North Atlantic are coherent with the insolation effect associated to the orbital changes. But significant contribution is also associated to the changes in cloud cover in view of the significant displacement of the ITCZ.

The enhanced baroclinicity between 20 and 35°S, mainly during the winter period, as measured by the intensification of the mid-tropospheric zonal flow, leads to the increase of the transient meridional heat transport. Thus, the model results are coherent with a scenario of more intense cold outbreaks on the tropical sector of South America. This effect is enhanced when the vegetation feedback is included in the model.

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