Forest and Rainfall Interactions in the Amazon Basin

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Abstract

Biosphere-atmosphere interactions in the Amazon region as seen from the point of view of rainfall production are presented in light of recent research results that focus not only on the natural environment but also on the effects of human intervention in the region through land use and land cover change and biomass burning activities. The effects of deforestation are seen as an initial enhancement of rainfall accumulation while the rate of deforestation is small and as deforestation progresses a warming trend and decrease in rainfall is expected. Aerosols from biomass burning act as a cooling agent at the surface and suppress rainfall from shallow clouds. For deep clouds the effect of aerosol increase is highly non-linear. The change in rainfall features in the Amazon Basin may have an impact on global climate through teleconnection.

Key words *deforestation, biomass burning, rainfall, Amazon*

Amazon Climate

The Amazon Basin rainforest is recognized for its huge biodiversity and majestic vegetation. Spread between just north of the Equator to about 13° S and about 30 degrees in longitude wide, the Amazon has heterogeneous climate with horizontal gradients of rainfall and the corresponding association with different features of local ecosystems and vegetation (Mahli et al, 2004). Figure 1 shows the yearly average rainfall accumulation throughout the Amazon and the monthly evolution for different sectors. Maximum values of rainfall over 2500 mm per year are seen in the northwest (NW) sector of the Amazon Basin and at the northern coast. The monthly evolution shows a gradual

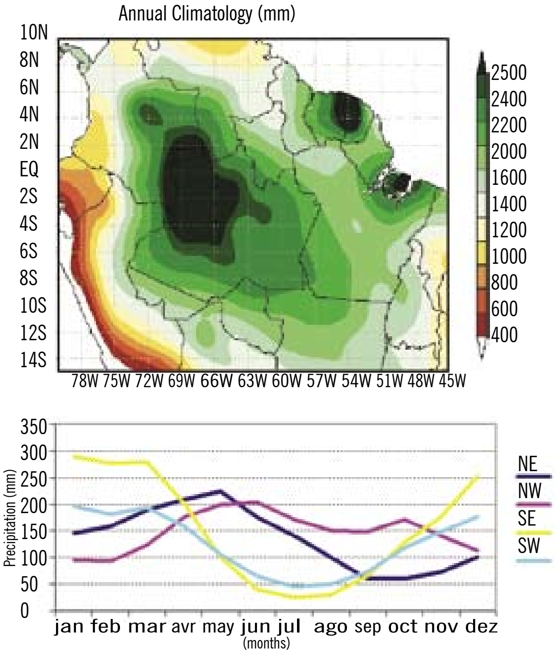

Figure 1 - a) Yearly average rainfall accumulation throughout the Amazon b) Monthly evolution of rainfall in the Amazon. and for subregions NW; SW; SE; NE

decrease in the length of the rainy season from northwest to southeast and also a shift in time of the month with highest rainfall accumulation, June in the northwest, January in the southeast and southwest and May in the northeast. Interannual global climate variations, such as El Niño/La Niña occurrence and different patterns of Atlantic sea surface temperatures (Moura and Shukla, 1991) disturb the average situation and are seen locally as a perturbation in the amount of rainfall (Marengo, 2004 a). Decadal and interdecadal variations are also seen in long term records, such as those imposed by the evolution of the Tropical Atlantic sea surface temperature pattern (Marengo, 2004b).

Rain forest processes impact on climate – and the effect of deforestation

The interaction of vegetation with the atmosphere takes place in what is called the surface layer. For grasses and seasonal crops, this layer is bounded by the solid earth and extends to about a few tens of meters above ground level with the vegetation occupying a meter or so in the lower end.

In the case of forest, one needs to consider an additional layer under the canopy separate from that above the canopy. In open forests, the communications between processes under the canopy and above the canopy is a continuous process of exchanges performed by turbulent eddies. Aggregation techniques are used such that area weighted averages of bare soil, low vegetation and tree processes are used to define biosphere-atmosphere interactions. In a closed canopy forest like the Amazon rainforest, communication between the sub-canopy and above-canopy takes place through intermittent bursts (Fitzjarrald and Moore, 1990, Fitzjarrald et al 1990) of turbulence that affect the composition and thermal structure under the canopy as well as the evolution of the above-canopy processes. The exchange between biosphere and atmosphere involves heat, moisture, trace gases and momentum fluctuations. Moisture exchange is performed by direct evaporation of soil moisture, evaporation of rain intercepted by the leaves and through transpiration by the trees. One characteristic of rain forest is maintaining evapotranspiration throughout the year, with higher values during drier months (Rocha et al 2004) due to more solar radiation (less cloudiness) and a slightly drier atmosphere. The deep roots of forest trees are able to pump water from deep layers in the soil and maintain evapotranspiration throughout the dry season. This feature is basically what distinguishes the forest from other vegetation like grasses or crops that will not be able to extract moisture from deeper layers due to shallow roots and will basically dry out during the dry season and shut down evapotranspiration and photosynthesis. In the dry season, the forest will use solar radiation to warm up and to evaporate while a pasture will use the solar energy only to warm up. Evapotranspiration will keep the atmosphere above the forest cooler than the one over the pasture. During the wet season the contrast in temperature is small. The amount of solar radiation reaching the surface in neighboring areas with different vegetation is about the same but the amount absorbed by the surface depends on the percentage that is reflected, the so-called albedo of the surface which is a function of its color. Forests in the Amazon Basin are a darker shade of green than grasses and most crops so that the amount of radiation entering the system is larger in forests than in other vegetation types. Another difference is in the roughness of the surface. Forest trees have an average height of 35 m but there is considerable variability with higher and lower trees forming a rough interface as the wind blows over them. In grass or crop land the variability in height is much smaller and the mechanical effect on the wind is reduced. The effect of the higher roughness affects the efficiency of the interchange between biosphere and atmosphere.

Neighboring areas with different vegetation types produce thermal circulation (Souza et al 2000, Silva Dias and Regnier, 1996) with lower level air parcels flowing from colder to warmer sides. Areas of deforestation surrounded by forest will experience a convergence during daytime which leads to increased cloudiness. Fig. 2 shows the a map of vegetation in the state of Rondônia, located SW of the Amazon Basin. The deforestation is located at the center, around the main road from Vilhena to Porto Velho. During the dry season, satellite images in the visible channel (Cutrim et al, 1995) show enhanced shallow cumulus clouds over deforested areas. Negri et al 2002 show that in the dry season not only shallow clouds but deep convection is also enhanced over deforested regions. Silva Dias et al (2002) show that first cumulus clouds develop in the morning over the forest in the wet season.

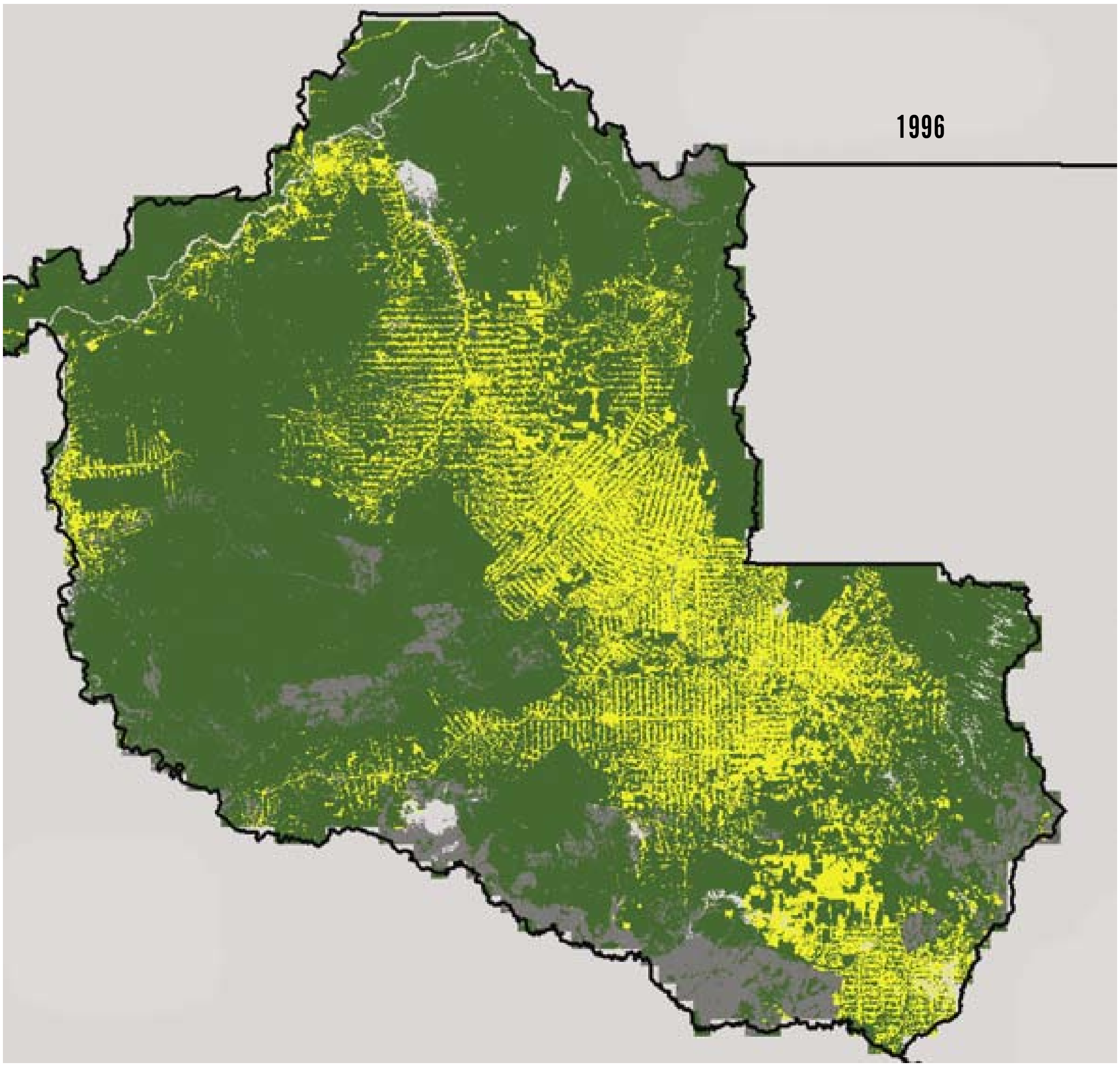

Figure 2 - Vegetation map for Rondônia

However, Laurent et al (2002) mention that the more intense rainfall of the afternoon and evening are initiated over mountains. Durieux et al (2003) compared cloudiness over square areas of about 250 km x 250 km with and without deforestation by using infrared satellite images. They show different results in the dry and wet seasons: during the dry season there are more low clouds over deforested areas in the afternoon and less deep clouds at night. During the wet season, clouds are deeper at night over terrain that includes deforestation. The case of the dry season is easily understood based on the difference in surface temperature over forest and pasture areas. The situation in the wet season is a bit more puzzling. But still, higher temperatures are observed over pasture in the afternoon than over forest. Silva Dias et al (2002b) show through high resolution numerical experiments that deforestation in the wet season tends to increase rainfall over the area as a whole. In a typical day, cloudiness starts over forest and over mountains. As soon as a few deep clouds start developing downdrafts generate new clouds and the whole system propagates westward through the area. This is basically due to larger gradients of temperature in the presence of deforestation. The conceptual result of increase of rainfall in regions with deforestation is discussed by Avissar et al (2002) and may be seen in Fig. 3a in a conceptual representation. It is indicated that a 10 % increase in rainfall is associated with deforestation of about 20 to 30 % of the area. Further decrease of rainfall is associated with further deforestation.

Numerical experiments with low resolution models where the whole forest is substituted by

pasture (e.g. Nobre et al 1991) have shown that precipitation is reduced by up to 30-40% and the surface temperature increased by 3-4°C, which is the limit shown in the right end of Fig. 3a.

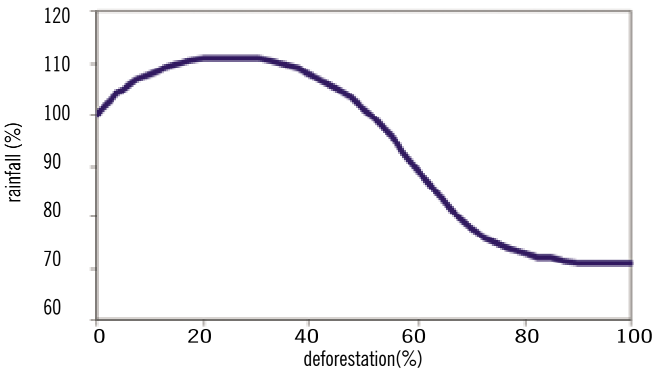

Figure 3a - Conceptual diagram of impacts on rainfall of deforestation

Biomass-burning aerosol climate impact

During the last three decades, the southern and eastern edges of the Amazon Basin have experienced an increase in deforestation through fire. Small farmers will also use fire to clear land to prepare for seeding. The shear amount of fires during the end of the dry season is seen as a 10-fold increase in the concentration of particles, called aerosols, and other gases such as carbon monoxide, nitrogen oxides and others (Artaxo et al, 2002). Due to increased amounts of aerosol, atmospheric visibility may drop from tens of kilometers typical of the clean atmosphere of the wet season to a few hundreds of meters. Impacts on health and on airport activity from the increase in aerosol concentration in the dry season are just a few impacts that begin to the addressed.

From the climate point of view, aerosol produced by biomass burning has several effects. Those that will be discussed here are a direct effect of radiation and an indirect effect involving the formation and features of clouds and rainfall.

Aerosols are small particles in the atmosphere and as such will interact with solar radiation. Depending on their composition, they may absorb radiation: darker aerosols related to biomass products absorb radiation and heat the atmosphere. Aerosol particles reflect solar radiation back to space reducing the radiation that reaches the surface. Procopio et al (2004) show that in the Amazon Basin what is called radiative forcing, the amount of radiation that is related to the aerosol effect, is on the order of tens of watts per square meter at the surface, and in the atmosphere: a reduction of radiation reaching the surface and an increase in the lower atmosphere. Less radiation reaching the surface has a direct impact on surface temperature that may be on the order of a few degrees (Longo et al, 2003). Cooler surface and warmer atmosphere also have an impact on the production of clouds generated during daytime. Several authors have shown (Kaufmann and Fraser, 1997) that in smoky conditions there is a suppression of shallow cumulus clouds. This is most likely a result of cooler surface but the indirect effect of aerosol on clouds has also been used to explain this feature.

The indirect effect of aerosols is through their role as cloud condensation nuclei (CCN), the portion of aerosol that serve as seeds for cloud drop formation. A classical result is that in clean atmospheres such as the ones found in maritime regions, there are low number concentration of aerosol and the corresponding CCN portion. Maritime CCN are mostly sulfates that are soluble and hygroscopic. In this case, cloud drops readily grow inside clouds reaching sizes large enough to fall against updraft motion. Maritime clouds are able to form rainfall easily, still being shallow and thus not reaching low temperatures, below 0°C. During the wet season in the Amazon, shallow clouds have been observed to rain and this has lead to calling the Amazon Basin a Green Ocean (Williams et al 2002, Andreae et al 2004). In the clean environment of the rainy season, aerosol in the Amazon Basin are of organic origin (Guyon et al, 2005, Roberts et al 2001, 2002) and are also due to conversion of volatile organic compounds into particles. Claeys et al (2004) indicate that photooxidation of isoprene emitted by vegetation results in a significant portion of the CCN in the Amazon. When aerosol concentration increases, because of dust or products of burning biomass, the number of CCN also increases and the available moisture is shared by a much larger number of particles than in a clean environment. Cloud dropplets formed in a high CCN environment are small and do not fall as rainfall. Droplets evaporate without producing rainfall at the surface. Fig. 3b show the conceptual effect of aerosol con-

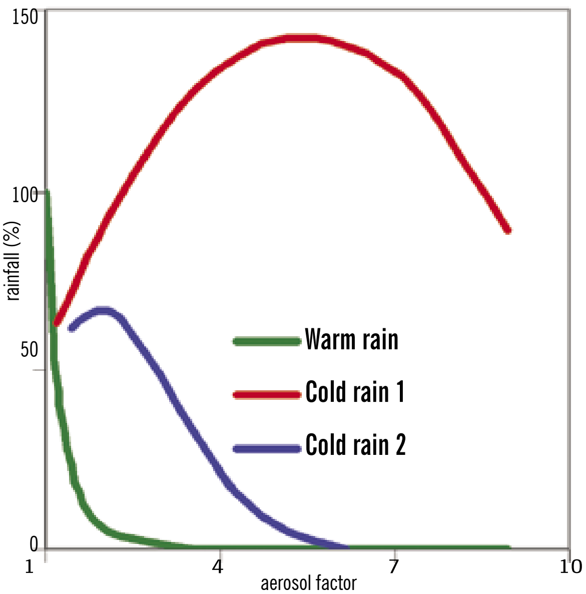

Figura 3b - Conceptual diagram of impacts on rainfall of (a) deforestation and (b) aerosol

centration on rainfall for a warm cloud indicating that rainfall from warm clouds is rapidly suppressed by the increase in aerosol concentration.

The pyrocumulus that forms directly over fires such as the one shown in Fig. 4, will not produce rain but have a vigorous updraft and enhanced turbulence. On the other hand, due to the direct effect of aerosol on radiation, the turbulence beneath clouds that form in a polluted airmass is weak and thus, with the added effect of large CCN concentration, is not particularly effective in producing rain clouds. In polluted environments, with a high concentration of aerosol, there is another possibility for cloud lifecycle rather than rapidly evaporating without raining. This possibility arises in regions where there is forced lifting of air parcels, for example over mountains. The release of latent heat from condensation warms the air parcels and induces upward buoyancy displacement of droplets to higher altitudes, beyond the 0°C level. The freezing of raindrops and sublimation directly forming vapor from solid ice is a process that pro-

Figure 4 - Pyrocumulus photograph

duces deep cumulonimbus clouds that eventually rain heavily, with strong winds, lightning and sometimes hail, especially in the southern Amazon Basin (Petersen et al 2001, Williams et al 2002). When the environment is moist like the one in the Amazon, the cumulonimbus clouds may actually produce significant amounts of rain as shown by Khain and Pokrovsky (2004) and conceptually represented in Fig 3b. The same figure also shows the rainfall accumulation in a drier environment which is not so efficient in rainfall production. The high variability of the effect of aerosol concentration on rainfall is due to the nonlinearity and complexity of the process and is still an open issue.

Remote impacts of Amazon rainfall

The Amazon Basin is regarded as a tropical heat source during the rainy season. The heat source is the latent heat of condensation that warms the air parcels and is thus responsible for updraft formation and the elevation of air up to the tropopause (~15 km altitude). The air that is lifted has to sink nearby and this sinking gives way to warming of large areas by compression. The rainfall is thus associated with the heating of the atmosphere. Silva Dias et al (1983) shows that tropical heat sources produce waves that propagate throughout the global atmosphere reaching remote regions. De Maria (1984) showed that if the tropical heat source is shallow, the effects are felt locally; when the tropical heat source has a maximum at the upper troposphere, the effect is a triggering of a teleconnection wave pattern that may be enhanced by the diurnal cycle of clouds (Raupp and Silva Dias, 2004). Grimm and Silva Dias (1995) have shown that the effect of anomalies of rainfall over the Amazon Basin and its extension to the southeast may have global impacts.

Another impact of biomass burning aerosols is seen regionally. Fig. 5a shows a model result of average mid level winds and aerosol concentration while Fig. 5b shows the corresponding value obtained by a MODIS sensor product (Terra and Acqua satellites). The so-called river of smoke that extends from the Amazon to southern Brazil spreading to northern Argentina and Uruguay has been studied by Freitas et al (2005) showing that the aerosol from biomass burning areas are lifted to higher levels by approaching fronts and by clouds.

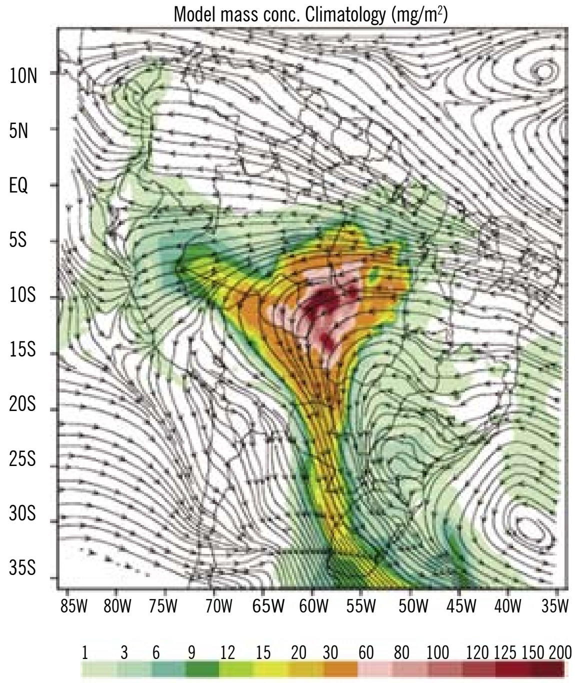

Figure 5 - a) Model result of average mid level winds and aerosol concentration

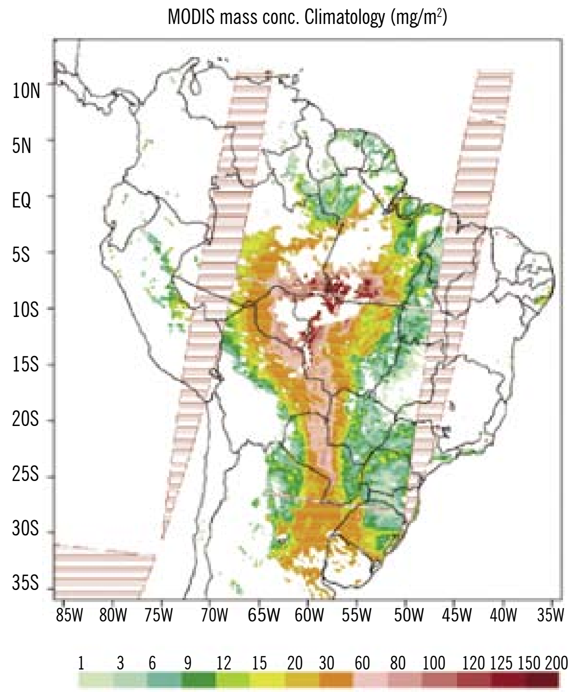

Figure 5 - b) Model obtained by a MODIS sensor product (Terra and Acqua satellites).

When the aerosols reach higher altitudes, they will be blown away by upper level winds and may reach remote areas where the direct effect of aerosol on radiation can reduce rainfall (Longo et al, 2003).

Summary

The combined effect of deforestation and biomass burning aerosol in the Amazon may be seen as a complex non-linear interaction process. Enhanced deforestation tends to increase temperature and reduce rainfall. Biomass burning aerosols provoke a surface temperature decrease, a reduction of rainfall from warm clouds and a quite variable effect on cold clouds, depending basically on thermal and humidity features of the environment. Human intervention in the Amazon region resulting in deforestation and biomass burning is seen to have an impact on rainfall with the possibility of feedback on global climate.

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