Interaction between vegetation and the atmosphere in cloud and rain formation in the Amazon: A review

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Introduction

THE RESEARCH results of the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) on the physics of the Amazonian climate have been remarkable and explain even complex mechanisms such as cloud and rain formation in the Amazon region. It has been proven that trees release Volatile Organic Compounds (VOCs); that VOC molecules form tiny crystals or aerosols in the forest atmosphere; and that, in the absence of other aerosols, these crystals serve as Cloud Condensation Nuclei (CCN), attracting a great deal of water vapor and forming large, heavy droplets that rapidly precipitate in the same region in which they formed in a fast and efficient manner. The importance of these natural VOC emissions that form CCNs lies in the hydrologic cycle: it is estimated that at least 20 to 30 percent of all the rainfall in the region results from this process.

This article is designed to review the knowledge available on vegetation-atmosphere interactions, and its importance is justified by problems related to deforestation and climate change.

Emissions of Volatile Organic Compounds (VOC) from vegetation

Plants in physiological process emit Volatile Organic Compounds (VOC) known as terpenes into the atmosphere. VOC emissions from vegetation are estimated to be comparable or exceed those from anthropogenic aerosols at a regional and global level. Volatile organic compounds include saturated and unsaturated non-metallic hydrocarbons and oxygenated hydrocarbons, such as carboxylic acids, aldehydes, ketones, ethers, esters, and alcohols. A large number of oxygenated compounds have been found in emissions from plants. Inventories for plant emissions show that isoprene and monoterpenes, classified as isoprenoids, are among the most abundant compounds, followed by alcohols and carbonyls. VOCs such as monoterpenes, esquiterpenes, alcohols, acids, aldehydes,

ketones, and esters are stored in different plant organs. Plants, which during photosynthesis fix from 0.5 to 2 percent of carbon, emit high levels of VOCs, leading to a loss of up to 20 percent of the fixed carbon (Souza et al., 2002).

Also according to Souza et al. (2002), the gases emitted by *Ficus benjamina L.*, an abundant species in the city of São Paulo, were chemically analyzed to characterize the emission of oxygenated VOCs. His study was part of a broad research project on VOC emissions from vegetation in São Paulo, which can affect the formation of photochemical oxidants in the metropolitan region of the city. Some of the compounds identified in the emissions from *Ficus benjamina L.* are known to play an important role in atmospheric chemistry as they are precursors of ozone and other toxic pollutants in the atmosphere. Carboxylic acids and aldehydes actively participate in the chemical reactions that take place in photochemical smog, a common problem in polluted atmospheres in large urban centers like São Paulo. Moreover, organic acids are responsible for the increased atmospheric acidity in urban areas and forests.

In the Amazon, a significant fraction of carbon released from the biosphere into the atmosphere is emitted in the form of VOCs. Aquino (2006) analyzed the VOC emissions associated with natural conditions and biomass burning emissions in the Amazon region and pasture areas. Two distinct environments were studied: a primary forest in the Jarú Biological Reserve and a pasture area in the Nossa Senhora Farm, both in the State of Rondônia. The characterization of VOC emissions often requires not only measuring total VOCs, but also determining each compound present in complex mixtures in the atmosphere. Aquino (2006) divided VOCs into two classes: the first includes non-methane organic compounds (NMOC), such as oxygenated organic, halogenated and hydrocarbon compounds and the second includes methane. High organic aerosol levels have been observed in the Amazon both in the dry and wet seasons. The abundance of suspended organic particles during the wet season is certainly associated with biogenic production, through gas-to-particle conversion of organic precursors. VOC emissions into the atmosphere can originate from both natural and anthropogenic processes. Biomass burning is a major VOC emission source in the regions studied. Along with water vapor and carbon dioxide, vegetation is responsible for about 90 percent of all volatile organic compounds emitted into the global atmosphere during physiological processes, about half a ton per ha/year. These compounds are formed by large molecules that can lead to a typical phenomenon in clean atmospheres, namely the crystallization of volatile organic compounds into tiny crystals.

Atmospheric chemistry

Emissions of dimethyl sulfide (DMS) from the ocean and of non-methane hydrocarbons (NMHCs) from terrestrial vegetation are the main biogenic aerosol sources, followed by their oxidation in the troposphere. The amount and composition of terpenes and other biogenic hydrocarbons depend on climatic

parameters such as temperature and solar radiation and may change radically as a result of changes in the type of vegetative cover due to land use or climate change. Finally, the production of aerosol precursor gases depends upon the oxidants in the atmosphere, and their removal is influenced by the dynamics of clouds and precipitation. As a result, the fundamental oxidation chemistry of the atmosphere is a significant factor in the production of atmospheric aerosols. Aerosols in turn may also play a significant role in atmospheric oxidation processes (Andreae & Crutzen, 1997).

While sulfate dominates the composition of marine and stratospheric aerosols, organic matter often accounts for the largest fraction over continental areas, particularly in remote areas. One of the surprising results of the Amazon Boundary Layer Experiment (ABLE-2) was the similarity of concentrations of particulate organic carbon and black carbon over the central Amazon Basin between the wet and dry seasons. In both seasons, organic matter made up about 90 percent of the aerosol mass. During the dry season, the emission of huge amounts of smoke from biomass burning explained the abundance of these carbon particles. The abundance of organic aerosols during the wet season was attributed to biogenic production, but without clear specification of how this source mechanism works. Assuming a range from 5 to 40 percent, we obtain an estimated 30 to 270 Tg/year for the production of secondary organic aerosols, a figure comparable to the production of biogenic and anthropogenic sulfate aerosols (90 and 140 Tg/year, respectively) (Andreae & Crutzen, 1997).

These production mechanisms cannot explain the presence, during the burning season, of black carbon (usually thought to be carbon from combustion), K, and Zn in the fractions of Amazonian aerosols. These components must represent primary biogenic aerosol, which consists of microbial particles (bacteria, fungi, algae, and spores), plant debris (cuticular waxes and leaf fragments), and humic matter. Such a primary biogenic origin may explain the presence of K and Zn, both abundant in plants (ibid).

Also according to these authors, unfortunately, there is little information available to allow a reliable estimate of primary biogenic particles in the organic aerosol in tropical regions. However, as even in an urban, temperate setting, these particles account for about 10 to 30 percent of the total aerosol number and volume concentration, their contribution in a dense tropical region is probably substantial. This primary biogenic aerosol likely plays a significantly important role in atmospheric chemistry and climate. Since both primary and secondary organic particles are effective Cloud Condensation Nuclei (CCN) and primary organic particles can be ice formation nuclei at temperatures of -4°C (71), it is obvious that the optical and microphysical properties of tropical continental clouds are strongly influenced by these particles.

Influence of Cloud Condensation Nuclei in cloud formation

About 60 to 80 percent of the Amazonian natural aerosol particles act as

Cloud Condensation Nuclei (CCNs). The difference in CCN concentrations between the wet and dry seasons (of around 200 to 20,000 particles/cm^3) in large Amazonian areas leads to a profound change in microphysical cloud properties (Silva-Days et al., 2002).

There are few CCNs in relatively clean, unpolluted areas. In competing for the existing water vapor, relatively large or water-soluble CCNs, if any, will grow rapidly, collide with smaller CCNs and fall as rain. As a result, clouds lack enough time to grow, reaching maximum heights of 4 to 5 kilometers. In an atmosphere polluted with very high CCN concentrations, such as during the burning season, the competition for the available water vapor increases and raindrops grow only slightly and slowly as clouds continue to grow. These clouds often do not turn into rain, with droplets evaporating and water and aerosols not falling back to the ground, but being rather carried by the wind to other regions (Silva-Days et al., 2005).

In the Amazon, rainfall is caused by two types of clouds (shallow and deep) that are seen together in the wet season, when the atmosphere is at its clearest. When the atmosphere is polluted by smoke from biomass burning, however, shallow clouds disappear and deep clouds are rarely observed, with lots of lightning and thunder.

CCN measurements have shown that smoke aerosols from biomass burning dramatically increase CCN concentrations. This likely increases colloidal stability and cloud lifetime, resulting in the well-developed, non-precipitating clouds observed in the burning season, with the droplet radium below the threshold required for warm precipitation (Roberts et al., 2001).

Deep clouds are carried by strong high-altitude winds for hundreds of kilometers from their origin, also carrying the CCNs within the original raindrops. Such suppression of precipitation can have major impacts on the functioning of Amazonian ecosystems. Another important aspect of the cloud structure during the dry season, when biomass burning emissions are very strong, is the significant number of particles that absorb radiation, the so-called "black carbon", which consists of smoke particles from biomass burning. Cloud droplets filled with soot particles absorb radiation in a very efficient manner – they evaporate before precipitating, thus intensifying the rainfall suppression. With high black carbon concentrations during the dry season (from 5 to 40 μg m-3), this phenomenon is particularly important in the Amazon as compared to other regions in the world (Artaxo et al., 2003, 2005).

An increased concentration of aerosol particles leads to a larger number of smaller droplets, producing two effects: first, the greater number of droplets reflects more solar radiation back into space (thus cooling the atmosphere); and second, a lower droplet size is less favorable for rainfall production, as very small droplets tend not to coalesce to form the large drops that fall as rain (Freitas & Long, 2005).

In turn, rainfall from shallow clouds in the wet season returns the CCNs to the surface almost at the same place where they were generated by the forest. For this reason, researchers have developed the concept that, during the wet season, the Amazon is a "green ocean", with a cloud structure that does not resemble continental, but rather oceanic areas. Conventionally, a distinction has been made in CCN environments, dividing them into "maritime" and "continental", which are characterized by low and high CCN concentrations, respectively. Most "continental" measurements were made in extratropical and moderately to heavily polluted regions (Roberts et al., 2001).

Roberts et al. (2001) discuss the results of the first experiments to measure CCN concentrations in the Amazon Basin, providing knowledge of their key role in the tropical continental climate and of the atmospheric physicochemical properties that allow the activation and subsequent growth of cloud droplets. These results were used to analyze the validity of the distinction between "maritime" and "continental" CCN concentrations.

Measurements were made during the CLAIRE-LBA campaign that took place from March 28 to April 15, 1998, at a ground site located 125 km northeast of Manaus in the state of Amazonas, without any influence of anthropogenic sources. The results indicated that CCN concentrations were low, within a typical "maritime" range. Such concentrations were consistent with observations of warm-precipitating clouds over the basin. Field observations suggest that these clouds have a less-developed convective structure that is usually related to oceanic CCN distributions. Despite the "maritime" character of the CCN spectra analyzed, the long distance of the site from the ocean and the high frequency of rainfall in the wet season resulted in maritime aerosols not contributing much to CCN concentrations at the site. A chemical analysis showed that the aerosol mass consisted of 80 percent of organic material, which probably originated from a combination of primary biogenic aerosol and the condensation of semivolatile oxidation products of volatile organic carbon (VOCs, such as terpenes) emitted from forest vegetation.

The low CCN concentrations in the unpolluted Amazon basin resemble conditions previously reported from maritime environments (Roberts et al., 2001).

A positive feedback was proposed for the maritime atmosphere where drizzle removes CCNs from the boundary layer and maintains the low CCN concentrations favorable for precipitation; a similar feedback can be applied to a forest environment. As interstitial aerosol grows to become a CCN, the cloud process that removes it provides a sink to maintain a balanced state. Studies have shown that the modification of cloud properties, such as its thickness, albedo (reflectivity at the top of the cloud) and lifetime, is more sensitive to low initial CCN concentrations. Due to the large thickness typical of convective clouds over the humid tropics, a significant albedo modification owing to increased CCN levels is not expected. (Silva-Days et al., 2005).

During the wet season, when natural emissions prevail, the concentration of aerosol particles is in the order of 10 to 15 µg m-3, with a concentration of 100 to 300 particles cm-3. In the dry season, on account of burning emissions, the mass concentration increases to about 300 to 600 µg m-3, while the number of particles rises to 15,000 to 30,000 particles cm-3 (Artaxo et al., 2005).

Most biogenic particles are in the coarse fraction, with diameters in excess of 2 µm, and are made up particularly of fungi, spores, leaf fragments, and bacteria in a wide variety of particles. Most particles are organic, with traces of potassium, calcium, magnesium, sulfur, phosphorus, zinc and other elements. Very low concentrations of particles are observed in the wet season (in the order of 10 to 15 µg m-3), while these concentrations increase pronouncedly in the period from August to October (dry season) (in excess of 100 µg m-3) (Andreae & Crutzen, 1997).

Hydrologic cycle

Preliminary studies on the water balance in the central Amazon basin pointed out that over half of the precipitated water goes back into the atmosphere through evapotranspiration, while approximately 45 percent are drained by rivers (Molion [1975] and Villa New et al. [1976] apud Salati et al., 1979). Moisture-laden winds from the Atlantic Ocean account for 52 percent of the precipitation in the region between Belém and Manaus, while the remaining rainfall results from water vapor recycled within the area (Marques et al [1977] apud Salati et al., 1979). The basin thus acts not only as a source for its own moisture, but also triggers rain producing processes in a dynamic fashion.

Using a methodology for analyzing the composition content of oxygen-18 stable isotopes in the rain in a network of rainfall stations in the Amazon in the 1971-1973 period, Salati et al. (1979) concluded that the net moisture fraction varies from 15 to 20 percent during the wet season to close to 100 percent in the October-November period, when evapotranspiration more or less makes up for the water loss by rainout.

Eltahir & Bras (1994), on the other hand, refute the theory proposed by Salati et al. (1979) by stating that precipitation in any given region is directly proportional to the latent heat transported vertically from the boundary layer limit to the upper troposphere. The diabatic heating associated with water vapor condensation is a major energy transport mechanism and is strongly linked to the tropical atmosphere dynamics. The precipitation recycling ratio is a measure of the amount of energy arising from evaporation within the Amazon basin. One-fourth of the latent heat released over the basin is a result of recycling the net surface energy that is consumed in evaporation by the rain forest, while the remaining three-quarters derive from advecting energy (horizontal transportation) from the Atlantic Ocean. The recycling of water vapor in the Amazon basin has a significant spatial and seasonal variability. The conclusion is that the atmosphere above the Amazon basin is not a closed system, suggesting that the

outflow of atmospheric moisture from the basin may play an important role in surrounding regions.

Conclusion

In several of the articles read, the authors stated that "Unfortunately, little information is available that would allow a reliable estimate of the contribution of primary biogenic particles to the organic aerosol burden in tropical regions" (Andreae & Crutzen,

1997);

> Studies to evaluate VOC emissions from plants are still insufficient due to the large number of plant species and the great diversity of chemical species emitted into the atmosphere. The estimated flow of different compounds in any given region requires detailed knowledge of the chemical composition of the gases emitted by the vegetation in that region. Although little known, vegetation emissions in tropical regions likely play a major role in atmospheric behavior, as these regions exhibit a large diversity of plant species and a very complex vegetation structure. (Souza et al., 2002)

Or that

> Existing data on VOCs and SVOCs (semi-volatile organic compounds) in the atmosphere, especially in remote areas, are insufficient to build close-to-reality scenarios. Particularly, few measurements have been made of oxygenated VOCs. While forests and tropical savannas are estimated to account for half of VOC emissions in the world, there is little field data available on these compounds in the Amazon region. (Aquino, 2006)

The authors therefore recognize that there is insufficient data to state that the forest emits VOCs enough to act as CCNs.

Furthermore, one cannot say that "the Amazon is a 'green ocean' during the wet season, with a cloud structure that does not resemble continental, but rather oceanic areas, where shallow clouds disappear and deep clouds are rarely observed when the atmosphere is polluted by smoke from forest fires, with lots of lightning and thunder" (Artaxo et al., 2003, 2005; Silva-Days et al., 2002, 2005), because during the rainy season the region is affected by a large-scale forcing (Intertropical Convergence Zone), with significant thundercloud formation. In fact, biomass burning can serve as a source of both heat (thermodynamic forcing) and aerosols that will act as CCNs, but this is not to say that these clouds will form from biomass burning only.

Undoubtedly, promoting efforts to study and deepen the knowledge of the interaction between forest and cloud and rain formation is important owing to the relationship between these processes and the hydrologic cycle. As at least 20 to 30 percent of the rainfall in the region originates from the forest, the conversion of this forest to other types of land uses will surely impact the local and regional climate, and may even lead to reduced rainfall in neighboring regions where the transport of moisture from the Amazon is important.

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SOUZA, S. R. et al. Emissão por folhas de *Ficus benjamina* L. (Moraceae) de compostos orgânicos voláteis oxigenados. *Revista Brasil. Botânica*, v.25, n.4, 413-18, December 2002.

Abstract – Several studies showed that the atmosphere over the forest, free of pollutants, have low concentrations of Cloud Condensation Nuclei, concentrations typical of the maritime atmosphere. In low concentrations of CCN, cloud microphysical properties are more sensitive to increased CCNs. In the Amazon, the main source is the forest vegetation cover. Therefore, any increase in CCN emissions from anthropogenic activities can have a strong impact on the local weather. These results are discussed in this paper.

Keyword: Volatile organic compound, Clouds, Precipitation.

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