Aerosol-cloud-precipitation-climate interactions in the Amazon rainforest

The interaction between the rain forest biosphere and its atmosphere is delicately balanced, with trace gases and aerosol particles playing key mediating roles. This equilibrium drives forest fertilization, carbon uptake and the formation of clouds and rainfall. Disrupting this delicate balance could have far-reaching consequences for atmospheric circulation, rainfall patterns and regional and global climate stability.

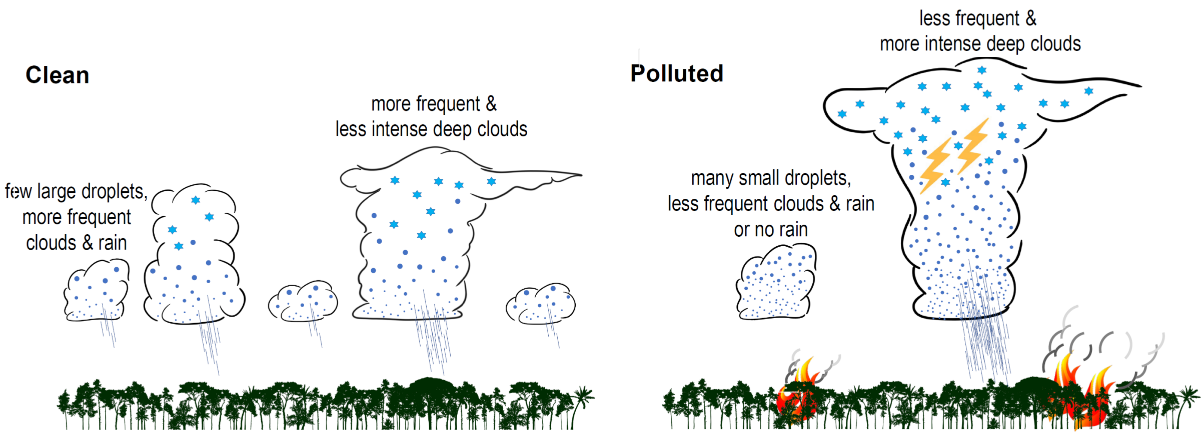

Figure 1. Schematic illustrating the contrasting effects of clean and polluted environments on shallow and deep convective clouds. Clean conditions favor more frequent and rain-efficient shallow clouds and weaker deep convection, whereas pollution suppresses cloud occurrence, reduces rain efficiency in shallow clouds, and intensifies deep convection and thunderstorm formation.

Preface

Atmospheric aerosols are tiny particles and droplets suspended in air, ranging from a few nanometers to several micrometers. Despite their small size, they scatter and absorb sunlight, shape cloud formation and rainfall, and connect the atmosphere with biogeochemical and water cycles. This makes them crucial players in the Earth's atmosphere and climate system. At the Amazon Tall Tower Observatory (ATTO), key aerosol parameters are continuously measured to provide a quantitative basis for the links to biogeochemical and water cycling[1,2].

Aerosols are broadly categorized as **primary** (emitted directly, e.g., dust, sea spray, smoke) or **secondary particles** (formed in air from gaseous precursors). Natural sources include vegetation, soils, ocean spray, and wildfires. Anthropogenic sources include biomass burning, industry, and traffic. In the Amazon, analyses show that submicron (<1 µm) particles are dominated by **secondary organic aerosol (SOA)** formed from the oxidation of **biogenic volatile organic compounds (VOCs)** such as isoprene, monoterpenes, and sesquiterpenes emitted by vegetation and soil. The precise origins of the exceptionally clean "background" aerosol during the wet season remained puzzling for decades, with recent work pointing to formation inside the forest and in the upper troposphere. Since 2012, the ATTO site has provided long-term measurements of aerosol size and composition and unique vertical profiles from the forest floor up to 325 m, helping to separate sources and formation pathways[3-6].

The contrast between seasons in the Amazon is stark (see Figures 1 and 2). In the wet season, the air is among the cleanest on Earth. In the dry season, fires in the deforestation hotspots flood the region with smoke, driving particle numbers from a few hundred cm^{-3} to tens of thousands cm^{-3}. Fire emissions raise aerosol optical depth and intensify scattering and absorption, measurably altering the regional radiation balance and air quality. These perturbations can reinforce drought and shift rainfall patterns via aerosol–cloud–circulation feedbacks, and they also **modify nutrient cycling** by changing the timing and composition of atmospheric deposition. Beyond local fires, long-range transport matters: African smoke can contribute substantially to the Amazon aerosol load with ~60 % in the wet season and ~30 % in the dry season. Sustained, high-quality observations at ATTO and beyond provide the evidence base for policies to curb fires, manage transboundary pollution, and protect the Amazon's climate, water, and nutrient cycles[7-11].

Relevance of aerosols for the water cycle, biogeochemistry and climate

ATTO has delivered the longest time series of aerosol observations in a near-pristine rainforest, revealing how the atmosphere and vegetation interact. Located deep in the central Amazon, ATTO samples exceptionally clean wet-season air that approximates pre-industrial conditions. This natural baseline enables clear comparisons with human-influenced periods and impacts. With measurements up to 325 m, ATTO resolves vertical aerosol stratification, canopy–atmosphere exchange, and the diurnal evolution of the boundary layer—crucial for understanding consequences for the water cycle, biogeochemistry, and climate.

Deforestation decreases the release of natural compounds as Biogenic Volatile Organic Compounds (BVOC), which play a role in cloud formation and rainfall

Deforestation reduces the biospheric source of biogenic volatile organic compounds (BVOCs), which help form atmospheric particles that can act as cloud-condensation nuclei (CCN). In the central Amazon, vegetation emits large amounts of BVOCs, and their oxidation within and above the canopy produces nanoparticles and secondary organic aerosol. During rainfall, scavenging lowers the condensation sink while downdrafts inject ozone, conditions that frequently trigger in-canopy particle bursts, linking BVOC oxidation to new-particle formation. In addition, deep convection enables isoprene-nitrate chemistry in the upper troposphere that nucleates new particles, which can grow and later act as CCN. Replacing forest with degraded or cleared land can depress BVOC supply and perturb these pathways, with effects of cloud microphysics and regional precipitation[5,6,12-14].

Figure 2. View from the Amazon Tall Tower Observatory (ATTO) under contrasting atmospheric conditions. The wet season (upper panel) represents the clean Amazonian background state with clear visibility, while the dry season (lower panel) is characterized by intense regional biomass-burning smoke and heavy pollution

Deforestation fires enrich the Amazonian atmosphere with smoke, changing rainfall patterns and lengthening the dry season

Fires inject dense smoke that loads the air with cloud-active aerosols; at high concentrations, these particles produce clouds with many small droplets that coalesce poorly, while absorbing smoke warms aloft and stabilizes the lower troposphere, together inhibiting convection and warm-rain formation. Long-term ATTO observations show seasonal shifts in aerosol and cloud regimes: smoke-dominated dry seasons push clouds toward updraft-limited behavior, whereas cleaner wet seasons and some long-range-transport periods fall in aerosol-limited or transitional regimes. A multi-decadal analysis across the Brazilian Amazon separates deforestation from broader climate variability and indicates that deforestation explains most of the observed dry-season rainfall decline and a notable share of regional warming. Beyond fueling fires, observations link deforested areas to lower dry-season rainfall, with pollution shifting clouds toward updraft-limited regimes. Overall, the evidence is consistent: smoke suppresses warm-rain formation and alters stability, reducing rainfall and intensifying the Amazon dry season[15-27].

Fires can intensify thunderstorms, increasing risks for local populations

Smoke affects cloud and rain processes, but forest fires can also make storms stronger and more dangerous. If the atmosphere is very unstable, the many small droplets formed due to the smoke can invigorate the clouds, producing thunderstorms that bring heavier rain, hail, and stronger winds. These more intense storms also produce more lightning, which can start new fires. The powerful winds and hail can increase population vulnerability as well as damaging the forest by intense winds and making it harder for it to recover. This creates a vicious cycle: fires can lead to stronger storms, which then cause more fires and more damage to the forest[28-29].

Deforestation and biomass burning smoke severely impact human health

Fire outbreaks from deforestation and the management of agricultural lands emit air pollutants that pose risks to human health. The biomass burning smoke contains particulate matter and trace gases that are carried away by the winds, reaching hundreds of kilometers away from the fire front. Short- and long-term exposure to biomass burning smoke are associated with adverse health outcomes. Climate change and deforestation increase the risks of fire outbreaks and spread in Amazonia, due to the intensification of heat waves, droughts and forest degradation. Deforestation pushes the frontier between wildland and human settlements. Fire outbreaks at wildland-urban interfaces increase public health concerns in Amazonia are require mitigation and adaptation measures[30-31].

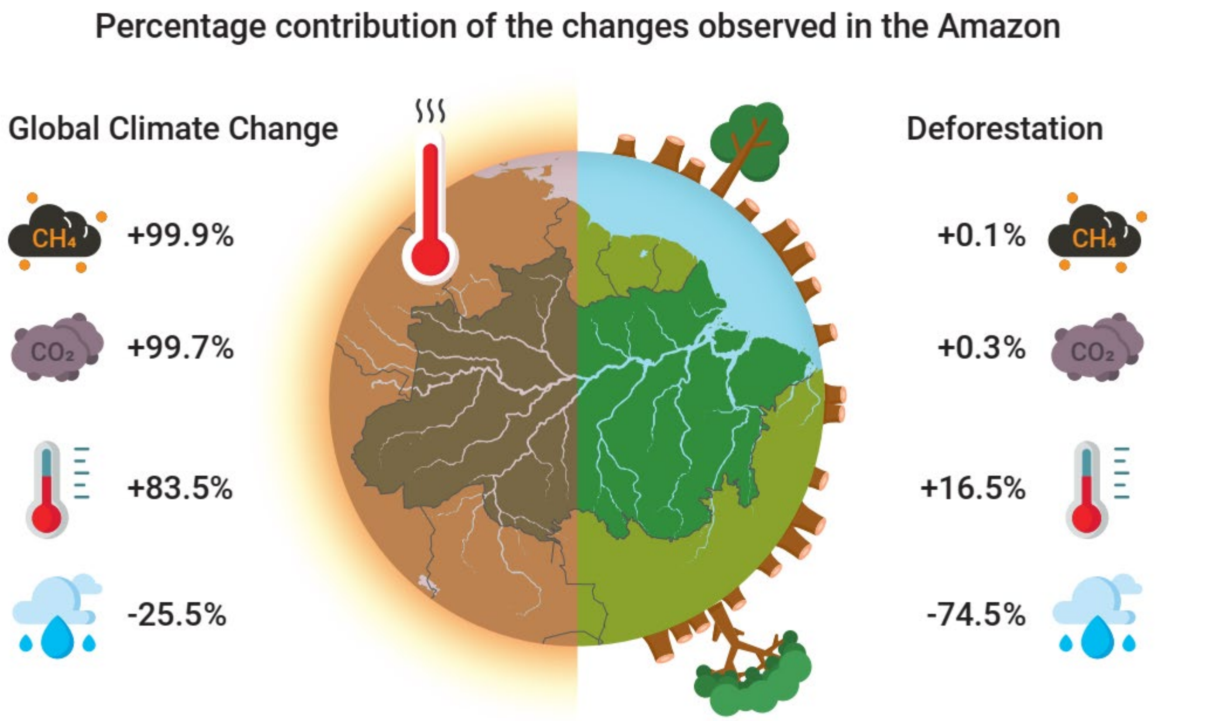

Figure 3. Diagram displaying the percentage contribution of global climate change and deforestation to changes in methane, carbon dioxide, maximum surface temperature, and total precipitation during the dry season[27]

Recommendations

Climate change and deforestation are interacting forces that may mutually reinforce each other, potentially disrupting the fundamental energy, carbon, water, and nutrient cycles in the Amazon. Beyond efforts to mitigate climate change, halting deforestation must therefore be pursued independently and with urgency.

The Amazonian forest is in equilibrium and should be preserved in its current state to help mitigate both regional and global climate change.

Biomass burning has significant impacts on the radiative energy budget, regional rainfall patterns, and human health. As such, it should be drastically reduced.

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