How do Amazon forests make their own rain?

Amazon rainforests recycle rainfall, contributing 'green' water that atmospheric rivers distribute downwind. Forests also supply aerosols needed for water to condense and form clouds and rain. Deforestation and climate change alter both processes and potentially endanger regional water supplies.

Preface

The ultimate source of rain in the Amazon Basin is water evaporated from the Atlantic Ocean. This atmospheric moisture - called 'blue water' due to its marine origins – travels with winds that move south and westwards across the continent until it reaches the 'wall' of the Andes mountains. There, it turns and flows south. This large-scale flow of moisture is known as the Amazon atmospheric or 'flying' river[1,2,3] to distinguish it from the massive and better-known reverse flow of water in the Amazon River.

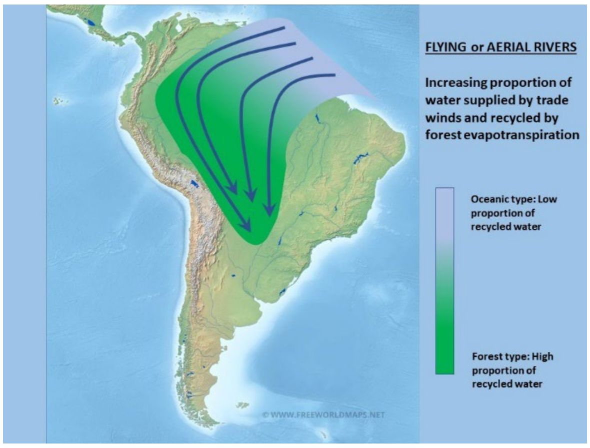

Figure 1. Flying or aerial rivers. Increasing proportion of water supplied by trade winds and recycled by forest evapotranspiration.

Rainfall would rapidly deplete the Amazon atmospheric river without a mechanism for replenishing the lost water. The Amazon rainforest – the world's largest tropical forest – does this by releasing moisture into the atmosphere through a process known as evapotranspiration, or ET. ET has two components: evaporation of water from surfaces and transpiration, evaporation that takes place through small openings called stomata in plant leaves. These processes recycle substantial amounts of rainfall back into the atmosphere as 'green' (terrestrially sourced) water, sustaining the Amazon atmospheric river. For example, by the time it reaches the Andes, up to ~60 %[4,5] of the atmospheric moisture is 'green' in origin, while in southern South America, this can reach nearly 100 %[6,7].

However, the supply of 'green' water is vulnerable to the compound effects of deforestation, forest degradation, and climate change, including droughts of increasing severity that cause leaves to close stomatal openings. Especially during the dry season, shallow rooting grasses or crops replacing forests, or highly drought stressed forest trees can dramatically reduce the flow of 'green' moisture back to the atmosphere, altering regional climate[5,6], and potentially risking water supply to the western and southern Amazon, and beyond.

Relevance of ATTO observations

Evaluating potential risks associated with climate change and deforestation to future water security requires improving our understanding of forest-atmosphere interactions. At ATTO, we continuously monitor the precipitation-ET recycling system to learn how its key processes function across the interconnected soil-vegetation-atmosphere system. By providing new scientific insights into this complex system, measurements at the Amazon Tall Tower Observatory (ATTO) support the development of effective policies and actions, both within the Amazon region and globally.

A major question being investigated at ATTO is: how do forests help to make their own rain? ATTO research contributes to answering this question in two ways:

1. by using unique tools to track 'green' water contributions and distinguish the forest recycling contribution to atmospheric moisture from the forest and

2. by increased understanding of the formation of atmospheric particles that are required to allow moisture to condense and form clouds and rain.

Using isotopes to track moisture sources

At ATTO, we make unique continuous measurements of the stable isotopes of water as a way to help distinguish the influence of 'green' water on the atmosphere. Isotopes of an element have the same number of protons, thus electrons and general chemistry, but they have different masses because of differences in the number of neutrons. The mass differences become important during processes like evaporation, which is favored for water molecules containing lighter isotopes.

At the ATTO site, we compare the isotopic composition in potential tree water sources (soil water, stem water, precipitation) to what is transpired by trees. This work showed that tall canopy trees use rainfall stored in deep soil water that fell in the previous wet season to maintain transpiration and moisture recycling during the dry season[8]. Our results also show that this 'green' moisture released from intact central Amazon rainforests around ATTO contributes 40 – 60% of atmospheric moisture[8]. Thus, these forests serve as a vital water source sustaining the atmospheric river even during the dry season. With continuous measurements ongoing, the water isotope data available from ATTO provide opportunities to improve our understanding of key water cycling processes within Amazon forests and provide a key benchmark for testing climate models[10-12].

Producing clouds and rain

Atmospheric moisture by itself is not sufficient to make it rain. Forming clouds and raindrops requires the presence of small particles, called aerosols, around which water can condense and make small droplets. In the Amazon, forests are the major sources of aerosols. ATTO researchers are simultaneously investigating how forests create primary aerosols, such as fungal spores and pollen. However, a key aerosol formation process relies on the fate of reactive organic gases emitted by the vegetation and soils. ATTO research over the last decade has delivered a new understanding of how important tropical forests are as a source for reactive biogenic trace gases feeding the production of secondary organic aerosols[14 – 20].

Understanding the release and production processes of forest-derived organic aerosols is of great importance for cloud processes and rainfall for a whole continent. As with water fluxes, aerosol-cloud-precipitation components are being altered by human activities, especially when natural forest aerosol cycles are overwhelmed by particles from fire smoke and man-made pollution. ATTO researchers are discovering the immense diversity of reactive volatile gases emitted and how they vary with biodiversity and environment, as well as the steps required to chemically alter them to make particles around which water condenses, and how that chemistry can affect the clouds formed (for more details, see our other science briefs on these topics!).

Figure 2. Precipitation over the Amazon rainforest. Seen from the ATTO tower in 2024.

Figure 3. Rising evaporation above the Amazon rainforest. Seen from the ATTO tower in 2024.

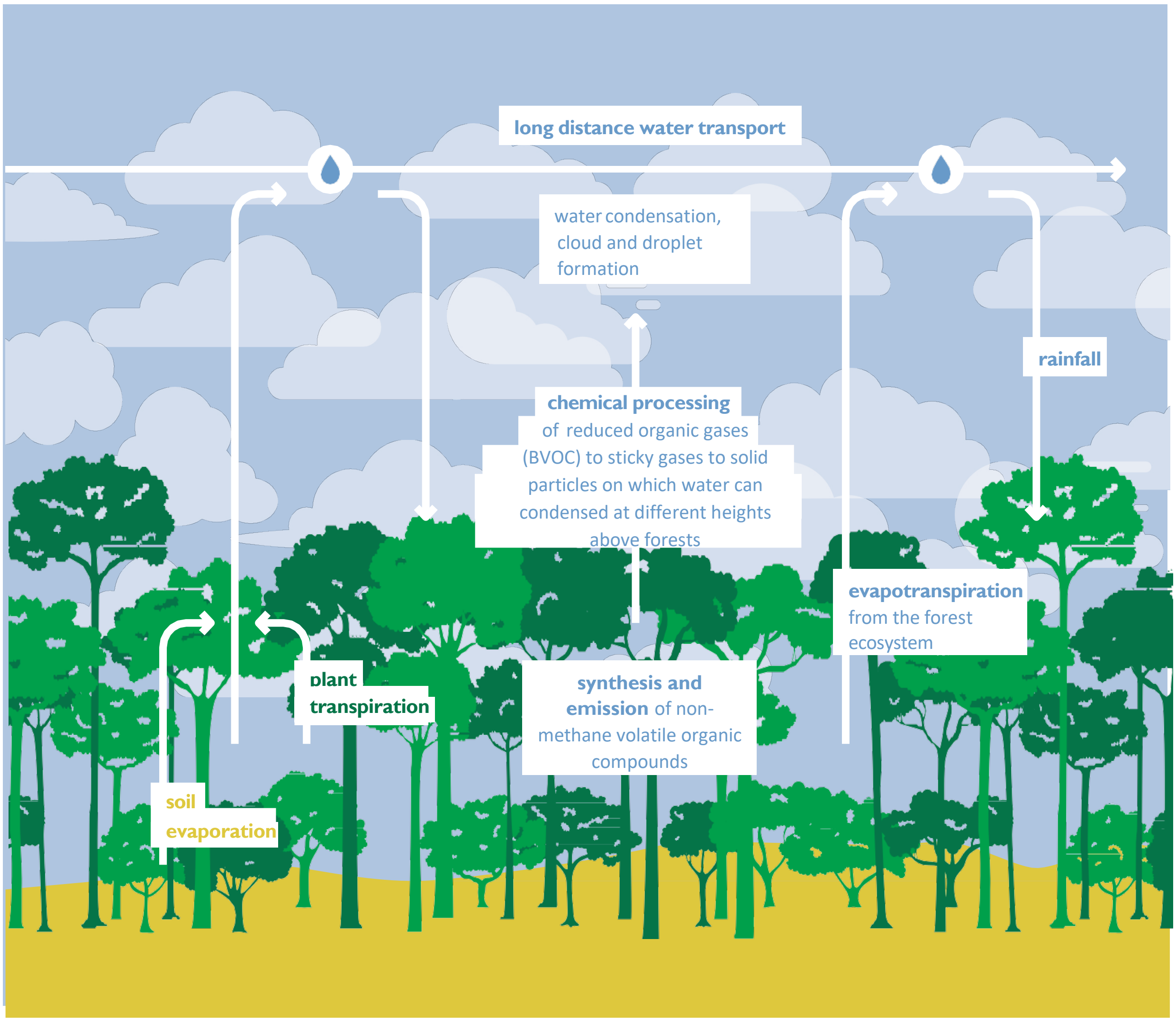

Figure 4. Biogenic emissions of the Amazonian rainforest contribute to water recycling and water transport (Flying rivers) by the production of aerosol particles serving as condensation nuclei for water vapor. The share of recycled water in the transport increases with distance from the oceanic contribution.

Recommendations

ATTO observations have highlighted two key soil-vegetation-mediated processes essential for sustaining the Amazon's atmospheric river: recycling of precipitation back to the atmosphere and the production of aerosols mediated by rainforests. Both are being influenced by human activities to an increasing degree through deforestation and fire, as well as through increased droughts that reduce the flux of water vapor from forest to atmosphere. To safeguard key rainforest water cycling functions, improve the understanding and prediction of changes in water resources under future climate scenarios, we recommend:

1. Continued monitoring of fluxes of atmospheric water and, where possible, stable water isotopes as critical tools to quantify the contribution of green moisture from central Amazon rainforests to the Amazon flying rivers. Expansion of measurement networks to connect from ATTO to areas downstream of the atmospheric river, especially the western and southern Amazon regions, and under ongoing and projected climate changes, including severe drought and flood events.

2. Co-located and continuous observations of gases and aerosols along with clouds are essential to enhancing the understanding and prediction of cloud-rain production in Amazon

rainforests. Improved understanding of how factors like smoke aerosols impact rain will also help improve local and regional weather forecasting, and further improve predictions of extreme weather events (e.g., intense rainfall, downbursts, and thunderstorms), that are already been changing in frequency over the last 40 years.

3. These scientific insights should be incorporated into comprehensive policies aimed at preserving and sustainably managing water resources from the Amazonian rainforest ecosystem. Current and future research should support actions across political, economic, and environmental sectors to prevent forest destruction or degradation and to promote investment in forest restoration imperative for sustaining the Amazon's atmospheric rivers and healthy water cycles throughout the Amazon basin and beyond.

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