From leaves to clouds—revealing how trees' emissions shape the air around us

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Researchers on the GoAmazon project had this view from the top of the Eddy Flux Tower in the canopy, where they measured trees' emissions. Credit: ARM Climate Research Facility

As he gazed down on the Amazon from above, shining leaves formed waves of foliage. The wind rippled through them, creating eddies and pools of green. From this point of view, some people may have just seen trees. But from his lofty perch, Kolby Jardine, a researcher at the

Department of Energy's (DOE) Lawrence Berkeley National Laboratory, saw more—the forest's complex ecological cycle. Starting from emissions put out by the leaves to the clouds high above, each component influences all of the others.

Jardine was part of the DOE Office of Science's "Green Ocean Amazon" or GoAmazon project, which focused on better understanding the Amazon Basin's water cycle. By taking data on a swaying, narrow platform taller than a 10-story building, Jardine hoped to peer into one part of this system—how tropical leaves produce emissions.

"You really feel what it's like to be a leaf in the upper canopy," he said.

The Amazon is the world's largest and most diverse tropical rainforest, stretching over nine countries. While human-made emissions pollute the air in the dry season, the air above the Amazon in the wet season is one of the cleanest places on earth.

That contrast makes it the perfect place for Jardine and other researchers to study how trees let off emissions and what effects those emissions have on climate.

Trees and other plants produce hundreds to thousands of volatile organic compounds (VOCs). These carbon-based chemicals easily evaporate from a liquid or solid into air at much lower temperatures than most chemicals. For example, your nose is sensing VOCs when you smell pine trees. Other VOCs are human-made, such as ones that produce the "new car smell." While human-made VOCs dominate in urban areas, VOCs produced by trees play a major role in the Amazon.

Within minutes to hours of trees releasing them, VOCs react with ozone and other chemicals in the atmosphere. They group together to become larger compounds or react with human-made emissions from diesel vehicles or fossil fuel-burning power plants. In both cases, they form secondary organic aerosols (SOAs), solid or liquid particles suspended in gas.

From forming smog to influencing cloud formation, SOAs drive a number of atmospheric and climatic processes. The interactions between aerosols, VOCs, and other biological emissions create one of the biggest uncertainties in climate models. The Department of Energy's Office of Science is supporting research on VOCs from trees and the SOAs they form.

The Big Impact of Tiny Particles

For compounds that often last fewer than two hours before reacting with something else, VOCs have a big impact. That's especially true in the tropics, where 30 to 50 percent of the trees emit VOCs. Via the SOAs they transform into, VOCs affect weather and climate in two major ways.

First, SOAs make up a large proportion of the tiny particles in the atmosphere. They influence how much sunlight the atmosphere absorbs or scatters, and thus the amount of light and heat that reaches Earth's surface.

Second, water vapor condenses on SOAs. Sometimes, the particle collects enough water to become a cloud droplet. If it continues to grow, it can become a rain droplet that falls to earth. The GoAmazon project tackled the challenge of gathering data on VOCs, SOAs, and their effects on weather. The GoAmazon team took data from January 2014 to December 2015 using the Atmospheric Radiation Measurement (ARM) Climate Research Facility, an Office of Science user facility.

What Happens When a Tree Breathes?

To map the role of biological VOCs in the rainforest, scientists have to understand how and why trees produce them. That's easier said than done.

The number of factors that determine VOC production is staggering. The season, species of tree, leaf age, carbon dioxide concentration in the air around the tree, light, and temperature are just a few. In addition, plants not only release VOCs; some even take certain VOCs in.

Another challenge is simply taking data in and above the forest canopy. One of researchers' main ways to sample air is to fly custom planes stuffed full of complex instruments right over the canopy.

In contrast to models, "the aircraft-based measurements provide [data on] the real atmosphere," said Jian Wang, a scientist at DOE's Brookhaven National Laboratory.

To understand the levels of isoprene (a major VOC) just above the canopy, the GoAmazon team ran eight different research flights in both the wet and dry seasons. Their data showed isoprene emission rates were three times higher than satellite data had revealed and 35 percent higher than models predicted. In particular, they found that neither models nor satellites took into account different elevations or the variety of plant species in the Amazon.

"We have to know who the players are and what their sources are," said Jardine.

Jardine and his team had a complementary approach—they perched for days on end atop a narrow tower rising out of the jungle. After hiking through the forest before sunrise, they sampled gases from different levels of the tower every 10 minutes. They then analyzed the contents using a specialized instrument that uses chemicals' masses to identify them.

Tracking the differences, they found that trees produced far more isoprene during the day than at night and during the dry season than the wet season. The more sunlight and higher the temperatures, the more isoprene plants emitted. The team also found that the more stress the leaves were under, the more isoprene they produced.

Both studies illustrated how complex the influences on trees' VOC production are. Taking these influences into account is essential to improving the data that goes into climate models.

The tower study also found that in particularly stressful circumstances, VOCs could react with oxygen inside of the plants themselves. Previous studies Jardine participated in with both loblolly pine needles and mango leaves show that this phenomenon extends beyond the Amazon. The fact that plants may produce secondary products themselves is another factor models need to include. In addition, it points to the potential importance of VOCs within plants themselves. They may actually help plants deal with environmental stressors.

What It Takes to Become a Secondary Organic Aerosol

Once trees release emissions into the air, even more interactions emerge. Which VOCs form which SOAs depends on the level of the VOCs, the gases the VOCs react with, and how much those mix together. VOCs can often react with oxygen and other chemicals several different times as they move through the atmosphere, each time producing different products. "It is important to know what will happen to the VOCs and

SOAs when they're transported [away] from sources," said Alla Zelenyuk-Imre, a researcher at DOE's Pacific Northwest National Laboratory (PNNL). These transformations affect both the SOAs' characteristics and how they influence cloud formation.

To investigate these reactions, scientists use both field and laboratory studies. Field studies, such as GoAmazon, offer real-world data. But scientists often can't fully analyze these chemical reactions in the field.

"The fundamental lab studies can help understand and interpret the more complex observation data," said Nga Lee "Sally" Ng, a researcher at Georgia Tech. "Both the lab and the field studies really complement each other."

A 2015 study led by Ng expanded scientists' understanding of isoprene's role in SOA formation. Previously, most scientists thought that the levels of nitrogen oxides—often produced by cars, trucks, and fossil fuel-burning power plants—determined SOA levels. Her study found that isoprene and the chemicals that form as a result of it were even more important than the nitrogen oxide levels alone. It was the complex interactions between VOCs (including isoprene) and the nitrogen oxides that had the largest effect of all on the SOA's characteristics.

Since then, other laboratory studies have examined how VOCs interact with a variety of pollutants from fossil fuel combustion, including sulfate and ammonia produced by agriculture. In both studies, the human-made emissions coated the biological VOCs. That fundamentally changed both how the VOCs became SOAs and the SOAs' characteristics themselves.

With these insights from the lab, the GoAmazon project examined how these interactions played out in the real world. In particular, the research team dug deep into the relationship between plants' emissions and human-made pollution.

To go where the data were, they flew a plane right through a floating column of pollution from the city of Manaus, which is deep in the Amazon. The scientists found VOCs reacted with oxygen several times faster and more intensely inside the polluted area than outside of it. In addition, the pollution fundamentally changed the process of VOCs turning into SOAs. Researchers measured a number of chemical compounds inside the plume that were absent outside of it.

On the ground, scientists sampled air in a large clearing surrounded by rainforest. By exposing ambient air to high concentrations of the gases that react with VOCs within a container, they simulated the results of days' or months' worth of SOA production. They found there were four to five times more SOAs during the dry season than the wet season. Surprisingly, they also found that there were significantly more SOAs than VOCs alone could produce. That result suggests that VOCs aren't the only gases playing a major role in SOA formation—yet another gap in our understanding.

Up in the Air

Things really take off when SOAs drift up into the atmosphere.

"Aerosols act like a seed to form clouds," said Ng. If enough water vapor condenses on them, they can eventually become raindrops.

But a lot has to happen before it rains. SOAs' size, what they're made of, how they move, and how long they've been in the air all determine how well they absorb or release water.

One of the GoAmazon studies looked at how carbon-based particles (mostly natural) and non-carbon-based particles (mostly human-made) absorbed and released water differently. Previous lab studies suggested the way particles collect water vapor depends mostly on the concentrations of pollutants interacting with SOAs. But in the real world, it depended much more on the concentrations of SOAs and other aerosols themselves.

Another GoAmazon study provided results that contradicted commonly held perceptions. Scientists didn't think the tiniest aerosols could affect cloud formation. They simply weren't big enough. But the study found that these tiny particles can actually make storms in the Amazon more intense, clouds bigger, and rain more likely to fall.

"This study opens a new door to understanding how aerosols affect clouds and weather in those warm and humid regions," said Jiwen Fan, another PNNL scientist.

While the study didn't determine if these tiny aerosols developed from VOCs, a follow-up study is looking at this issue. Expanding scientists' knowledge of SOAs' effects on cloud formation helps scientists trace how weather and climate systems change over time.

The Amazon's intertwined ecological relationships, ranging from the trees to the clouds, continues to surprise scientists.

As Jardine said, "Looking at the interfaces of these systems is very challenging, but it's also where most of the opportunity is."

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