A path through the Amazon rainforest near Manaus, Brazil.
(Photo by Dennis Jarvis.)

CLIMATE

The Changing Global Tropics: Hot Droughts in the Amazon

By Jeff Chambers, Clarissa Fontes, and Bruno Oliva Gimenez

When you step into a tropical forest, you expect to feel the humid air on your face, step on soft wet topsoil made mainly from decaying leaves, and see bright green surroundings of different vegetation layers. Yet that wasn't what we observed in late September of 2015 when we entered the oddly dry air of a forest in the Amazon of central Brazil. The surface leaf and twig litter crunched and snapped as we walked on exceptionally dry soil, and the leaves of many sapling and adult trees were wilted in a way we had never seen before. The hot and dry drought conditions imposed by the 2015-2016 El Niño were strongly affecting the world's largest rainforest.

Droughts are nothing new. They occur with a large drop in a region's expected precipitation from a variety of causal factors. What is new — and becoming increasingly problematic — are droughts that occur simultaneously with historically high temperatures due to climate change.

Since the onset of the industrial revolution, human activities have continually pushed atmospheric CO_2 (carbon dioxide) concentrations to current levels not seen on Earth for probably millions of years. Year-by-year, Earth's temperature will act to equilibrate to this changing atmosphere, and the additional heat is pushing our warmest tropical ecosystems to new novel higher temperatures beyond current conditions. The last time the planet had a heat-trapping atmosphere of similar composition — in the Pliocene, 2.6 to 5.3 million years ago — sea levels were at least 10 meters (30 feet) higher, temperatures were warmer by four to five degrees Celsius (seven to nine degrees Fahrenheit), and modern humans were not among Earth's inhabitants. Climate warming lags behind greenhouse gas changes to the atmosphere, yet in 2021 we are already at least halfway (about +0.75°C/1.35°F) to the level of warming (+1.5°C/2.7°F) that is expected to cause major disruptions to human

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A dry riverbed in Amazonas, Brazil.

Photo by Hudsön.

and planetary systems. We are in the midst of creating a hotter climate maximum that has been absent on Earth for millions of years. What can we expect from this new hypertropical climate?

The Global Tropics

The region of the tropics lies geographically between the parallel latitudes of the Tropics of Capricorn and Cancer and includes the hottest deserts and wettest forests on the planet. The biomes of these latitudes cycle more carbon, water, and energy than any other global region and play critical roles in regulating Earth's climate. The tropics are also home to vast biodiversity including more than 40 percent of the world's human population. Most of Latin America resides within the tropics, from the latitudes of central Mexico and all of Cuba, down through to São Paulo in Brazil and the entire country of Bolivia.

The Global Tropics reside at the center of a number of globally important topics, yet the Global North is often woefully ignorant of these leading roles. For example, a better understanding of tropical ecosystems is essential to project how climate change will impact Earth system processes and human livelihoods from local to global scales as our climate continues to heat up: expected precipitation is essential for agriculture; temperatures even hotter than our current maxima directly impact human activities; forests play key roles in regulating climate both regionally and globally; and trees provide a number of renewable resources. We study how tropical forest trees interact with the climate system, a knowledge base that continues to expand thanks to strengthening pantropical partnerships across Latin America, Southeast Asia, and Africa.

Clarissa Fontes measures leaf water potential in the Amazon.

Photo courtesy of Kolby Jardine.

One of the best-known direct effects of additional CO_2 is its beneficial effect on plants. CO_2 is the substrate for photosynthesis, and additional CO_2 can also improve how efficiently a plant uses water — the fraction of water lost per unit carbon gain. In fact, this effect is precisely what we've seen as CO_2 has accumulated in the atmosphere: plants, ecosystems, and the oceans act as "net sinks" for atmospheric CO_2 to the tune of about 50 percent of anthropogenic (human-produced) emissions. But the consensus among scientists across the planet studying plant–atmosphere interactions is that this carbon sink service will dramatically change: the beneficial direct CO_2 effect will soon be reduced by negative climate impacts as the planet warms at an ever-accelerating rate. "Hot droughts" are one way that this fundamental change in how ecosystems interact with the climate system will become increasingly apparent as the climate system continues to ramp up to increasingly hotter temperatures.

Plants are adapted to a set of conditions that have prevailed for thousands of years under the current Holocene climate, a climate that has been relatively steady for the past 15,000 years or so. We've already increased Earth's temperature to levels that are pushing the high temperature maxima for those 15,000-odd years, and within this century, we'll reach conditions that have not been prevalent for hundreds of thousands, if not millions, of years. As a result, droughts will occur at increasingly elevated temperatures, and tree communities will be pushed past irreversible physiological thresholds that cause irreparable harm to plant tissues and structures. Hot droughts will also be extremely challenging to human communities, causing shortages of drinking water, decreased food production, and poor air quality from drought-associated fires, particularly in the Global Tropics. Let's take a closer look at some of the things we have learned with our Brazilian partners.

Examples from the Brazilian Amazon

From late September of 2015 through early 2016, huge swathes of the Amazon experienced one of these hot droughts that was associated with a strong El Niño climate event. We hear a lot about how El Niño affects temperate regions and our local California climate, but the direct impacts of El Niño over the vast expanses of the Amazon basin are often more severe and occur as intense droughts. This 2015-2016 harbinger of hotter future tropical climate conditions, which will be much more prevalent on Earth in the coming decades, provided opportunities to study how high temperatures coupled with low moisture supplies affect tropical forests.

We work with groups of international researchers, students, and *mateiros* (forest workers) in the Amazon with leadership from Brazil's Instituto Nacional de Pesquisas da Amazônia (INPA, National Institute for Amazon Research). This partnership has grown from many decades of deeply collaborative research, and we are building a knowledge base that is simply not possible without such a strong reciprocal relationship. These collaborations generated opportunities to study the hot El Niño drought of 2015-2016 using a number of novel approaches.

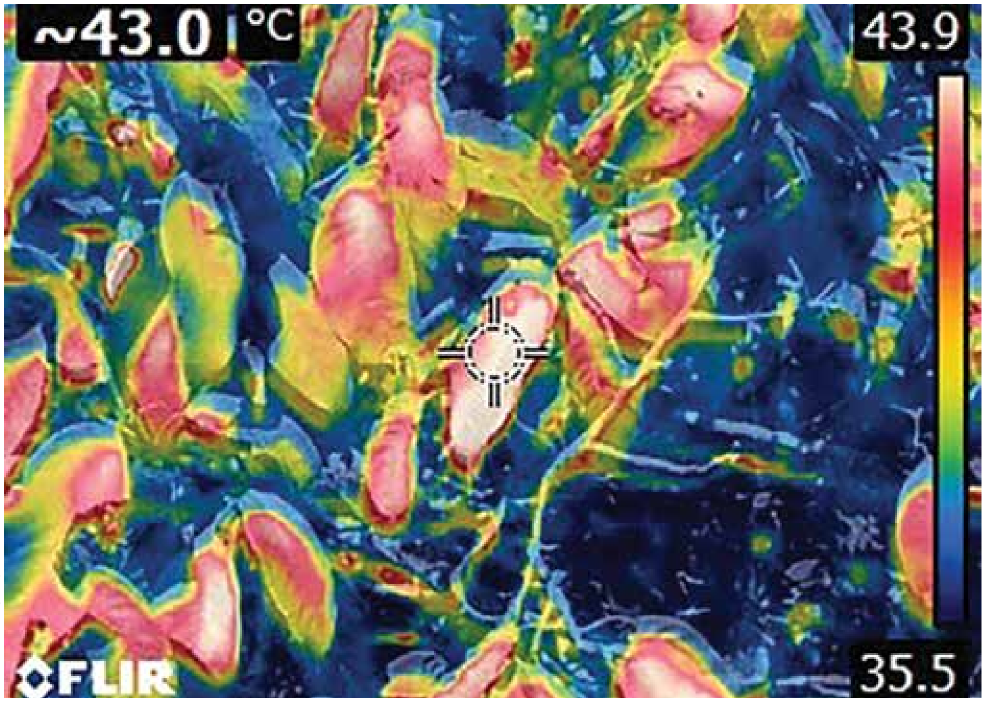

Photo courtesy of Jeff Chambers.

An infrared image of temperature in the forest canopy shows 109°F.

Many tropical forests experience a dry season lasting anywhere from one to five months. The local plants and trees are adapted to the associated seasonal moisture deficits and happily photosynthesize and thrive throughout the sunny dry-season months. Droughts are different, and in the tropics, they often develop as an extension of the dry season, creating conditions that tropical trees are less able to tolerate. Add to this mix a warming climate, and trees are often pushed past irreversible thresholds causing permanent damage or death.

The hot and dry conditions we encountered in the Brazilian Amazon in September 2015 motivated a quest to find out how water stressed the trees were. For a number of these tree species, we measured the "turgor loss point," also known as leaf wilting point. The wilting point is the minimum soil moisture required by a plant to not wilt and is irreversible. Once a plant crosses its wilting point, leaf cells are not able to rehydrate, leaves dry out, droop, and wither, causing permanent damage. We found that many trees passed their turgor loss point during that extreme drought, and many others were very close to reaching it. These types of studies are vital if we are to predict what will happen to plant communities and forest ecosystems under a hotter and drier climate.

Trees are also limited by factors that determine their maximum height. Water moves under tension from the soil to the root up the stem and out the pores on leaves, which are called stomata. That tension is caused by a drier atmosphere pulling water off the wet internal surfaces of leaves — the vapor pressure deficit (VPD). Under a warmer climate, VPD induces an increase in tension in the conductive tissue of the trunk (the xylem), and the water stream can snap under this elevated pressure, producing what is known as a "cavitation bubble" in the water stream that can damage or kill a tree. You can actually hear this cavitational popping with a special audio device similar to a stethoscope placed on the trunk of a drought-stressed tree.

But plants have defenses: they can close stomata to increase leaf hydration. There are costs for this hydration control, however, because the transpiration of water off the leaf surface also cools the leaf, and CO_2 enters those same pores. Preventing cavitation can come at the cost of higher leaf temperatures and carbon starvation, which can reduce plant growth, flowering, and fruit production. Trees often push their height to balance these costs, edging out their neighbors for additional photosynthetic light, but that maximum height was originally determined by a cooler climate. Many trees might be just a little too tall for the hotter tropical climate humans are creating.

Understanding how tropical trees will respond to hot droughts requires accessing the crowns of canopy trees, and those crowns often sit 30 meters (100 feet) or more off the ground. This accessibility issue is a real problem and has hampered tropical forest research for decades, consigning the upper-canopy biosphere

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to a largely unknown biological frontier. Our research group in the central Amazon has tried everything to overcome this challenge. Local forest para-botanists, whose incredible skills come from a life of experiential knowledge, are often amazing climbers, quickly ascending trunks and vines to frightening heights, but this approach is too risky. Tree-ascending gear akin to rock-climbing equipment is another approach, but only a few trees per day can be safely accessed. Some research groups have resorted to permanent canopy cranes that enable access to about a hectare (2.5 acres) of trees, but one small breeze and your leaf is sheared away from the photosynthesis chamber by the swaying basket that sits dangling at the end of a cable. Some researchers have even resorted to mini inflatable zeppelins. Our group is developing a new canopy system that includes a 25-meter (82-foot) telescoping lift, a “cherry picker,” that was recently transported from California to Manaus. We’ll be testing this approach soon at our research site 50 kilometers (31 miles) north of Manaus.

The relationship between climate and tropical forests is reciprocal: forests affect the climate as much as they are affected by the climate. Rain that falls on a patch of tropical rainforest only occasionally makes its way straight to a river. Most precipitation is captured by the roots of plants and then transported up the trunk and out the stomatal pores of leaves right back to the atmosphere. This recycling of precipitation by the forest acts to pump water deeper into the interior of the Amazon basin. The loss of forest by human land-use activities, such as deforestation for pasture or soybean production, can diminish this pump, acting to reduce precipitation patterns far from the regions that experience deforestation. A major challenge is protecting the role of forests in regulating a region’s precipitation patterns, while also developing sustainable agricultural practices.

Welcome to the Hypertropics

While we have a good qualitative understanding of how climate change will impact forests, we are lacking quantitative precision on exactly how climate change impacts will play out over the next few decades. Even if we make major progress in reducing CO_2 emissions and slowing the relentless rise of heat-trapping gases in the atmosphere, human activity has already changed the atmosphere enough to cause major disruptions, and we lack clarity on how those disruptions will play out with enough detail to make meaningful interventions.

Left: A telescopic lift raises researchers to the top of the forest canopy. (Photo courtesy of Bruno Oliva Gimenez.)

Photo courtesy of Bruno Oliva Gimenez.

Graduate student Daisy Souza works in the lift basket high in the canopy.

As a hotter tropics emerge over the coming decades, impacts to human livelihoods will also be numerous. An important trait enabling the broad biogeographical distribution of human populations is our ability to efficiently wick heat away. An interesting aspect of the hot and humid tropics is that the direct air temperature rarely exceeds approximately 32°C (90°F) due to the effect of atmospheric moisture in keeping temperatures lower.

But simple air temperature does not sufficiently convey the level of stress on the human body — just imagine spending a day laboring outdoors in the tropics under high humidity at more than 30°C (86°F). A better measure of heat stress comes from the “wet bulb temperature” determined by wrapping a water-soaked cloth on the thermometer. A wet bulb temperature of 32°C (90°F) has a human-felt heat index of 55°C (130°F). Human survival outdoors is limited to a few hours when the wet bulb temperature exceeds 35°C (95°F), representing a literally off-the-charts heat index of 70°C (160°F).

The emergence of the hypertropics throughout the Global Tropics will bring with it many challenges. Addressing these challenges requires deep engagement with communities that span planetary boundaries. A worldwide approach toward knowledge that will help in mitigating impacts to people and ecosystems cannot be only centered on institutions and scholars from the Global North. A path forward benefits from deep partnerships and reciprocal engagements with an international academy that is inclusive of a multitude of languages, ethnicities, genders, social status, and approaches to scholarship. One metric of success in creating a global academy is the development and co-authorship in the production of new knowledge with international partners. Science works best at problem solving with a diverse community, and that community needs better engagement with the Global Tropics.

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