The Diurnal Beating of the Amazonian Hydroclimate

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Abstract
About one third of the atmospheric moisture over the Amazon forest comes from transpiration from the dense canopy and evaporation from soils within the forest. It has been known for decades that between 20 and 40% of the Amazonian precipitation originates from the forest itself. The advent of new methods to quantify the sources of atmospheric moisture and the possibility of adequately visualizing the results, as shown in the exploratory video, led us to the discovery of a characteristic "beating" of the atmospheric moisture of Amazonian origin. Water vapor originating from Amazonian ET ebbs and flows with a characteristic diurnal timescale which becomes evident with our visualization. The timescale is a result of the diurnal cycle of ET, convective precipitation and advection by the winds. These processes come together to form a "beating" pattern that characterizes atmospheric moisture of the Amazon forest.

Introduction
Transpiration from plants is an important source of moisture for the atmosphere, in particular for densely vegetated regions like the Amazon forest. However, routine measurements of temperature and humidity of the atmosphere do not allow us to differentiate between different sources of moisture. In other words, measuring humidity will provide no information as to whether those water molecules came from the ocean or from land. Fortunately, there are alternative ways by which we can identify and quantify sources and sinks of water in the atmosphere [Gimeno et al, 2012; Dominguez et al., 2020]. In the late 1970's Salati et al., [1979] used observations of isotopes to estimate that more than half of the precipitation over the Amazon originated from transpiration from plants within the forest. Numerical models have also been used to estimate the contribution of evaporation from the soil and transpiration from plants (also known as evapotranspiration or ET) to atmospheric moisture and precipitation. Based on these estimates, we know that between 20% and 40% of Amazonian precipitation originates as local ET [Brubaker et al., 1993; Eltahir and Bras, 1994; Zemp et al., 2014]. We call this recycled precipitation.

These estimates are based on relatively simple offline methods that use existing data, mathematical relationships and important assumptions. However, more recent methods use water tracers directly embedded into regional climate models. We can think of this at putting dye into the model's hydrologic cycle [Sodemann et al., 2009]. The tracers include a more physically realistic representation of the processes that affect water in the atmosphere, including advection, diffusion, change of phase etc. Among these methods, water vapor tracers embedded in the Weather Research Forecast (WRF) model [Insua-Costa and Miguez-Macho, 2018] is perhaps one of the most comprehensive. Using this method, [Yang and Dominguez, 2019] estimated that approximately 30% of Amazonian precipitation comes from Amazonian ET. Furthermore, this moisture continues its journey into southern South America and contributes to about 16% of precipitation in the La Plata river Basin. [Eiras Barca et al., 2020] took this a step forward and evaluated the effect that future deforestation could have on this moisture. They found that the largest changes in recycled precipitation occurred during the dry season, with very significant reductions in water vapor of Amazonian origin.

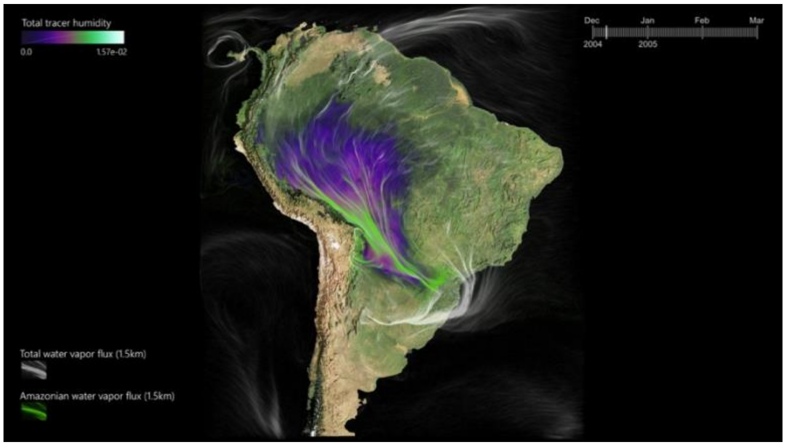

Figure 1 Visualization of WRF-WVT simulations. Shaded colors indicate atmospheric moisture originating from Amazonian ET. White stream lines indicate total water vapor flux at 1.5km, green stream lines indicate water vapor flux of Amazonian origin at 1.5km altitude.

However, these numbers refer to averages over many years. What happens within a day? Unlike simple offline models, WRF with water vapor tracers (WRF-WVT) allows us to evaluate hydrological processes at the diurnal time scale. This opens a window into processes that had not been previously investigated in the precipitation recycling literature. The opportunity to study the diurnal timescale became evident after the team examined the visualization (See Figure 1). The first idea that comes to mind is a beating heart that follows the rhythm of the days. What are the processes that lead to this rhythmic beating? This is what we explore in this work.

Methods

Simulations: In this work, we use the mesoscale model WRF-WVT tool. The South American continent has been taken as the simulation domain, with 6-hour outputs and a spatial resolution of approximately 20 km for the period 2003-2013. Additionally, a series of tools have been coupled online to the WRF, allowing a more detailed study of the land-atmosphere interactions, and adding confidence in the results obtained. The first tool is the MMF "groundwater scheme" [Fan et al., 2007], implemented in the Noah-MP soil model. This tool takes into account the interaction between the soil column and the shallow aquifers, resolving groundwater-atmosphere interactions particularly important during the dry season [Martinez et al., 2016].

The second tool is given by the implementation of moisture tracers (WRF vapor tracers, WRV-VT) in the WRF simulations. These tracers allow the identification of the fate of the moisture contribution made by a specific region. In the case of these simulations, the region that has been selected as a mask, and from which we are able to identify the evapotranspired humidity, is the Amazon basin. With this tool, it is possible to know what part of the content of the moisture column, or of the subsequent precipitation, is attributable to the contribution of the region itself; or how much moisture is exported from one region to another. It is a very useful tool when calculating the recycling ratio, or analyzing the export of moisture [Dominguez et al., 2016; Eiras Barca et al., 2017]. More detailed information on the settings used in the WRF, and on this particular configuration WRF + MMF + Noah-Mp + WRF-VT can be found in [Eiras Barca et al., 2020], where it has been used for the analysis of the impacts of the deforestation process in the Amazon. Extensive validation of the simulations can also be found in [Yang and Dominguez, 2019].

Time Series Analysis: To analyze the time series, two techniques aimed at obtaining the fundamental frequencies that make up the resulting signal are used; Fourier Transform Analysis (Harris, 1978) and Singular Spectrum Analysis (Hassani, 2007). Although both techniques have a different mathematical nature, they are similar in terms of the applications for which they can be used. In this case, they will allow to know which natural frequencies are those that compose the resulting signal, allowing, for example, to detect a diurnal cycle or an annual cycle inside a signal composed by the sum of both. In the case of Fourier, the frequencies will be identified as peaks in the transform, while in the case of Singular spectrum analysis, the characteristic periods will be directly those of the empirical orthogonal functions. Although these techniques applied independently have some limitations and associate some uncertainty, when applied together, obtaining coincident results, they constitute a very reliable tool.

Results

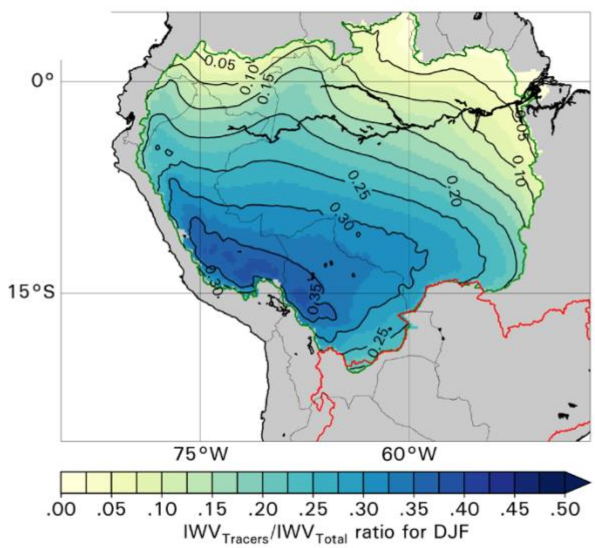

Figure 2 Fraction of integrated water vapor (IVT) originating from the Amazon, to total IWV for the Southern Hemisphere summer season.

We focus our result on the wet season of the Southern Hemisphere summer (December-January and February). In our visualization, we focus on the period December 2004-March 2005, however, our analysis encompasses 10 years of simulations. During the summer, winds enter from the Atlantic carrying moisture and travel in a southwesterly direction turning southeast as they encounter the Andes. As the winds travel, they pick up moisture from the Amazonian forest which is then carried by the prevalent winds. The moisture of Amazon is blocked by the Andes and accumulates along the southwest of the Amazon basin (see Figure 2), and some of this moisture is transported out of the basin into higher latitudes further south. As expected, the fraction of water in the atmosphere that comes from the Amazon forest follows a similar pattern with a maximum along the southwestern part of the basin. Occasionally, plumes of Amazonian moisture extend further south into Argentina.

Using Fourier analysis, we can extract the dominant timescales of variability in the different variables. The characteristic timescale of total water vapor is dominated by the annual timescale, while the tracer water vapor (the water vapor of Amazonian origin) doesn’t show a predominant annual cycle but shows a very important diurnal signal. The characteristic timescales of evapotranspiration, precipitation and moisture transport by winds drive the characteristic timescale in tracer water vapor. As expected, evapotranspiration shows the strongest diurnal cycle strength following the atmospheric evaporative demand and photosynthetic cycle of plants. Precipitation also shows a strong diurnal cycle as convection peaks in the late afternoon. Finally, advection of moisture in the column by winds (which we call integrated vapor transport or IVT) also shows a strong diurnal cycle because the winds peak at night. We can think of it as an accumulation of evapotranspired moisture as the plants and soil evaporate, then some of this water is rained out through convective precipitation and then “swept away” by nocturnal winds. This can be clearly seen in the video.

Visualization

In this exploratory video, we apply visualization techniques that lead to the discovery of a characteristic “beating” of the atmospheric moisture of Amazonian origin. A custom visualization software system is used to visualize, animate, and render the sequence across time. Our software uses a distributed, physical-based ray-tracer [Pharr and Humphreys, 2004] that renders simulation data mapped to integrated volumes, surfaces, and particle path-lines in the scene. This system has been used to visualize results from a variety of other science applications including cyclone-ocean interactions [Bock et al., 2017], wind-farm simulations [Stevens et al., 2015], tornadic storms [Bock et al., 2015], and swirling strengths [Cantero et al., 2008]. Visualization techniques for this simulation are used to show the temporal relationships between total tracer humidity, total water vapor flux, and the Amazonian water vapor flux across the South American continent. Since these relationships are closely influenced by the topography of the land, we map elevation height and satellite imagery of the South American continent to underlying geometry as a reference for the visualization. The total tracer humidity is volume-rendered using a color-map with linearly-ramped luminance and both the total and Amazonian water vapor flux are rendered as colored particle path-lines advected by wind velocity. To generate the path-lines, large numbers of particles are released and fade within the wind field at regular intervals. Using these techniques, the previously unseen diurnal movement within the Amazon region becomes evident.

Discussion and Conclusions

When our team visualized the output from the WRF-WVT simulations we realized that we had the opportunity to explore the moisture that originates from the Amazon forest at a timescale that researchers had previously not been able to investigate. The atmospheric moisture of Amazonian origin pulses on a diurnal timescale as a result of transpiration from the underlying canopy, convective precipitation and advection – all acting together to provide this characteristic “beating” pattern of the Amazon Forest.

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