# Ecohydrology of the Amazon supersystem

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**Abstract.** Here, we present an extended rationale for the ecohydrology science whereby climate change connects typical river basin ecology and hydrology with ocean dynamics and productivity. Such connectivity of diverse components creates a self-regulated supersystem. To support the discussion on the supersystem hypothesis, we used a negative sigmoidal function is used to model the limiting effect of salinity on productivity using satellite data and spectrally analysed in the time domain. There are evidences that the Amazon river plume comprises different environmental regimes, or habitats, that are physically structured by the influence of the North Brazil Current, its seasonal retroflection, mixing and river discharge. The extended ecohydrology of the Amazon basin proposed here offers a coherent synthesis that integrates atmosphere and ocean dynamics with ecological changes of tropical forests (both natural and anthropogenic), rivers and marine primary production. Such an extended framework is designed to improve the diagnostic of the causes of environmental variability from interannual (climate change) to subannual scales of (precipitation and ocean circulation and productivity).

**Keywords:** ecohydrology, Amazon river plume, climate change, ocean productivity.

## 1. Ecohydrology of the Amazon basin

The scale and magnitude of processes that characterize the ecohydrological system of the Amazon basin are closely linked with two ocean basins, the Pacific and the Atlantic, which could be described as a supersystem. Ultimately, the interactions between these two oceans and the atmosphere connects to the North Brazil Shelf Large Marine Ecosystem (NBLME) affecting primary productivity and atmospheric carbon balance (Subramaniam et al., 2008), and contributes to the meridian heat flux driven by the tropical surface ocean circulation. The increasing capability of earth observing systems and the availability of high quality global datasets open new possibilities of tackling critical environmental issues integrating global, regional and local processes in the interface land-ocean-atmosphere.

Both the Amazon basin and the tropical Atlantic ocean respond to remote forcing, during El Niño Southern Oscillation (ENSO) events, through the atmospheric teleconnection. This links the Pacific and the Atlantic oceans following complex coupling processes. These involve the eastward displacement of the Walker cell and the upper-tropospheric Rossby-wave train, that extends from the equatorial eastern Pacific to the northern tropical Atlantic. This coupling is also modulated by the inter-hemispheric sea surface temperature (SST) gradient of the tropical Atlantic (Alexander et al., 2002; Enfield and Mayer, 1997; Giannini et al., 2004; Hastenrath, 2006; Lanzante, 1996; Pezzi and Cavalcanti, 2001). However, the consequences for the large-scale ecosystem functioning of such forcing mechanisms remain elusive, sometimes resulting in contrasting responses. For example, it has been shown that the geographical boundaries of the North Atlantic Large Marine Ecosystem can become significantly offset from the spatial patterns of climate-induced variations. This could cause policy makers to react to a confounded scenario of environmental change due to mixed responses at the ecosystem level (Soares et al., 2014).

When the tropical Atlantic SST is phase-locked with the Pacific warm ENSO (El Niño Southern Oscillation), weak westerly trades and warmer than usual north Atlantic SST impede the seasonal southward excursion of the ITCZ (Intertropical Convergence Zone). This results in consistent negative rainfall anomalies and reduced streamflow of the Amazon river, in both interannual and decadal time scales, with impacts on water supply, water harzards and forest fires (Dettinger et al., 2000; Phillips et al. 2009, Aragão et al. 2014). However, rainfall response to El Niño can vary as pointed out by Marengo and Nobre (2001). Negative rainfall anomalies over the western Amazonia and near the mouth of the Amazon river are correlated with the El Niño event of 1972-73, while the 1982-83 El Niño produced negative rainfall anomalies over the eastern and central Amazonia and positive anomalies occurred in the western Amazonia.

Calculations made by Marengo et al. (2001) using hydrometeorological observations and moisture fluxes showed that, between 1970 and 1998, the northern portion modulated the water budget of the whole basin at interannual timescales while the southern (and larger) portion modulated the seasonal cycle. They suggested that northern Amazonia is more strongly linked to the interannual variability of the Pacific because an anomalous warm tropical Pacific and cold tropical Atlantic are correlated with the delay of the rainy season. Evidences from tree-ring chronology obtained for central and northwest Amazonia (Schongart et al., 2004) also indicate the sensitivity of this region to ENSO-related interannual rainfall variability.

Here, we propose an extended rationale for the ecohydrology research of the Amazon viewed as a supersystem, based on the connections of forcing mechanisms, such as atmospheric and ocean dynamics, with ecological changes of tropical forests, rivers and present preliminary results for marine primary production. Soares et al. (2014) showed that we need to understand how local ocean–atmosphere dynamics interact with remote-forced climatic regimes to be able mitigate the effects of climate change on the spatial scale of LMEs. We argue that climate change connects river basin ecology and hydrology with ocean dynamics and productivity, so depicting the connections among land, ocean and atmosphere over this region is an important step towards establishing the future states of the Amazon supersystem and its feedbacks with global climate system.

## 2. Materials and methods

First, the empirical surface salinity (ESS) for each pixel within the Amazon river plume and its surrounding oceanic area was estimated using a linear regression fit between *in situ* salinity data from a thermosalinograph and a CTD along a sampling transect at the river mouth, complemented with Argo floats data, and the absorption coefficient for dissolved and detrital material at 443 nm ($a_{443}$), following Molleri et al. (2010) and Fournier et al. (2015). The limiting effect of salinity on the productivity in the plume was estimated by fitting a inverse logit function. For the $a_{443}$ we used the GSM model (Garver-Siegel-Maritorena) from the Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day/4 km data (Maritorena et al., 2002) from July 2002 to March 2016. The relation between ESS and primary production was then established using the absorption Vertically Generalized Production Model (VGPM, Behrenfeld and Falkowski, 1997). Typical freshwater salinity was considered to be < 30 and mesohaline plume water ranges between 30 and 35. The spectral decomposition was obtained with the Wavelet code from Matlab (Mathworks) developed by Torrence and Compo (1998).

## 3. Scales and processes of the Amazon plume

River discharge and ocean circulation are key elements that control the seasonal variability of dissolved organic matter (DOM) that has recently been called the river-ocean continuum (Medeiros et al., 2015). The refractory and continental terrigenous fractions tend to dominate the DOM exported from the continental margin to the tropical Atlantic. Around 8% of the total DOM variability in the plume is accounted for by autochthonous molecules originated from phytoplankton blooms during high river discharge (Medeiros et al., 2015). What is simplistically described as the Amazon river plume, is actually a highly complex system characterized by: i) fast consumption of labile DOM near the river mouth, ii) the export of the refractory fraction to oceanic waters, iii) phytoplankton blooms, and iv) photochemical and selective bacterial degradation of DOM. These processes are all modulated by the dilution of plume water by the ocean circulation of the western tropical Atlantic.

Looking at the spatial and temporal dependencies of marine productivity as a function of salinity, the importance of ocean variability becomes more evident. This can be illustrated by comparing a map of the maximum spatial expression of the Amazon plume as depicted from the relation between light absorption in 443 nm and an inverse logit model that explains the limiting effect of salinity on productivity (Fig. 1). The former shows how far CDOM (chromophoric dissolved organic matter), assumed to be a proxy of the Amazon river plume, influence the NBLME and the latter highlights the average explaining power of ocean variability on productivity, given as net primary production from chlorophyll.

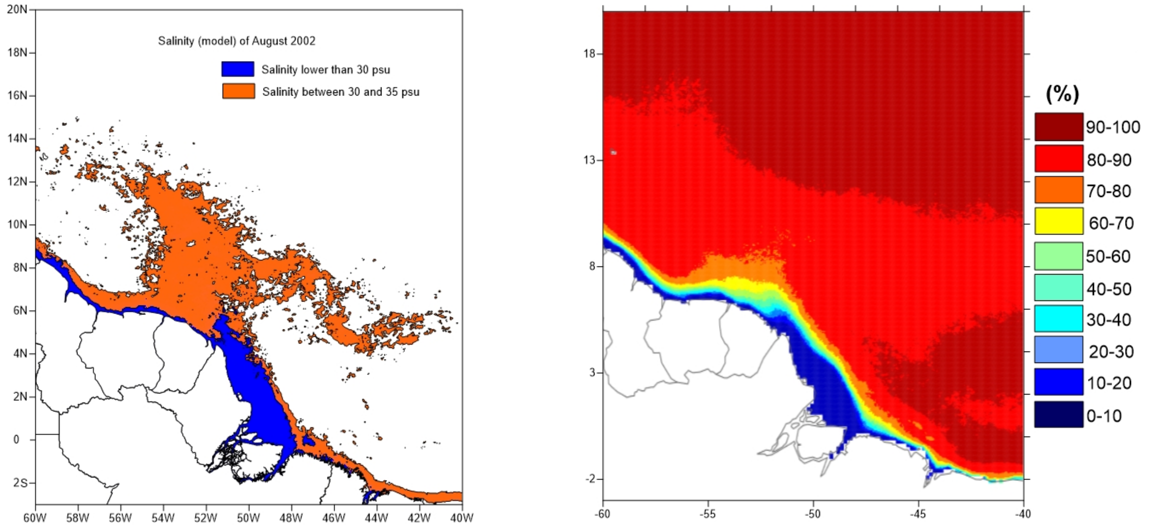

Figure 1. Maximum spatial expression of the Amazon plume based on $a_{443}$ (left, low salinity in blue and mesohaline in orange) and the inverse logit model that explains the limitation of productivity by salinity (right, 0% means no limitation).

We know that the Amazon river plume exports large quantities of organic and inorganic material more than 1000 km into the Atlantic and that ocean circulation modulates plume dispersion (Molleri et al, 2010, Fournier et al., 2015). A large fraction of this is likely to be terrigenous and refractory DOM, as the labile fractions tend to be consumed within the river (Medeiros et al., 2015). However, DOM variability is largely modulated by oceanic processes since exudates, i.e., phytoplankton-derived DOM, were found in the low salinity region of the river plume.

Time-domain spectral decomposition of the primary productivity of the low salinity region (<30) shows the predominance of subannual variability (Fig. 2) which tends to increase in variance from 2010 to 2016. Low variance regions in figure 2d appear to be related to periods of long positive Multivariate ENSO index (MEI) anomalies, wich are likely to reduce the seasonal signal of incursion of continental river water into the plume due to drought. In contrast, the mesohaline region shows significant variance of productivity only at the annual scale (Fig. 3), showing an increasing average variance from 2008 onwards. This could be related to positive SST anomalies in the tropical Atlantic and the intensification of droughts that cause reduction of streamflows, as shown by Lopes et al. (2016). A contrast between short-term reduction in precipitation as a response to positive SST anomalies in the tropical North Atlantic and long-term wetting trend in the Amazon was identified by Gloor et al. (2013). This wetting would lead to grater differences between peak and minimum flows and the itensification of the hydrological cycle. What is important, however, is that the ENSO-related drying seems to be more closely related to a reduction in precipitation, while the wetting trend may be related to incomming water vapour from the tropical Atlantic Ocean. It is clear that an intensification of the hydrological cycle would likely enhance the subannual variability of primary productivity in the river plume due to greater differences in the Amazon river flows.

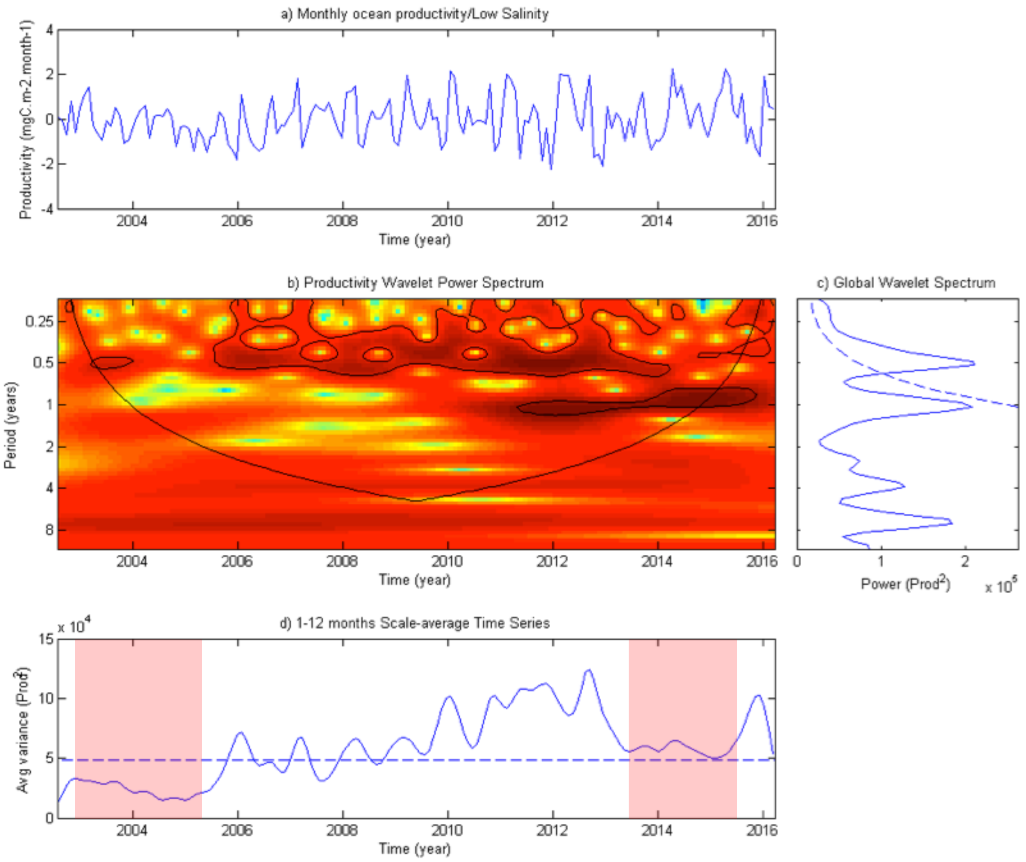

Figure 2. Wavelet decomposition of marine productivity representing the low salinity zone (blue area in Fig. 1) dominated by subannual variability. Red boxes indicate periods with sustained (over one year) positive Multivariate El Nino Index anomalies.

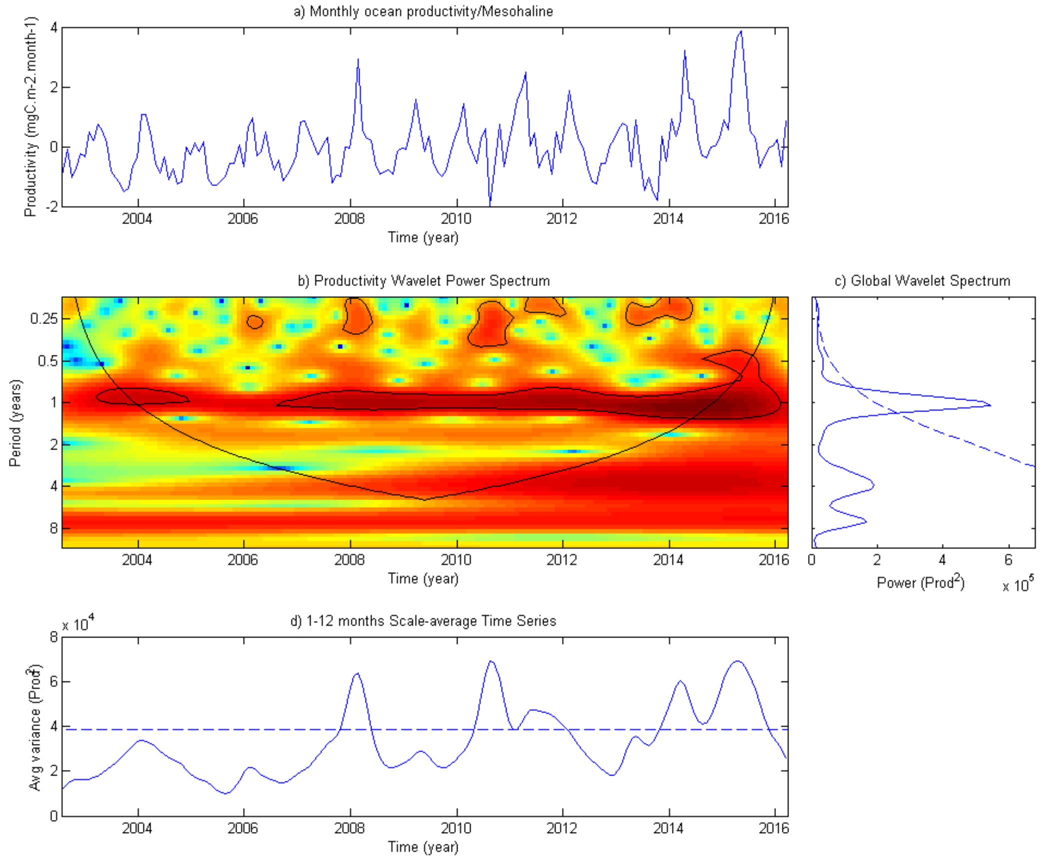

Figure 3. Wavelet decomposition of marine productivity representing the mesohaline zone (orange area in Fig. 1, left) dominated by annual variability.

## 4. Ocean primary productivity: light and nutrient limitation, plume dynamics and ocean circulation

We contend that the best way to understand the dynamics of the Amazon river plume is to approach it as a system composed of different environmental regimes, or habitats, that are physically structured by the influence of NBLME ocean circulation, namely, the NBC and its seasonal retroflection, mixing and river discharge. These habitats within the river plume tend to evolve responding changes in river discharge. The ITCZ meridional excursions is one of the main controlling factors, increasing fresh water input when achieving its southernmost position. When the ITCZ is in its northernmost position, between September-December, salinity reaches maximum values (see Coles et al., 2013). Therefore, the influence of Pacific ocean on the ITCZ position *via* the eastward displacement of the atmospheric Walker cell, together with the Atlantic meridional mode, has the potential to determine the habitat structuring of the Amazon river plume by changing rain patterns in the Amazon basin, river flow and mixing due to surface ocean circulation.

So, the importance of irradiance availability and nutrient concentration as limiting factors of phytoplankton photosynthesis along the amazon river plume continuum (Simth and DeMaster, 1996) looks now as an oversimplification. It is about time to try a new synthesis capable of integrating ocean basin variability, rainfall and river flow anomalies with diazotrophy (N2 fixation by symbiotic cyanobacteria) activity in the mesohaline region (sensu Subramanian et al., 2008) of the plume, biologically-induced alterations in DOM composition modulated by river discharge and the dynamic interaction between ocean circulation and plume waters.

## 5. Conclusions

We propose an extended ecohydrology of the Amazon basin based on a supersystem approach, composed of different environmental regimes, or habitats, controlled by the tropical Pacific and Atlantic variability and regional ocean dynamics. This could offer a coherent synthesis that integrates atmosphere and ocean dynamics with ecological changes of tropical forests (both natural and anthropogenic), rivers and marine primary production.

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