Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Land-atmosphere interactions in the tropics

Pierre Gentine
Department of Earth and Environmental Engineering,
Earth Institute
Columbia University, New York, USA

Adam Massmann
Department of Earth and Environmental Engineering,
Earth Institute,
Columbia University, New York, USA

Benjamin R. Lintner
Department of Environmental Sciences
Rutgers, The State University of New Jersey
New Brunswick, NJ, USA

Sayed Hamed Alemohammad
Department of Earth and Environmental Engineering,
Earth Institute,
Columbia University, New York, USA

Rong Fu
Atmospheric and Ocean Sciences Department
University of California, Los Angeles

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Julia K. Green

Department of Earth and Environmental Engineering,
Earth Institute,
Columbia University, New York, USA

Daniel Kennedy

Department of Earth and Environmental Engineering,
Earth Institute,
Columbia University, New York, USA

Jordi Vilà-Guerau de Arellano

Meteorology and Air Quality Group
Wageningen University, Wageningen, the Netherlands

Corresponding author address: Pierre Gentine, Department of Earth and Environmental Engineering, Columbia University, NY 10027, USA.
E-mail: pg23288@columbia.edu
Phone number: +1-212-854-7287

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

ABSTRACT

The continental tropics play a leading role in the terrestrial water and carbon cycles. Land-atmosphere interactions are integral in the regulation of surface energy, water and carbon fluxes across multiple spatial and temporal scales over tropical continents. We review here some of the important characteristics of tropical continental climates and how land-atmosphere interactions regulate them. Along with a wide range of climates, the tropics manifest a diverse array of land-atmosphere interactions. Broadly speaking, in tropical rainforests, light and energy are typically more limiting than precipitation and water supply for photosynthesis and evapotranspiration; whereas in savanna and semi-arid regions water is the critical regulator of surface fluxes and land-atmosphere interactions. We discuss the impact of the land surface, how it affects shallow clouds and how these clouds can feedback to the surface by modulating surface radiation. Some results from recent research suggest that shallow clouds may be especially critical to land-atmosphere interactions as these regulate the energy budget and moisture transport to the lower troposphere, which in turn affects deep convection. On the other hand, the impact of land surface conditions on deep convection appear to occur over larger, non-local, scales and might be critically affected by transitional regions between the climatologically dry and wet tropics.

1 Introduction

Tropical ecosystems play a substantial role in regulating the global carbon and hydrologic cycles. Tropical rainforests are one of the main terrestrial carbon sinks [*Nakicenovic*, 2000] but their projected response to a warming climate remains unclear because of uncertainties associated with the representation of abiotic and biotic processes in models as well as confounding factors such as deforestation and changes in land use and land cover [*Wang et al.*, 2009; *Davidson et al.*, 2012; *Fu et al.*, 2013; *Saatchi et al.*, 2013; *Hilker et al.*, 2014; *Boisier et al.*, 2015; *Doughty et al.*, 2015; *Gatti et al.*, 2015; *Knox et al.*, 2015; *Saleska et al.*, 2016]. The ecosystems of tropical monsoonal and seasonal wet-dry climates are also important contributors to the global carbon cycle, especially with respect to the interannual variability of the tropical terrestrial carbon sink [*Poulter et al.*, 2014; *Jung et al.*, 2017].

Some regions of the tropics have been further identified as hotspots of land-atmosphere interactions, modifying the regional climate [*Green et al.*, 2017] either locally, i.e. at horizontal scales on the order of a few boundary layer heights, regionally, at scales up to a few hundreds of kilometers, or at large scales, over several of thousands of kilometers, through coupling between the surface and the overlying atmosphere [*Lintner and Neelin*, 2009]. While tropical land-atmosphere interactions are often examined through the lens of coupling between land surface states (e.g., soil moisture) and rainfall, other aspects of the coupling are also important. For example, even under nonprecipitating conditions, surface radiation, temperature and vapor pressure deficit (VPD) may be altered [*Lawton et al.*, 2001; *Pielke et al.*, 2016; *Green et al.*, 2017] through coupling with clouds, aerosols and shallow (non-precipitating) convection [*Avissar and Nobre*, 2002; *Medvigy et al.*, 2011; *Seneviratne*, 2013; *Cook et al.*, 2014; *Guillod et al.*, 2015; *Krakauer et al.*, 2016; *Martin et al.*, 2016; *Green et al.*, 2017; *Khanna et al.*, 2017; *Martin et al.*, 2017; *Thiery et al.*, 2017; *Vogel et al.*, 2017]. It is clear that the tropical energy, water, and carbon cycles cannot be understood in isolation; rather, interactions among these cycles are critical, especially in determining whether the terrestrial tropics will act as a future carbon sink or source [*Zhang et al.*, 2015][*Swann et al.*, 2015].

The two-way interactions that occur between the land surface and overlying atmosphere represent one of the more uncertain aspects of the terrestrial climate system, particularly in the tropics [*Betts and Silva Dias*, 2010]. While the land surface is widely recognized as integral to the occurrence of important tropical climate phenomena such as monsoons [*Zeng and Neelin*, 1999; *Zeng et al.*, 1999], isolating and quantifying its precise role remains elusive. Indeed, such efforts have frequently been hampered by the paucity of observational data, not to mention the complex and multiple pathways through which land-atmosphere interactions can take place.

Several field campaigns have been conducted in the tropics with the purpose of advancing knowledge of land-atmosphere interactions. One of the first campaigns was the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) [*Avissar et al.*, 2002; *Keller et al.*, 2004], which aimed at refining our understanding of climatological, ecological, biogeochemical and hydrological processes of the Amazon and their linkages, in addition to the anthropogenic impacts (e.g., land-use land cover changes and deforestation, in particular) on these. Among many other topics, LBA generated fundamental insights on the structure of the tropical atmosphere, processes generating precipitation, and the seasonal variability of rainforest surface turbulent fluxes [*Avissar and Nobre*, 2002; *Betts et al.*, 2002; *Laurent et al.*, 2002; *Machado and Laurent*, 2002;

Acevedo et al., 2004; *Khairoutdinov and Randall*, 2006; *Fitzjarrald*, 2007; *Juárez et al.*, 2007; *Restrepo-Coupe et al.*, 2013]. Much of the initial LBA research attempted to isolate the effect of deforestation on precipitation, both in a local context as well as remotely via teleconnections [*Avissar et al.,* 2002]. Much of this research pointed to deforestation decreasing precipitation, albeit with uncertain magnitude. Even now, two decades after the inception of LBA, the relationship between tropical deforestation and precipitation remains uncertain, despite progress with respect to key processes such as the forest's role in accessing deep water in the dry season, and cloud-cover's role in modulating energy availability for photosynthesis [*Betts and Dias*, 2010].

Another noteworthy field campaign, the African Monsoon Multidisciplinary Analysis (AMMA) campaign, focused on the West African monsoon system, especially the Sahel transition zone [*Redelsperger et al.*, 2006; *Boone et al.*, 2009b]. AMMA built upon previous field work in the region [*e.g. HAPEX-Sahel*, *Gourtorbe et al. 1993*], and substantially advanced understanding of mesoscale convective systems and their initiation the role of surface professes, and the vegetation water stress response in semi-arid regions [*Lebel et al.*, 2009; *Taylor et al.*, 2009; *Boone et al.*, 2009a; *Lohou et al.*, 2010; *Couvreux et al.*, 2011a; 2011b]. More recently, the 2014-2015 Green Ocean Amazon (GO-Amazon) campaign [*Martin et al.*, 2016] sought to quantify the impact of atmospheric composition and aerosols under clean and polluted conditions on cloud formation and radiation over the basin, as well as on shallow to deep convection development [*Anber et al.*, 2015a; *Tang et al.*, 2016; *Giangrande et al.*, 2017].

The remainder of this review article is organized as follows. We first review the typical definitions of the tropics and of land-atmosphere interactions in section 2. In section 3 we discuss the seasonality and characteristics of the climate of the tropics. The different types of feedbacks from local to non-local (i.e. remote influences) are then highlighted in section 4, and we close in arguing that shallow cloud feedback and its impact on radiation has received too little attention compared to precipitation feedback, in rainforests especially.

2 Definitions of land-atmosphere interactions in the tropics

2.1 What (where) are the Tropics?

There exist multiple definitions of the Tropics. On the one hand, the Tropics can be defined spatially as the area between the Tropics of Cancer and Capricorn, located at ~23½° N and ~23½° S, respectively. On the other hand, it is sometimes useful to define the Tropics in terms of underlying climate or physical characteristics. One such physically-motivated definition of the Tropics is the region over which mean top-of-the-atmosphere solar incoming radiation exceeds outgoing radiation (reflected shortwave and outgoing longwave), which occurs equatorward of ~35°. Another definition is the region near the equator where the Coriolis effect is small and planetary scale equatorial wave dynamics are dominant, which strongly affects the dynamics, as we elaborate below [*Sobel et al.*, 2001; *Sobel and Bretherton*, 2003; *Lintner and Chiang*, 2005; *Raymond and Zeng*, 2005].

Over land, the Tropics are often defined biogeographically, as in the traditional Köppen climate classification scheme [*Köppen*, 1884]: tropical regions are divided into three main groups—tropical rainforest, tropical monsoon, and tropical wet and dry (or savanna)—all of which are characterized by annual mean temperatures exceeding 18°C but which differ in terms of precipitation amount and seasonality.

The latitudes between the Tropics of Cancer and Capricorn encompass some regions of large-scale subsidence and limited rainfall, including drylands and deserts, which we largely neglect here, even though land-atmosphere coupling processes within these regions is clearly of interest. Thus, throughout this manuscript, we define the Tropics as the latitudinal band between -15° S and 15° N, as it captures most of the wet regions of the Tropics while excluding many of the more arid regions at higher latitudes.

2.2 How to define land-atmosphere interactions?

There are typically two main definitions of land-atmosphere interactions:

2.2.1 Surface turbulent fluxes

While many potential definitions of land-atmosphere interactions exist, we propose a definition of land-atmosphere interactions as the study of turbulent fluxes and associated momentum, energy, water and trace gases exchanges between the biosphere and the atmosphere [*Goulden et al.*, 2004; *Fisher et al.*, 2009; *Restrepo-Coupe et al.*, 2013]. Surface turbulent flux measurements in the tropics are usually obtained from eddy-covariance methods, typically above the canopy [*Baldocchi et al.*, 2001]. Observing turbulent fluxes is challenging in tropical environments for many reasons including logistics, maintenance and the harsh environment such as intense rainfall, high wind, and relative humidity, which impacts the sensors [*Campos et al.*, 2009; *Da Rocha et al.*, 2009; *Restrepo-Coupe et al.*, 2013; *Zahn et al.*, 2016; *Chor et al.*, 2017; *Gerken et al.*, 2017]. In light of these challenges, it is perhaps not surprising that even the best estimates of surface turbulent fluxes manifest large uncertainties [*Mueller et al.*, 2011].

Apart from site level measurements, remote sensing observations can provide information about surface turbulent fluxes and other relevant quantities over tropical land regions. There is considerable uncertainty in upscaling point observations to larger areas. Remote sensing observations are useful to generalize and compare fluxes across the tropics even if they are not as direct as point observations, which are limited to ~ 10 local stations across the wet tropics. We emphasize that there are considerable uncertainties in remote sensing and reanalysis estimates of rainfall [*Washington et al.*, 2013; *Levy et al.*, 2017], radiation [*Jimenez et al.*, 2011], and surface turbulent fluxes [*Alemohammad et al.*, 2016].

While direct, satellite-based retrievals of turbulent fluxes of carbon (i.e. gross primary production (GPP))) and water would be most suitable for the study of tropical land-atmosphere interactions, such retrievals are beyond current remote sensing capability. However, some recent work demonstrates that existing satellite observations may still be leveraged to study surface turbulent fluxes in the tropics. *Alemohammad et al.* [2016] applied a machine learning algorithm based on remotely-sensed Solar-Induced Fluorescence (SIF), called WECANN (Water Energy and Carbon Artificial Neural Network) to derive surface turbulent fluxes. WECANN reproduces the seasonality in the wet tropics and exhibits plausible interannual. In contrast to the normalized difference vegetation index (NDVI) or many other vegetation indices which are indirect byproducts of photosynthesis, SIF (at the leaf scale) is directly related to the ecosystem-scale photosynthesis rate, providing important information on the impact of stressors on photosynthesis and is available from existing remote sensing platforms [*Frankenberg et al.*, 2011; *Joiner et al.*, 2011; *Frankenberg et al.*, 2012; *Joiner et al.*, 2013; *Frankenberg* *et al.*, 2014; *Guanter et al.*, 2014; *Lee et al.*, 2015; *Duveiller and Cescatti*, 2016; *Liu et al.*, 2017; *Thum et al.*, 2017; *Alexander et al.*, n.d.]. SIF is thus an important indicator of the rates of photosynthesis and transpiration through stomatal (small pores at the leaf surface) opening [*Alemohammad et al.*, 2017]. Indeed, during photosynthesis plants take up CO_2 from the atmosphere while releasing water to the atmosphere through stomata. WECANN performs well compared to eddy-covariance observations and has less uncertainty compared to many other retrievals (see [*Alemohammad et al.*, 2017]). We note that recent developments in observations of SIF seem to indicate that the major fraction of the SIF signal might be related to chlorophyll photosynthetically active radiation and that changes in SIF yield (equivalent to light use efficiency) may account for only a small fraction of the observed SIF signal [*Du et al.*, 2017]. This is still an open topic to better understand what is actually observed by SIF remote sensing.

2.2.2 Weather and climate feedback

A second definition of land-atmosphere interactions relates to the feedback between surface processes (radiation, surface turbulent fluxes) and the overlying atmosphere, which may occur across multiple temporal and spatial scales. Throughout this manuscript, we highlight contribution of three types of feedbacks:

1) feedbacks between the surface and low-level clouds, including surface fog and shallow convection;

2) feedbacks between the surface and deep convection, i.e. deep raining clouds extending above the freezing level;

3) feedbacks between the surface and large-scale circulation.

The distinction between shallow and deep convection remains elusive, as these have been regarded as both fundamentally distinct or as a continuum, in both observations and model convection parameterizations [*Khairoutdinov and Randall*, 2006; *Bretherton and Park*, 2009; *Park and Bretherton*, 2009; *Rio et al.*, 2009; *Wu et al.*, 2009; *Del Genio and Wu*, 2010; *Hohenegger and Bretherton*, 2011; *Böing et al.*, 2012; *D'Andrea et al.*, 2014; *Rochetin et al.*, 2014b]. We will loosely refer to shallow convection as convection confined below the freezing level (typically less than 3km deep) and comprising non-precipitating clouds with motions of small scale (typically less than a km in the horizontal).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

An important point is that shallow convection is frequently generated by thermals rooted in the boundary layer and is thus ultimately related to surface sensible (H) and latent heat (LE) flux and their partitioning [*Gentine et al.*, 2013a; 2013b; *de Arellano et al.*, 2014]. The impact of surface heat fluxes and their partitioning on shallow convection is demonstrated in the Amazon in **Figure 1**. Shallow convection frequently occurs over the vegetated surface away from the ocean; also, over cooler and more humid river basins, shallow clouds are virtually absent [*Gentine et al.*, 2013a; *Rieck et al.*, 2014; 2015]. In addition, shallow convection is strongly influenced by the diurnal cycle of surface radiation and surface turbulent heat fluxes [*Gentine et al.*, 2013a; 2013b; *de Arellano et al.*, 2014].

On the other hand, we use the term deep convection in association with deep, precipitating clouds. Deep convection may be triggered by boundary layer thermals [*D'Andrea et al.*, 2014; *Guillod et al.*, 2014; *Rochetin et al.*, 2014a; 2014b; *Anber et al.*, 2015a] as well as other processes such as radiative destabilization [*Anber et al.*, 2015b], meso- and large-scale circulations [*Werth and Avissar*, 2002; *Roy et al.*, 2003], cold pools (cold density currents due to rain evaporation that cools the air within precipitating downdrafts) [*Engerer et al.*, 2008; *Del Genio and Wu*, 2010; *Böing et al.*, 2012; *Feng et al.*, 2015; *Torri et al.*, 2015; *Gentine et al.*, 2016; *Heever*, 2016; *Drager and van den Heever*, 2017] and wave activity [*Kuang*, 2008; 2010]. As such, deep convection may be viewed as less dependent on the surface state compared to shallow convection.

Over the central Amazon a large fraction of wet season precipitation occurs during the nighttime (Figure 2). Moreover, during the daytime in both the dry and the wet seasons, the diurnal cycle reflects not only locally surface-triggered deep convection [*Khairoutdinov and Randall*, 2006; *Ghate and Kollias*, 2016] but also mesoscale convective systems propagating on daily time scales throughout the Amazon basin [*Ghate and Kollias*, 2016]. However, during the dry season, precipitation occurs more frequently with the "popcorn type" deep convection that is more locally triggered and thus directly related to the state of the land surface [*Ghate and Kollias*, 2016] (see an example here https://youtu.be/c2-iquZziPU).

Current generation climate models struggle to represent both shallow and deep convection over continents [*Guichard et al.*, 2004; *Bechtold et al.*, 2013; *Yin et al.*, 2013; *D'Andrea et al.*, 2014; *Couvreux et al.*, 2015], and especially in the tropics, as they exhibit substantial errors in the phasing and intensity of both the diurnal and seasonal cycles of convection [*Bechtold et al.*, 2013], as well as biases in the climatological distribution of rainfall over land. For example, over the Amazon, many climate models underestimate surface precipitation, evapotranspiration, and specific humidity [*Yin et al.*, 2013], with the dry bias in moisture extending upwards into the lower free troposphere {Lintner:2017gm}. Such biases are largely thought to reflect deficiencies or errors in how convection is represented in models [*Yano and Plant*, 2012; *Stevens and Bony*, 2013; *Bechtold et al.*, 2014]. Indeed, in current generation climate models, cloud processes occur at scales smaller than resolved grid-scale prognostic variables and therefore need to be parameterized, i.e. represented as a function of the resolved-scale variables. This is important as it means that climate models do not explicitly represent the small-scale convective physics of the climate system. We do note, however, that cloud resolving models which include explicit convection at scales of ~1km alleviate many of the biases observed in climate models, especially in terms of the diurnal cycle of convection or the sign and magnitude of the feedbacks between deep convection and surface evaporative fraction [*Taylor et al.*, 2013; *Anber et al.*, 2015a]. Nonetheless, due to convective wave coupling in the Tropics, a simple prescription of lateral boundary conditions in small-domain cloud-resolving model may be problematic, as the convective scales ultimately interact and are coupled with the planetary scales. With a sufficiently large domain and fine enough resolution, coupling between the convective scales and planetary scales may be explicitly resolved, but simulations of this nature are likely too be computationally too expensive for many applications. However, techniques exist to represent the effect of large-scale dynamics on the convective scales, which, when combined with cloud resolving simulations, yield powerful tools for understanding land-atmosphere interactions in the tropics, as we elaborate further below.

3 Characteristics of the tropics

3.1 Weak temperature gradient approximation – nonlocality

One key concept in tropical climate is the Weak Temperature Gradient (WTG) approximation. In the tropical free troposphere, horizontal gradients of temperature (and pressure) are small in part because of the relative weakness of the Coriolis parameter (as

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

on large-scales, geostrophic balance holds poleward of ~5 degrees). Homogenization occurs over a spatial scale comparable to the Rossby radius of deformation, which is inversely proportional to the Coriolis parameter. In midlatitudes, the Rossby radius is of order 10^2 km (similar to climate model resolution). In the tropics, the Rossby radius is typically an order of magnitude larger. Consequently, localized convection, and the diabatic heating associated with condensation and freezing of water, cannot be viewed in isolation from the large-scale in the tropics: in other words, in the tropical free troposphere, the temperature and pressure fields rapidly adjust to localized perturbations, effectively spreading the effect of these perturbations. In addition, it is relatively straightforward to show that adiabatic cooling, associated with large-scale vertical ascent in the presence of a vertical gradient of dry static energy $h = c_p T + gz$, effectively balances the diabatic heating rate **Q**, which in rainy regions of the tropics is mostly associated with convective processes. This further emphasizes the coupling between diabatic heating and large-scale ascent. Since the introduction of WTG, related and refined frameworks, such as weak pressure gradient [*Romps*, 2012a; 2012b] or damped gravity waves [*Wang et al.*, 2013], have been proposed. It should be emphasized that the WTG framework is only valid in the free troposphere, above the boundary layer, as it relates to wave dynamics in a stratified atmosphere.

The WTG framework has been used in single-column model and cloud-resolving models of the tropics [*Sobel et al.*, 2007; *Daleu et al.*, 2012; 2014; *Sentić and Sessions*, 2017] to obtain boundary conditions consistent with convective activity in the domain, thus avoiding the issues of inconsistent boundary forcing alluded to in section 2.2.2. While the WTG framework has often been applied in an oceanic context, [*Anber et al.*, 2015a] have demonstrated its utility in studying the coupling between regional land surface processes and larger-scale circulation, as discussed in Section XX.

3.2 Surface turbulent fluxes climatology and seasonality

Given that few flux towers are available across the tropics, we use WECANN [*Alemohammad et al.*, 2017] to calculate surface flux climatologies across the continental tropics. WECANN has been validated against available flux tower data and outperforms other products in terms of reproducing both the seasonality and interannual variability [*Alemohammad et al.*, 2017]. While remote sensing retrievals are not perfect and cannot be considered the truth, they do provide spatially extensive data coverage, including regions with sparse (or no) site-level measurements (e.g., Congo), which are hard to upscale to larger scale. In what follows, we evaluate climatologies of evapotranspiration (ET) and gross primary production (GPP) against precipitation (based on GPCP 1DD v1.2 [*Huffman et al.*, 2001]) and net radiation (based on CERES SYN [*Kato et al.*, 2013]) (Figure 4 to Figure 8).

We first focus on the main tropical rainforests and the northeastern savanna (or Cerrado) region of Brazil (Figure 4). In the wetter part of the Amazon, net radiation, Rn, peaks in the dry season (August to November) (Figure 4) when precipitation and cloud cover—especially shallow cloud cover, including fog—are reduced, [*Anber et al.*, 2015a]. As a result of the reduced cloud cover, incident surface solar radiation increases, and both GPP (Figure 6) and ET (Figure 7) increase in the dry season (Figure 4). As discussed further in the next section, the forest in the climatologically wetter Amazon is primarily light limited, while water stress there is moderate in the dry season. The seasonal cycle is more pronounced for GPP than for ET (Figure 4), as canopy rain interception comprises a large fraction of total ET in the wet season [*Scott et al.*, 1997; *Oleson et al.*, 2008; *Miralles et al.*, 2010; *Sutanto et al.*, 2012; *van Dijk et al.*, 2015; *Andreasen et al.*, 2016] and partly compensates for reduced transpiration in the wet season. In fact, because of this compensation, the wettest parts of the Amazon exhibit weak ET seasonality. On the other hand, most land-surface models exaggerate water stress in the Amazon [*Powell et al.*, 2013] and typically exhibit much lower rates of ET and GPP in the dry season, as well as opposite seasonality of net ecosystem exchange, than are observed [*de Gonçalves et al.*, 2013; *Alemohammad et al.*, 2016; 2017].

In contrast to the everwet central Amazon, over the Cerrado region of Northeastern Brazil, the seasonal cycles of Rn, precipitation, GPP and ET are much more pronounced, with a marked dry season (Figure 4). The seasonal cycle of GPP tracks precipitation, exhibiting a strong increase during the wet season. Similarly, ET increases sharply in the wet season and then decreases more slowly than precipitation in the dry region (Figure 4). Conversely, net radiation increases sharply during the dry season. This region clearly exhibits a strong water stress response.

Over the Maritime Continent, rainfall is intense throughout the year and seasonality is modest, with a short peak in November to January (Figure 4). Much of the seasonal cycle is attributable to monsoon circulations, which are strongly influenced by topography and the land- and ocean-surface thermal contrast [Chang 2005]; however, the complexity of the topography and the distribution of island land masses leads to strong local variability. Additionally, the Madden Julian Oscillation, an important mode of climate variability in in the tropical Indo-Pacific with a lifecycle of 30-90 days, strongly impacts rainfall on intraseasonal timescales [Hidayat and Kizu, 2009]. Convective activity in the region also regulates the East Asian Monsoon [*Huang and Sun*, 1992]. The region is also influenced by topographic effects and land-see breeze interactions at shorter time scales, and exhibits a strong diurnal cycle in convection [*Nitta*, 1987; *Hamada et al.*, 2008]. Given the relatively steady annual cycle of precipitation with regular convection, ET and GPP remain relatively steady throughout the entire year, exhibiting minimal seasonality, in this light limited environment (Figure 4).

The Congo basin exhibits two rainy seasons (Figure 4), with peaks in March-April-May and September-October-November, related to seasonal changes in moisture convergence due to the African Easterly jet and Intertropical Convergence Zone (ITCZ) over the Atlantic [*Washington et al.*, 2013]. Throughout the year, monthly-mean precipitation is much less than that observed over the Amazon or Indonesia. The seasonality of GPP and ET, to a lesser extent, tracks that of precipitation, with substantial decreases during the June to August dry season and even more pronounced reduction during the December to February period. This seasonality in GPP and ET (Figure 4) suggests that the Congo basin should exhibit substantially more water stress during dry seasons compared to the Amazon or Indonesian rainforests (Guan et al. 2015).

Integrated over the entire tropical latitudinal band, precipitation is highest in DJF and MAM when the wet season extends over most of the Amazon and adjacent savanna regions (Figure 5). GPP is maximized during the wet season in South America, as GPP is highest in the savanna regions while GPP over the rainforest is effectively seasonally invariant (Figure 7). The seasonal pattern of ET resembles GPP (Figure 7), mostly reflecting the seasonality of water availability in drier, water-limited regions and increased radiation in the dry season in the wetter, more energy-limited portions of the Amazon. The seasonal cycle of sensible heat flux (Figure 8) largely follows water stress, especially in the rainforest where radiation remains high throughout the year, with an increase during the dry season. Water stress is further evidenced in the evaporative fraction, EF, the ratio of latent heat flux to latent and sensible heat fluxes (Figure 9).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Tropically-averaged EF does not evolve much reflecting seasonal variation in the latitudinal peak in radiation and compensation of decreased canopy interception by transpiration (because of increased net surface radiation) in the dry season. However, in transitional and dry regions to the east, EF exhibits substantial seasonal variation between the wet season, when it peaks, and the dry season. The surface moist static energy flux (assuming sea level elevation) shows variations in SON and JJA but otherwise remains steady across longitudes because of compensation between the increased H and reduced ET. In the dry to wet transition, SON, moist static energy flux exhibits an interesting peak at about -60 longitude (Figure 10) though the combined increase in radiation, due to reduced cloudiness, inducing higher sensible heat flux and maintained high ET rates.

Over tropical Africa, the precipitation is highest in JJAS during the wet phase of the West African Monsoon, with a secondary maximum in DJF corresponding to the Southern African Monsoon (Figure 5). Similarly the latitudinal-averaged GPP and ET increase during the West African Monsoon (Figure 6, Figure 7), accompanied by a strong decrease in sensible heat flux (Figure 8). In DJF the southern African Monsoon displays increased water flux (Figure 7) and photosynthesis tracking the increased rainfall (Figure 5). The Congo rainforest clearly exhibits two brief rainy seasons (Figure 4, Figure 9), with peaks in March-April-May and September-October-November (Figure 4) and displays substantial water stress and strong reduction in EF to values below 0.6 during the dry season (Figure 9).

3.3 Rainforest water stress

One outstanding challenge in modeling tropical land regions is why do most contemporary land-surface models incorrectly represent the wettest rainforest GPP and ET rates, their seasonal cycles, and how they relate to water stress? Capturing this accurately will help better understand the seasonal course of GPP and ET in the tropics.

In the wettest tropical forests, such as the western portion of the Amazon or Indonesia, energy and light limit the rates of ET and GPP. It is thus natural to conclude that soil moisture and water stress have only minor effects in such regions and thus that precipitation variability would not matter much. In fact, there exist sharp vertical gradients in the canopy (as well as at the surface of the soil in the dry season) in terms of light and water availability (along with nutrient allocation) (Figure 3). Understory species receive only a small amount of mostly diffuse light. However, water is not typically limiting for low-canopy species. Moreover, because relative humidity is high and VPD is low, leading to low stress on understory stomatal and ecosystem conductance [*Leuning*, 1995; *Leuning et al.*, 1995; *Wang and Leuning*, 1998; *Medlyn et al.*, 2011; 2012; *Heroult et al.*, 2013].

On the other hand, top canopy species receive a large amount of radiation, especially in the dry season, causing sunlit leaf warming and desiccation leading to heat and water stress [*Jardine et al.*, 2014]. Leaf and xylem water status are regulated by the relative demand of sap from transpiration, which depends on incoming radiation, temperature and VPD. It also depends on the supply of sap to the leaves which is controlled by xylem conductivity and reduced by cavitation in the xylem [*Martinez-Vilalta et al.*, 2014; *Martinez-Vilalta and Garcia-Forner*, 2016]. To avoid leaf desiccation and xylem cavitation (formulation of air bubbles blocking the ascent of sap flow from the roots to the leaves) stomatal closure is usually observed during peak daytime sunlight hours in rainforest canopy species [*Brodribb*, 2003; *Pons and Welschen*, 2003; *Zhang et al.*, 2013]. This reduces the drop in leaf and xylem water potential and thus avoids important leaf desiccation or xylem cavitation (Figure 12). This type of behavior with strong stomatal regulation appears to be the norm in the wettest tropical forests [*Fisher et al.*, 2006; *Konings and Gentine*, 2016].

In tall canopy species the flow in the xylem from the roots is limited and cannot sufficiently rehydrate the upper xylem and leaves, and it cannot be compensated by the plant internal storage, whereby stomatal shutdown is inevitable to avoid desiccation and xylem cavitation (Figure 12) [*Phillips et al.*, 1997; 2004; *Lee et al.*, 2005; *Oliveira et al.*, 2005; *Phillips et al.*, 2008; *Scholz et al.*, 2011; *Zeppel et al.*, 2014; *Konings and Gentine*, 2016]. In summary, water stress in tropical rainforest canopy species is not primarily due to soil water stress but rather to the atmospheric demand and the build up of water stress in the soil-plant continuum. Radiation, temperature and VPD are therefore essential for tropical forests further emphasizing the importance of radiation and light on those forests. Land-surface and ecosystem models, apart from a few exceptions [*Xu et al.*, 2016; *Kennedy et al.*, 2017], do not represent plant hydraulics and typically only rely on an empirical reduction of stomatal and ecosystem conductance, and therefore transpiration and GPP, as functions of root-averaged soil moisture or water potential (e.g., [*Noilhan and Planton*, 1989; *Sellers et al.*, 1996a; 1996b; *Ek*, 2003; *Boulet et al.*, 2007; *Gentine et* *al.*, 2007; *Ngo-Duc et al.*, 2007; *Stoeckli et al.*, 2008; *Balsamo et al.*, 2009; *Boone et al.*, 2009a; *Bonan et al.*, 2011; *Lawrence et al.*, 2011; *Niu et al.*, 2011; *Bonan et al.*, 2012; *Canal et al.*, 2014; *Han et al.*, 2014; *Naudts et al.*, 2014; *De Kauwe et al.*, 2015; *Chaney et al.*, 2016; *Chen et al.*, 2016; *Haverd et al.*, 2016] among others). The root profile averaging of soil moisture or water potential to define water stress exaggerates the impact of surface drying, as in reality deeper roots may still effectively transport water to the plant xylem even if surface roots experience dry conditions and therefore can maintain overall high rates of GPP and transpiration.

The inclusion of plant hydraulics in tall canopy species leads to strong differentiation between leaf (and upper xylem) and soil water potential (Figure 12) during midday, especially in the dry season. Indeed, leaf and xylem water potentials substantially drop because of the large transpiration rates through the stomata and because the xylem cannot be instantaneously refilled due to the large flow drag in the elongated xylem. As a result, plant hydraulics induce a shutdown of stomata during the day reducing the transpiration rate near peak solar hours, also knownknows as "midday depression," in order to reduce desiccation of the leaf and xylem. In addition, plant hydraulics also induces a natural hydraulic redistribution of water in the root profile reducing dryness in the upper profile in the dry season [*Lee et al.*, 2005; *Oliveira et al.*, 2005; *Domec et al.*, 2010; *Prieto and Ryel*, 2014; *Kennedy et al.*, 2017], using deep root moisture rather than surface soil moisture when needed, as the water flows down gradient of water potentials. This is fundamentally different from typical parameterizations using average water stress of the root water profile, which are oversensitive to surface water stress, in typical parameterizations [*Kennedy et al.*, 2017]. Both of those effects lead to reduced sensitivity to water stress [*Kennedy et al.*, 2017] and help maintain higher rates of transpiration throughout the entire dry season [*Kennedy et al.*, 2017], whereas typical land surface models overestimate water stress in the dry season [*de Gonçalves et al.*, 2013; *Alemohammad et al.*, 2016; 2017].

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

4 Land-atmosphere interactions – local and nonlocal

4.1 Local feedback and heterogeneity – shallow clouds (fog and shallow convection)

We suggest that that the most critical land-atmosphere feedbacks in tropical rainforests involve shallow clouds and fog rather than deep convective clouds. Clearly, much of the focus of tropical land-atmosphere interactions has been on feedbacks involving precipitating deep convection, and the impact of heterogeneity on convective rainfall. On the other hand, the coupling of the land surface to radiation has been relatively understudied. Shallow clouds lead to reduced productivity and transpiration [*Anber et al.*, 2015a], yet the latter depends on cloud thickness as cumulus (shallow convection) generate more diffuse light and can boost photosynthesis when they are not too thick [*Ouwersloot et al.*, 2017] . Fog on the other hand, strongly diminishes the amount of light received by the ecosystems. Fog [*Anber et al.*, 2015a] and shallow clouds [*Giangrande et al.*, 2017] appear to be one of the primary differences between the dry and the wet season (in addition to the preferential occurrence of nighttime mesoscale convective systems in the rainy season, which are not directly relevant for land-atmosphere interactions associated with daytime processes). Low-level cloudiness largely affects the surface incoming radiation by reducing shortwave surface incoming radiation in the wet season, especially in the morning [*Anber et al.*, 2015a; *Giangrande et al.*, 2017], which in turn leads to strong reduction in GPP and ET. These clouds are also tightly connected to surface processes and especially the surface energy partitioning. Indeed nighttime fog, which often persists into the early daylight hours, is largely induced by longwave temperature cooling, especially in the presence of evening rain in the wet season, which generates dew formation [*Anber et al.*, 2015a]. Shallow clouds are themselves directly forced by surface-generated thermals due to boundary layer processes [*de Arellano et al.*, 2014], and they are modified by the sensible and latent heat flux magnitude [*de Arellano et al.*, 2014]. Shallow convection and low-cloud cover are also tightly connected to the seasonality of the forest and to the diurnal cycle [*Anber et al.*, 2015a; *Tang et al.*, 2016; *Giangrande et al.*, 2017].

Historically, the study of land-atmosphere interactions in the Tropics, and tropical rainforests in particular, has emphasized effects of heterogeneity, especially due to

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Discussions
Open Access

deforestation, on the generation of deep convection through mesoscale circulations (see [*Lawrence and Vandecar*, 2015] for a complete review, as well as [*Avissar and Pielke*, 1989; *Pielke and Avissar*, 1990; *Pielke et al.*, 1991; *Dalu et al.*, 1996; *Avissar and Schmidt*, 1998; *Taylor et al.*, 2007; 2009; 2011; *Rieck et al.*, 2015; *Khanna et al.*, 2017]). The hypothesis behind this is that deforestation reduces EF and surface roughness [*Khanna et al.*, 2017]. The associated increased buoyancy flux over the deforested areas, mostly reflecting a shift toward increased sensible heating, induces mesoscale circulations. These circulations enhance cloudiness through local buoyancy fluxes, turbulent kinetic energy generation, and low-level moisture advection from adjacent forested areas, thus providing all the key ingredients for moist convection generation [*Rieck et al.*, 2014; 2015]. It seems unlikely however that momentum roughness plays a major role in this high radiation environment [*Park et al.*, 2017], where circulations are mostly buoyancy-driven. Instead, the heat and moisture roughness lengths [*Park et al.*, 2017] as well as leaf area index and stomatal conductance, which scales the magnitude of the evapotranspiration flux, are the main players, in addition to changes in soil moisture availability, for the circulation.

Induced mesoscale circulations and associated deep convection are clearly observable with remote sensing observations [*Khanna et al.*, 2017] and are more important in the dry season [*Khanna et al.*, 2017], when convection is more locally, and regionally, triggered [*Anber et al.*, 2015a; *Ghate and Kollias*, 2016]. Once precipitation occurs though, cold pools, i.e., density currents induced by ice melt and evaporating rain in downdrafts, dominate the surface-induced mesoscale circulation [*Rieck et al.*, 2015], and reduce the surface heterogeneity signal. In the wet season, the relative contribution of local forcing to the total rainfall is small as the bulk of the precipitation is due to mesoscale convective systems or larger-scale systems propagating throughout the basin, less tightly connected to surface and boundary layer processes [*Ghate and Kollias*, 2016].

Even during the dry season, a large fraction of the Amazon and of Indonesia only experience minimal water stress (Figure 9 and Figure 8) so that increased radiation generates higher rates of photosynthesis (Figure 6) and ET (Figure 7) [*Anber et al.*, 2015a]. As such the radiation feedback of mesoscale-induced clouds may systematically impact clearings and deforested regions (Figure 13) and are more systematic and longer lasting than mesoscale-induced convective rainfall. Fewer studies have studied changes

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Discussions
Open Access

in shallow clouds [*Wang et al.*, 2000; *Lawton et al.*, 2001; *Chagnon et al.*, 2004; *Ray et al.*, 2006; *Wang et al.*, 2009; *Pielke et al.*, 2011; *Rieck et al.*, 2014; *Anber et al.*, 2015a], even though the impact of changes in the surface energy partitioning and heterogeneity on low-level clouds is clear and spatially systematic (Figure 1). Given the importance of cloud cover on shortwave radiation and their importance for the differentiation between the dry and wet seasons over wet tropical rainforests we believe that this low-cloud feedback might be quite critical for rainforest ecosystem functioning. Indeed it was pointed out by [*Morton et al.*, 2014; *Anber et al.*, 2015a; *Morton and Cook*, 2016] that light changes between the dry and wet season due to changes in cloud cover were one of the primary reasons for changes in the seasonality of surface fluxes, in addition to leaf flush out [*Lopes et al.*, 2016; *Saleska et al.*, 2016]. We also note that the shading due to low clouds reduces surface temperature and ecosystem respiration [*Mahecha et al.*, 2010; *Peterhansel and Maurino*, 2011; *Thornley*, 2011; *Hadden and Grelle*, 2016; *Ballantyne et al.*, 2017]. So, cloud-induced reductions in respiration can cancel reductions in photosynthesis, such that the net effect of cloud shading on net ecosystem exchange is unclear. In an academic study inspired in the thermodynamic characteristics in the Amazonia, [*Horn et al.*, 2015] showed that coupling with the surface leads to a change in the length scales that characterized clouds, and a reduction of the cloud life time. As a result, there are larger populations of smaller shallow cumuli.

In addition to regulating radiative energy balance at the surface, [*Wright et al.*, 2017] have shown that shallow convection transports moisture, provided by plants' transpiration, from the atmospheric boundary layer to the lower troposphere during the late dry season and early dry to wet transition seasons (July-September). This mechanism, referred to as the "shallow convective moisture pump", plays an important role in priming the atmosphere for increasing deep convection (e.g., [*Schiro et al.*, 2016] [*Zhuang et al.*, 2017]), and wet season onset over the Amazon [*Wright et al.*, 2017].

The results discussed until now omitted the relation between physical processes and the atmospheric composition, and more specifically the role of chemical reactions and aerosol. Over rainforests, the pristine and undisturbed conditions of the atmospheric boundary layer described in the seminal study by [*Garstang and Fitzjarrald*, 1999] are currently undergoing rapid changes due to atmospheric composition modifications. Their direct impact on the radiative and microphysical properties are due to biomass burning

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

and enhancement of concentrations of secondary organic aerosol precursors. Biomass burning in Amazonia leads to increase aerosol optical depth and to abnormal distributions of the heating rate profile. Analyzing systematic experiments performed by large-eddy simulations, [*Feingold et al.*, 2005] studied the processes that lead to the suppression of clouds. Firstly, at the surface there is clear indications that the latent and sensible heat flux are reduced, yielding convective boundary layers characterized by less turbulent intensity and by delays in the morning transition [*Barbaro and Arellano*, 2014]. Both aspects tend to reduce cloud formations. Secondly, [*Barbaro and Arellano*, 2014] indicated that the vertical location of the smoke layer is crucial in determining how the cloud characteristics*, i.e* cloud cover, will change. As described by [*Feingold et al.*, 2005], smoke confined in the well-mixed sub-cloud layer might positively benefit the cloud formation since it distributes the heat uniformly that contributes to enhance convection. On the other hand, smoke layers located within the cloud layer tend to stabilize the cloud layer and therefore decrease the possibility of cloud formation. These results are very much dependent on the aerosol optical properties defined by their heating, scattering and hygroscopic properties. As a first indicative figure, the mentioned LES study and observations by [*Koren et al.*, 2004] stressed that smoke layers with an aerosol optical depth larger than 0.5 might already lead to cloud suppression by 50%. [*Yu et al.*, 2008] have shown observationally that the influence of aerosols on shallow clouds varies with meteorological conditions. When the ambient atmosphere is drier (relative humidity ≤60%), the aerosol induced cloud burning effect (evaporation of cloud droplets) due to increased absorption of solar radiation by aerosols out-weight the increase of cloud droplets due to aerosol-cloud microphysical effect. The reduced shallow clouds can further enhance the surface dryness. In contrast, when the ambient atmosphere is relatively humid (relative humidity ≥60%), the aerosol-cloud microphysical effect out-weighs the cloud burning effect, leading to an increase of shallow clouds and relative humidity near surface. In so doing, aerosols can amplify the original moisture anomalies near the surface. Aerosols have also shown to increase of the life time of mesoscale convection over Congo and Amazon, due to delay of the precipitation that enhances ice formation and increase lifetime of the mature and decay phase of deep convection [*Chakraborty et al.*, 2016].

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

These modifications are not only related to the direct emission of aerosol, but also to changes in the gas phase chemistry that act as a precursor for the formation of secondary organic aerosol. [*Andreae et al.*, 2002] already described the differences in NO_x and ozone (O_3) mixing ratio depending on the Amazonia site. From rather pristine conditions with NO_x and ozone levels below 0.1 ppb and 20 ppb, to values above 0.1 ppb and maximum levels of O_3 near 50 ppb. Recent field experiments within the Green Ocean Amazon campaign (GoAmazon) (Fuentes et al., 2016; [*Martin et al.*, 2016] corroborate these levels as well as the high levels of the bio-organic compounds, in particular isoprene and monoterpene. Closely related, these changes are accentuated by anthropogenic emissions, i.e. Manaus. The unique distribution of aerosols in Amazonia might explain observed differences in deep convection, in particular lighting frequency, between Amazonia, the Maritime continent and the Congo basin [*Williams et al. 2004*]. To represent these chemistry changes and their effect on convection adequately, the dynamic effect that drive processes such as the entrainment of pollutants from the free troposphere need to be taken into account [*Vila-Guerau de Arellano et al.*, 2011]. As a result of this interaction between radiation, the land surface, dynamics and chemical processes, the transition from turbulent clear convective conditions to shallow cloudy convection may be modified in the future. Current efforts in monitoring them and improving the parameterizations of convection are under way [*Dias et al.*, 2014]. These efforts should include also in an integrated manner the combined role of dynamics and chemistry to quantify relevant processes like the ventilation of pollutants from the sub-cloud layer into the cloud layer, i.e. mass flux parameterizations, under representative Amazon conditions [*Ouwersloot et al.*, 2013].

In addition to affecting cloud microphysics, biomass burning in the tropics significantly affects the global carbon budget. For example, in September and October of 2015 fires in the Maritime continent released more terrestrial carbon (11.3 Tg C) than the anthropogenic emissions of the EU (8.9 Tg C) [*Huijnen et al.*, 2016]. The extent of forest fires in this region is tied to El Niño-induced drought conditions, and antecedent SST patterns are closely related to burned area at the global scale, particularly in hotspots concentrated in the tropics [*Chen et al., 2016*]. Aerosol emissions and biomass burning exert a strong control on land-atmosphere coupling of the carbon and water cycles, and the consequences of this coupling is observable globally.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences Discussions
Open Access

1.1. Nonlocal feedback – deep convection and large-scale circulation

Thus far, we have largely viewed land-atmosphere coupling through the lens of local conditions, but how should we modify this view in light of remote influences (see WTG discussion) or coupling between local and larger-scale conditions? Here we illustrate some aspects of how land-atmosphere coupling in the Tropics is impacted by the larger-scale.

4.1.1 Large-scale coupling, idealized modeling

Consider the Lagrangian tendency equation for conservation of atmospheric water vapor, expressed in terms of specific humidity q:

$$\frac{dq}{dt} = S(q) \qquad (3)$$

where $S(q)$ is the sum of sources and sinks of specific humidity. In the absence of sources and sinks, (3) implies that the specific humidity of a parcel of air is conserved following the atmospheric flow. In what follows, we consider a vertically-integrated form of (3) such that:

$$\langle \frac{\partial q}{\partial t} \rangle = E - P - \langle \mathbf{v_H} \cdot \nabla q \rangle - \langle \omega \frac{\partial q}{\partial p} \rangle \qquad (4)$$

Here E and P represent, respectively, the surface evapotranspiration source and the precipitation sink of water vapor, while $\langle \ldots \rangle$ represents a mass-weighted vertical (pressure) integral from the surface (at pressure p_s) to the nominal top of the troposphere (at pressure p_t), i.e., $\langle \ldots \rangle = \int_{pt}^{ps} \ldots \frac{dp}{g}$. The third and fourth terms on the right-hand side (RHS) of (4) are horizontal and vertical moisture advection. Equation (4) is normalized such that $\langle q \rangle$ has units of mm, thus effectively corresponding to column water vapor, and terms on the right hand side are given in units of mm/day. Equation (4) is often used to construct a diagnostic budget of precipitation, or in perturbation form, precipitation anomalies. As a caveat, within the tropics, the dominant large-scale balance in deep convecting regions is typically between vertical moisture advection (or equivalently in the vertically-integrated form, moisture convergence) and precipitation, which may limit the utility of (4) in attributing causality.

Using equation (4) as a starting point, [*Lintner and Neelin*, 2007; 2009] constructed a framework for estimating *where* spatial transitions between tropical non-precipitating and precipitating conditions, referred to as convective margins, should occur. By coupling

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

the water and energy (surface and atmosphere) equations, and invoking WTG and convective quasi equilibrium assumptions, as well as a zero-surface flux constraint over land, [*Lintner and Neelin*, 2009] derived the following expression for locating the convective margin, x_c, along a prescribed inflow air-mass trajectory from an initial point over the ocean onto land (see Figure 15 for a schematic overview):

$$x_c = L_c \ln\left[\frac{q_c+q_E}{q_0+q_E}\right] \qquad (5)$$

L_c denotes a length scale defined as $\frac{v_q Ms}{Mq_p(R_{toa,net}-E)}$ where v_q is the mean horizontal wind field, weighted with respect to the vertical moisture profile. From the WTG temperature equation, and subject to the zero net surface flux constraint over land, the divergent component of the large-scale circulation can be related to the net TOA radiative heating, $R_{toa,net}$. Ms is the dry static stability and Mq_p the vertical moisture stratification per unit moisture. The moisture values q_0, q_c, and q_E denote, respectively, the initial inflow air mass moisture, a moisture-related threshold for initiation of deep convection,; and a moisture scale associated with evapotranspiration over the inflow path, $q_E=\frac{v_q E}{L_c}$. Because of vertical integration, these quantities are column integrated values.

Note that the advantage of coupling the atmospheric moisture equation to the temperature equation is that under the WTG approximation, the divergent component of the flow is itself diagnosed, which can be instructive for identifying mechanisms involved. Also, in equation (5) and the definition of q_E, we have assumed that $L_c > 0$ and that convergent low-level flow is signed positive.

Evapotranspiration gives rise to two opposing effects on x_c. First, with increasing E , q_E should increase, which causes x_c to decrease, i.e., moistening from evapotranspiration experienced along the inflow path leads to the convective margin being reached closer to the inflow point. Second, as E increases, L_c increases: this can be understood as the indirect effect of E, acting through reduction of convergence along the flow path, which shifts the onset point for deep convection away from the inflow point (see Figure 15).

Lintner et al. (2013) developed an idealized prototype for diagnosing large-scale land-atmosphere coupling constructed from the idealized temperature and moisture equations used in developing the convective margins model described, but further coupled to a simple bucket soil moisture model. From this model, [*Lintner et al.*, 2013] derived an analytic expression for the sensitivity of precipitation to soil moisture variation from which it is possible to infer dependences on key model parameters, such as the timescale for convective adjustment (assumed in the Betts and Miller-type convection scheme applied), cloud-radiative feedback strength, and surface turbulent flux exchange. [*Schaefli et al.*, 2012] developed a conceptually similar model from which an analytic expression for the ratio of evaporated moisture integrated along flow path to precipitation (or recycling ratio) was obtained (Figure 16). We suggest that such idealized model frameworks, which consider tropical land-atmosphere interactions by coupling both water and energy cycles, should continue to be brought to bear on observations as well as more sophisticated regional or global climate or earth system models, as they can be helpful in diagnosing linkages between local and non-local feedbacks.

4.1.2 Coupling

[*Green et al.*, 2017] recently developed a method to define the feedback between the biosphere and atmosphere using multivariate conditional Granger causality (based on lagged autoregressive vectors). We here use a similar framework using ET from WECANN and precipitation from GPCP as well as photosynthetically active radiation from CERES (Figure 18).

Most of the feedback between surface ET and precipitation occurs in the spatial transitional, Monsoonal regions, such as the Savanna region of Northeastern Brazil, the Monsoonal region of the Sahel and Southern Africa, as well as India and Northern Australia. In Brazil, these results are consistent with the above-mentioned concept of convective margin and the impact of soil moisture and transpiration rate on the location of the transition between the dry and wet regions. The Sahelian and Southern African Monsoon are also located in regions between very dry (deserts) and humid regions, where surface feedback may be crucial for the penetration of the Monsoonal flow inland [*Lintner and Neelin*, 2009; *Lintner et al.*, 2015]. Indeed, the biosphere in this region modulates the local climate state: multiple equilibrium states, corresponding to different ecosystem initial conditions, exist under the same external forcing [*Wang et al.*, 2000]. The effect of vegetation on land-atmosphere coupling manifests itself at multiple timescales. At short timescales after precipitation, evaporation is accelerated with intercepted water in the canopy. However, at longer timescales vegetation acts to delay and prolong evaporation of water stored in the root zone. The magnitude and timescale of

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Discussions
Open Access

these sources of water recycling will vary depending on ecosystem structure, including rooting depth and canopy structure, which may co-evolve with atmospheric conditions at the interannual timescale [*Nicholson*, 2000]. This represents a clear pathway for two-way feedbacks between the land surface and precipitation.

We further emphasize that those feedbacks (Figure 18) are likely to also be influenced by non-local conditions, with regional and large-scale changes in ocean to land flow and the in-land distance of penetration influencing local coupling. We note that climate models seem to exhibit soil moisture (and therefore evapotranspiration)- precipitation feedbacks in similar tropical regions, when averaged across models, even though individual model response varies [*Koster et al.*, 2011; *Seneviratne*, 2013] (one degree pixel and monthly time scales). We emphasize that the PAR radiation product is very uncertain in the tropics [*Jim nez et al.*, 2011] as it ultimately relies on a model to obtain surface incoming radiation, which might explain the reduced feedback strength. It is also likely that the bulk of the radiative feedbacks are taking place at smaller times scales such as the ones observed with MODIS (Figure 14). This shallow cloud cover is relatively steady spatially and in time, especially in the dry season.

4.1.3 Moisture tracking and source attribution

A fundamental consideration in the study of the hydrologic cycle over tropical continents is where the moisture for precipitation ultimately derives. As [*van der Ent et al.*, 2010; *van der Ent and Tuinenburg*, 2017] note, this consideration is not merely of academic interest: indeed, it is quite likely that anthropogenic modification of the land surface has altered terrestrial evapotranspiration (as well as runoff) to impact precipitation. A common approach to moisture source attribution over tropical land regions involves deriving air mass histories using Lagrangian trajectories. Such trajectories are obtained by temporally integrating the 3-dimensional wind field to estimate the positions of idealized air mass parcels through time. Trajectories can be computed in either a forward or backward sense: the latter are initialized from an arrival point and integrated backward through time. Combining a Lagrangian back trajectory approach with rainfall and leaf area index data, [*Spracklen et al.*, 2012] quantified the linkage between downstream rainfall amount and upstream air mass exposure to vegetation (Figure 17). Over more than half of the tropical land surface, the Spracklen et al. estimates indicate a twofold increase in downstream rainfall for those air masses

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

passing over extensive vegetation compared those passing over little upstream vegetation. Based on these estimates and extrapolating current Amazonian deforestation trends in the future, these authors project wet and dry season rainfall decreases of 12 and 21%, respectively, by the year 2050.

Other analyses using air mass histories have demonstrated the significance of terrestrial E sources for remote land regions. For example, [*Drumond et al.*, 2014] used the FLEXPART model forced with ERA-Interim reanalysis to estimate $E - P$ along trajectories passing over the La Plata Basin in subtropical South America to establish that much of the moisture entering this region derives from the Amazon Basin to the north and west.

4.1.4 Seasonality and seasonal transitions

One of the outstanding issues in the study of tropical land region climates involves controls on precipitation seasonality, particularly its regional variability. To leading order, the seasonality follows the variation in maximum solar heating, but other factors, such as ocean thermal inertia, topography, dynamics and circulation, and moisture transport, as well as the state of the land surface, can exert considerable influence on the timing and amplitude of tropical land region seasonal evolution. Over the Amazon basin, seasonality exhibits marked variation in both latitude and longitude: for example, at 5S, the dry-to-west transition proceeds from the central Amazon eastward toward the Atlantic coast [*Liebmann and Marengo*, 2001]. It is also worth noting a pervasive tendency for the dry-to-wet season transition to occur much more rapidly than the wet-to-dry transition, as evident in tropical monsoon systems including South Asia, West Africa, and South America.

Analyzing multiple observational and reanalysis products, [*Fu and Li*, 2004] identified a strong influence of surface turbulent fluxes on the dry-to-wet transition and its interannual variability over the Amazon. In particular, their results link earlier wet season onset to wetter conditions in the antecedent dry season: the higher latent fluxes at the end of a wetter dry season encourage weaker convective inhibition (CIN) but enhanced CAPE, both of which are more favorable to wet season rainfall occurrence. However, these authors also underscore the participation of the large-scale circulation and its role in establishing a background environment (e.g., moisture convergence) to support wet season rainfall. Incursion of cold fronts into the southern Amazon may act as triggers for rapid initiation of wet season onset once the local thermodynamics become favorable [*Li et al.*, 2006].

Recent researches suggest that the land-atmospheric coupling plays a central role in determining the earlier timing of the wet season onset over western and southern Amazonia, relative to that of eastern Amazonia. Both in situ and satellite ecological observations have consistently shown that rainforests increase their photosynthesis, thus evapotranspiration (ET), during late dry season across Amazonia (e.g., [*Huete et al.*, 2006; *Lopes et al.*, 2016; *Munger et al.*, 2016; *Wehr et al.*, 2016]). The wet season onset over the southern hemispheric western and southern Amazonia occurs during September to October, about two to three months before the arrival of the Atlantic ITCZ [*Fu et al.*, 2016]. Using several satellite measurements, including deuterium (HDO) of the atmospheric water vapor and SIF, Wright et al (2017) have shown that such an increase of ET in the late dry season is the primary source of increasing water vapor in the lower troposphere that initiates the increase of deep convection and rainfall over southern Amazonia. In particular, the increase of water vapor with enriched HDO in the boundary layer and free troposphere, follows the increase of photosynthesis during late dry season. The HDO value of the atmospheric moisture is too high to be explained by transport from Atlantic Ocean, and is consistent with that from plant transpiration. Such a moistening of the atmosphere starts in western southern Amazonia, the part of Amazonia that is most remote from the Atlantic Ocean with high biomass. It then progresses towards eastern southern Amazonia. Thus, during the late dry season this appears to contribute to the timing and spatial variation of the initial moistening of the atmosphere, that ultimately lead to wet season onset over southern Amazonia.

Wet season onset over southern Amazonia has been delaying since the late 1970s [*Marengo et al.*, 2011; *Fu et al.*, 2013]. In addition to the influence of global circulation change, such a change has been attributed to land use. For example, [*Butt et al.*, 2011] have compared long-term rainfall data between deforested and forested areas over part of the southern Amazonia. They observed a significant delay in wet season onset over the deforested areas, consistent with that implied by Wright et al. (2017). In addition, [*Zhang et al.*, 2008; 2009] have shown that biomass burning aerosols, which peak in late dry season, can also weaken and delay dry to wet season transition by stabilizing the atmosphere, reducing clouds and rainfall.

5 Discussion - conclusions

In this review paper, we have discussed some of the important aspects of land-atmosphere interactions pertaining to the tropics. This review article is by no means exhaustive but rather provides insights into some of the important coupled land-atmosphere processes at play in the tropics and in rainforest ecosystems in particular.

We have argued that feedbacks between the land surface and precipitation in the tropics are possibly non-local in nature and mostly impact moisture advection from the ocean and the position of deep convection onset. Local rainfall feedback associated with mesoscale heterogeneities appear to be rather small in magnitude, at least compared to the annual-mean rainfall, and not sufficiently spatially systematic to truly affect ecosystem functioning.

Moreover, we contend that land surface-cloud feedbacks, especially those involving shallow clouds and fog, are critical in terms of regulating light (direct and diffuse), temperature, and water vapor deficit over tropical forest, but such feedbacks have received relatively little attention. Remote sensing platforms provide useful information for quantifying such feedbacks, but these need to be complemented by ground measurements (especially of photosynthetic rates and respiration). Eddy-covariance measurements may prove difficult to use, as mesoscale circulations alter the homogeneity assumption of eddy-covariance methods.

We have also discussed errors and biases in the representation of tropical continental climates in current generation climate and Earth system models. The average soil moisture-precipitation feedback strength across earth system models (based on the GLACE experiment) [*Koster et al.*, 2004] tend to exhibit land-precipitation feedbacks in similar transitional regions as the ones observed, which seems to be mostly related to modification of the moisture advection penetration distance from the ocean rather than to local feedbacks. These feedbacks appear to be of relatively minor importance in the core of tropical rainforests but are more critical for more marginal rainfall regions (savanna). These regions are of critical importance for the terrestrial global carbon cycle, providing the main terrestrial sink, but might be severely impacted by climate change and droughts

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Discussions

in particular [*Laan Luijkx et al.*, 2015]. Whether the interannual variability in surface CO_2 flux in those regions is a zero-sum game with wet years compensating dry years still is an open question especially in the context of rising CO_2 concentration.

The core of rainforests seems to be more affected by radiation feedbacks at relatively small spatial scales (~1km), which can be dramatically influenced by land cover and land use change. Projected rates of future deforestation are poorly constrained, especially regionally, though in recent years, the Congo and Indonesia have experienced increasing deforestation while the deforestation rate in the Amazon has dropped.

Earth system models tend to predict very diverse responses to global warming leading to broad spread in the capacity of rainforests to continue to act as net carbon sinks [*Swann et al.*, 2015] in the future. Indeed, in the Amazon in particular, the models' response varies from becoming much drier to more humid. El Niño events are sometimes thought as a proxy of global warming in the tropics [*Pradipta et al.*, 2016] as they warm the free-troposphere. Nonetheless for continents the change in the Walker circulation associated with El Niño may strongly differ from the change associated with a more uniform sea surface temperature warming in future climate. In particular, mature El Niño events are associated with strong subsidence over Indonesia, increased ascent off the coast of Peru but reduced precipitation over the Amazon basin and a relatively neutral response over the Congo basin. With SST warming across the tropics, the Maritime continent will most likely become wetter [*Byrne and O'Gorman*, 2015; *Wills et al.*, 2016]. The fate of the Amazon basin is less clear, as the climate in the region will be impacted by a combination of free tropospheric warming stabilizing the atmosphere to deep convection while warming of the Atlantic enhances the low-level MSE of inflow into the basin. Additionally, warming-induced changes to large-scale circulation such as the intensity or orientation of low-level Atlantic trade winds could impact Amazonian precipitation change. Knowledge of the Congo basin remains limited but it appears that the basin will become dryer under the combined effect of increased temperature and reduced precipitation [*Greve et al.*, 2014]. One important question involves how the effect of rising [CO_2] modifies surface energy flux partitioning though changes in stomatal physiology and modify the regional climate though land-atmosphere interactions [*Lemordant*, 2016].

Acknowledgments. This work was supported by Pierre Gentine's new investigator grant NNX14AI36G, DOE Early Career grant DE-SC0014203, NSF CAREER and GoAmazon DE-SC0011094. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

REFERENCES

Acevedo, O. C., O. L. L. Moraes, R. da Silva, D. R. Fitzjarrald, R. K. Sakai, R. M. Staebler, and M. J. Czikowsky, Inferring nocturnal surface fluxes from vertical profiles of scalars in an Amazon pasture, *Global Change Biol*, *10*(5), 886–894, doi:10.1111/j.1529-8817.2003.00755.x, 2004.

Alemohammad, S. H., B. Fang, A. G. Konings, F. Aires, J. K. Green, J. Kolassa, D. Miralles, C. Prigent, and P. Gentine, Water, Energy, and Carbon with Artificial Neural Networks (WECANN): a statistically based estimate of global surface turbulent fluxes and gross primary productivity using solar-induced fluorescence, *Biogeosciences*, *14*(18), 4101–4124, doi:10.5194/bg-14-4101-2017, 2017.

Alemohammad, S. H., B. Fang, A. G. Konings, J. K. Green, J. Kolassa, C. Prigent, F. Aires, D. Miralles, and P. Gentine, Water, Energy, and Carbon with Artificial Neural Networks (WECANN): A statistically-based estimate of global surface turbulent fluxes using solar-induced fluorescence,, 1–36, doi:10.5194/bg-2016-495, 2016.

Alexander, J. N., J. R. Peter, and N. K. Ernest, Assimilating solar-induced chlorophyll fluorescence into the terrestrial biosphere model BETHY-SCOPE: Model description and information content, *geosci-model-dev-discuss.net*, doi:10.5194/gmd-2017-34, 2017.

Anber, U., P. Gentine, S. Wang, and A. H. Sobel, Fog and rain in the Amazon, *Proceedings of the National Academy of Sciences*, *112*(37), 11473–11477, doi:10.1073/pnas.1505077112, 2015.

Anber, U., S. Wang, and A. Sobel, Effect of Surface Fluxes versus Radiative Heating on Tropical Deep Convection, *Journal of Atmospheric Sciences*, *72*(9), 3378–3388, doi:10.1175/JAS-D-14-0253.1, 2015.

Andreae, M.O., Artaxo, P., Brandao, C., Carswell, F.E., Ciccioli, P., Da Costa, A.L., Culf, A.D., Esteves, J.L., Gash, J.H.C., Grace, J. and Kabat, P., Biogeochemical cycling of carbon, water, energy, trace gases, and aerosols in Amazonia: The LBA-

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

EUSTACH experiments, *J Geophys Res-Atmos*, *107*(D20), doi:10.1029/2001JD000524, 2002.

Andreasen, M., K. H. Jensen, D. Desilets, M. Zreda, H. Bogena, and M. C. Looms, Can canopy interception and biomass be inferred from cosmic-ray neutron intensity? Results from neutron transport modeling,, 1–42, doi:10.5194/hess-2016-226, 2016

Avissar, R., and C. Nobre, Preface to special issue on the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), *J Geophys Res-Atmos*, *107*, –, doi:10.1029/2002JD002507, 2002

Avissar, R., and R. A. Pielke, A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology, *Mon Wea Rev.*, 1989.

Avissar, R., and T. Schmidt, An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using large-eddy simulations, *J Atmos Sci*, *55*(16), 2666–2689, 1998.

Avissar, R., P. Dias, M. Dias, and C. Nobre, The Large-Scale Biosphere-atmosphere Experiment in Amazonia (LBA): Insights and future research needs, *J Geophys Res-Atmos*, *107*(D20), doi:10.1029/2002JD002704, 2002.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R. and Fuentes, J.,FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bull. Amer. Meteor. Soc.*, *82*(11), 2415–2434, 2001.

Ballantyne, A., Smith, W., Anderegg, W., Kauppi, P., Sarmiento, J., Tans, P., Shevliakova, E., Pan, Y., Poulter, B., Anav, A. and Friedlingstein, P., Accelerating net terrestrial carbon uptake during the warming hiatus due to reduced respiration, *Nature Climate Change*, *7*(2), 148–152, doi:10.1038/nclimate3204, 2017.

Balsamo, G., A. Beljaars, K. Scipal, P. Viterbo, B. van den Hurk, M. Hirschi, and A. K. Betts, A Revised Hydrology for the ECMWF Model: Verification from Field Site to

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Terrestrial Water Storage and Impact in the Integrated Forecast System, *J Hydrometeorol*, *10*(3), 623–643, doi:10.1175/2008JHM1068.1, 2009.

Barbaro, E., and J. Arellano, Aerosols in the convective boundary layer: Shortwave radiation effects on the coupled land-atmosphere system , *J of Climate*, doi:10.1002/(ISSN)2169-8996., 2014

Bechtold, P., N. Semane, P. Lopez, J.-P. Chaboureau, A. Beljaars, and N. Bormann, Representing equilibrium and non-equilibrium convection in large-scale models, *J Atmos Sci*, *71*(2), 130919100122007–753, doi:10.1175/JAS-D-13-0163.1, 2013.

Bechtold, P., N. Semane, P. Lopez, J.-P. Chaboureau, A. Beljaars, and N. Bormann, Representing Equilibrium and Nonequilibrium Convection in Large-Scale Models, *J Atmos Sci*, *71*(2), 734–753, doi:10.1175/JAS-D-13-0163.1, 2014.

Betts, A. K., and M. A. F. Silva Dias, Progress in understanding land-surface-atmosphere coupling from LBA research, *J. Adv. Model. Earth Syst.*, *2*, 6, doi:10.3894/JAMES.2010.2.6, 2010.

Betts, A. K., L. V. Gatti, and A. M. Cordova, Transport of ozone to the surface by convective downdrafts at night, *J of Climate,* 2002.

Boisier, J. P., P. Ciais, A. Ducharne, and M. Guimberteau, Projected strengthening of Amazonian dry season by constrained climate model simulations, *Nature Climate Change*, *5*(7), 656–660, doi:10.1038/nclimate2658, 2015.

Bonan, G. B., K. W. Oleson, and R. A. Fisher, Reconciling leaf physiological traits and canopy flux data: Use of the TRY and FLUXNET databases in the Community Land Model version 4 , *J of Climate*, 2012.

Bonan, G. B., P. J. Lawrence, K. W. Oleson, S. Levis, M. Jung, M. Reichstein, D. M. Lawrence, and S. C. Swenson, Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data, *J Geophys Res-Biogeo*, *116*, 1–22, doi:10.1029/2010JG001593, 2011.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Boone, A., De Rosnay, P., Balsamo, G., Beljaars, A., Chopin, F., Decharme, B., Delire, C., Ducharne, A., Gascoin, S., Grippa, M. and Guichard, F., The AMMA Land Surface Model Intercomparison Project (ALMIP), *Bull. Amer. Meteor. Soc.*, *90*(12), 1865–1880, doi:10.1175/2009BAMS2786.1, 2009.

Boone, A., A. Getirana, J. Demarty, and B. Cappelaere, The African Monsoon Multidisciplinary Analyses (AMMA) Land surface Model Intercomparison Project Phase 2 (ALMIP2), *GEWEX News*, 2009

Boulet, G., A. Chehbouni, P. Gentine, B. Duchemin, J. Ezzahar, and R. Hadria, Monitoring water stress using time series of observed to unstressed surface temperature difference, *Agr Forest Meteorol*, *146*, 159–172, doi:10.1016/j.agrformet.2007.05.012, 2007.

Böing, S. J., H. J. J. Jonker, A. P. Siebesma, and W. W. Grabowski, Influence of the Subcloud Layer on the Development of a Deep Convective Ensemble, *J Atmos Sci*, *69*(9), 2682–2698, doi:10.1175/JAS-D-11-0317.1, 2012.

Bretherton, C. S., and S. Park, A New Moist Turbulence Parameterization in the Community Atmosphere Model, *J Climate*, *22*(12), 3422–3448, doi:10.1175/2008JCLI2556.1, 2009.

Brodribb, T. J. Stomatal Closure during Leaf Dehydration, Correlation with Other Leaf Physiological Traits, *Plant Physiol*, *132*(4), 2166–2173, doi:10.1104/pp.103.023879, 2003.

Butt, N., P. A. de Oliveira, and M. H. Costa, Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil, *Journal of Geophysical Research: Atmospheres (1984–2012)*, *116*(D11), 407, doi:10.1029/2010JD015174, 2011.

Byrne, M. P., and P. A. O'Gorman, The Response of Precipitation Minus Evapotranspiration to Climate Warming: Why the "'Wet-Get-Wetter, Dry-Get-Drier'" Scaling Does Not Hold over Land, *J Climate*, doi:10.1175/JCLI-D-15-0369.s1, 2015.

Campos, J. G., O. C. Acevedo, J. Tota, and A. O. Manzi, On the temporal scale of the turbulent exchange of carbon dioxide and energy above a tropical rain forest in Amazonia, *J Geophys Res*, *114*(D8), D08124–10, doi:10.1029/2008JD011240., 2009

Canal, N., J. C. Calvet, B. Decharme, D. Carrer, S. Lafont, and G. Pigeon, Evaluation of root water uptake in the ISBA-A-gs land surface model using agricultural yield statistics over France, *Hydrol Earth Syst Sc*, *18*(12), 4979–4999, doi:10.5194/hess-18-4979-2014-supplement, 2014.

Chagnon, F. J. F., R. L. Bras, and J. Wang, Climatic shift in patterns of shallow clouds over the Amazon, *Geophys Res Lett*, *31*(24), L24212, doi:10.1029/2004GL021188, 2004.

Chaney, N. W., J. D. Herman, M. B. Ek, and E. F. Wood, Deriving Global Parameter Estimates for the Noah Land Surface Model using FLUXNET and Machine Learning, *J Geophys Res-Atmos*, 1–41, doi:10.1002/2016JD024821, 2016.

Chen, Y., Ryder, J., Bastrikov, V., McGrath, M.J., Naudts, K., Otto, J., Ottlé, C., Peylin, P., Polcher, J., Valade, A. and Black, A., Evaluating the performance of land surface model ORCHIDEE-CAN v1.0 on water and energy flux estimation with a single- and multi-layer energy budget scheme, *Geosci Model Dev*, *9*(9), 2951–2972, doi:10.5194/gmd-9-2951-2016, 2016.

Chor, T. L., N. L. Dias, A. Araújo, S. Wolff, E. Zahn, A. Manzi, I. Trebs, M. O. Sá, P. R. Teixeira, and M. Sörgel, Flux-variance and flux-gradient relationships in the roughness sublayer over the Amazon forest, *Agr Forest Meteorol*, *239*, 213–222, doi:10.1016/j.agrformet.2017.03.009, 2017.

Cook, B. I., S. P. Shukla, M. J. Puma, and L. S. Nazarenko, Irrigation as an historical climate forcing, *Climate dynamics*, *44*(5-6), 1715–1730, doi:10.1007/s00382-014-2204-7, 2014.

Couvreux, F., Roehrig, R., Rio, C., Lefebvre, M.P., Caian, M., Komori, T., Derbyshire, S., Guichard, F., Favot, F., D'Andrea, F. and Bechtold, P., Representation of daytime moist convection over the semi-arid Tropics by parametrizations used in climate and

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

meteorological models, *Q J Roy Meteor Soc*, *141*(691), 2220–2236, doi:10.1002/qj.2517, 2015.

Couvreux, F., C. Rio, and F. Guichard, Initiation of daytime local convection in a semi-arid region analysed with high-resolution simulations and AMMA observations - Quarterly Journal of the Royal Meteorological Society, 2011

Couvreux, F., C. Rio, F. Guichard, M. Lothon, G. Canut, D. Bouniol, and A. Gounou, Initiation of daytime local convection in a semi-arid region analysed with high-resolution simulations and AMMA observations, *Q J Roy Meteor Soc*, *138*(662), 56–71, doi:10.1002/qj.903, 2011.

Da Rocha, H. R. et al., Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil, *J Geophys Res*, *114*, G00B12, doi:10.1029/2007JG000640, 2009.

Daleu, C. L., S. J. Woolnough, and R. S. Plant (2012), Cloud-Resolving Model Simulations with One- and Two-Way Couplings via the Weak Temperature Gradient Approximation, *J Atmos Sci*, *69*(12), 3683–3699, doi:10.1175/JAS-D-12-058.1.

Daleu, C. L., S. J. Woolnough, and R. S. Plant, Transition from suppressed to active convection modulated by a weak-temperature gradient derived large-scale circulation, *J Atmos Sci*, 141023140130007, doi:10.1175/JAS-D-14-0041.1, 2014.

Dalu, G. A., R. A. Pielke, M. Baldi, and X. Zeng, Heat and momentum fluxes induced by thermal inhomogeneities with and without large-scale flow, *Journal of the atmospheric Science,* 1996.

Davidson, E.A., de Araújo, A.C., Artaxo, P., Balch, J.K., Brown, I.F., Bustamante, M.M., Coe, M.T., DeFries, R.S., Keller, M., Longo, M. and Munger, J.W., The Amazon basin in transition, *Nature*, *481*(7381), 321–328, doi:10.1038/nature10717, 2012

de Arellano, J. V.-G., H. G. Ouwersloot, D. Baldocchi, and C. M. J. Jacobs, Shallow cumulus rooted in photosynthesis, *Geophys Res Lett*, doi:10.1002/2014GL059279, 2014.

De Kauwe, M. G., J. Kala, Y. S. Lin, A. J. Pitman, B. E. Medlyn, R. A. Duursma, G. Abramowitz, Y. P. Wang, and D. G. Miralles, A test of an optimal stomatal conductance scheme within the CABLE land surface model, *Geosci Model Dev*, *8*(2), 431–452, doi:10.5194/gmd-8-431-2015, 2015.

Del Genio, A. D., and J. Wu, The Role of Entrainment in the Diurnal Cycle of Continental Convection, *J Climate*, *23*(10), 2722–2738, doi:10.1175/2009JCLI3340.1, 2010.

Domec, J.-C., J. S. King, A. Noormets, E. Treasure, M. J. Gavazzi, G. Sun, and S. G. McNulty, Hydraulic redistribution of soil water by roots affects whole-stand evapotranspiration and net ecosystem carbon exchange, *New Phytologist*, *187*(1), 171–183, doi:10.1111/j.1469-8137.2010.03245.x, 2010.

Doughty, C.E., Metcalfe, D.B., Girardin, C.A.J., Amézquita, F.F., Cabrera, D.G., Huasco, W.H., Silva-Espejo, J.E., Araujo-Murakami, A., Da Costa, M.C., Rocha, W. and Feldpausch, T.R., Drought impact on forest carbon dynamics and fluxes in Amazonia, *Nature*, *519*(7541), 78–82, doi:10.1038/nature14213, 2015.

Drager, A. J., and S. C. van den Heever, Characterizing convective cold pools, *J. Adv. Model. Earth Syst.*, 1–55, doi:10.1002/2016MS000788, 2017.

Drumond, A., J. Marengo, T. Ambrizzi, R. Nieto, L. Moreira, and L. Gimeno, The role of the Amazon Basin moisture in the atmospheric branch of the hydrological cycle: a Lagrangian analysis, *Hydrol Earth Syst Sc*, *18*(7), 2577–2598, doi:10.5194/hess-18-2577-2014, 2014.

Du, S., L. Liu, X. Liu, and J. Hu, Response of Canopy Solar-Induced Chlorophyll Fluorescence to the Absorbed Photosynthetically Active Radiation Absorbed by Chlorophyll, *Remote Sensing*, *9*(9), 911–19, doi:10.3390/rs9090911, 2017.

Duveiller, G., and A. Cescatti, Spatially downscaling sun-induced chlorophyll fluorescence leads to an improved temporal correlation with gross primary productivity, *Remote Sensing of Environment*, *182*(C), 72–89, doi:10.1016/j.rse.2016.04.027, 2016.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

D'Andrea, F., P. Gentine, and A. K. Betts, Triggering deep convection with a probabilistic plume model, *J Atmos Sci*, *71*(11), 3881–3901, doi:10.1175/JAS-D-13-0340.1, 2014.

Ek, M. B., Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J Geophys Res*, *108*(D22), 8851, doi:10.1029/2002JD003296, 2003.

Engerer, N. A., D. J. Stensrud, and M. C. Coniglio, Surface Characteristics of Observed Cold Pools, *Mon Wea Rev*, *136*(12), 4839–4849, doi:10.1175/2008MWR2528.1, 2008.

Feingold, G., H. L. Jiang, and J. Y. Harrington, On smoke suppression of clouds in Amazonia, *Geophys Res Lett*, *32*(2), doi:10.1029/2004GL021369, 2005.

Feng, Z., S. Hagos, A. K. Rowe, C. D. Burleyson, M. N. Martini, and S. P. de Szoeke, Mechanisms of convective cloud organization by cold pools over tropical warm ocean during the AMIE/DYNAMO field campaign, *J. Adv. Model. Earth Syst.*, *7*(2), 357–381, doi:10.1002/2014MS000384, 2015.

Fisher, J.B., Malhi, Y., Bonal, D., Da Rocha, H.R., De Araujo, A.C., Gamo, M., Goulden, M.L., Hirano, T., Huete, A.R., Kondo, H. and Kumagai, T.O., The land-atmosphere water flux in the tropics, *Global Change Biol*, *15*(11), 2694–2714, doi:10.1111/j.1365-2486.2008.01813.x, 2009.

Fisher, R. A., M. Williams, R. L. Do Vale, A. L. Da Costa, and P. Meir, Evidence from Amazonian forests is consistent with isohydric control of leaf water potential, *Plant Cell Environ*, *29*(2), 151–165, 2006.

Fitzjarrald, D. R., Turbulent trasnport just above the Amazon, *J Geophys Res-Atmos*, 1–13, 2007.

Frankenberg, C., Fisher, J.B., Worden, J., Badgley, G., Saatchi, S.S., Lee, J.E., Toon, G.C., Butz, A., Jung, M., Kuze, A. and Yokota, T., New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

primary productivity, *Geophys Res Lett*, *38*(17), n/a–n/a, doi:10.1029/2011GL048738, 2011.

Frankenberg, C., C. O'Dell, J. Berry, L. Guanter, J. Joiner, P. Köhler, R. Pollock, and T. E. Taylor, Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2, *Remote Sensing of Environment*, *147*(C), 1–12, doi:10.1016/j.rse.2014.02.007, 2014.

Frankenberg, C., C. O'Dell, L. Guanter, and J. McDuffie, Remote sensing of near-infrared chlorophyll fluorescence from space in scattering atmospheres: implications for its retrieval and interferences with atmospheric CO_2 retrievals, *Atmos Meas Tech*, *5*(8), 2081–2094, doi:10.5194/amt-5-2081-2012, 2012.

Fu, R., and W. Li, The influence of the land surface on the transition from dry to wet season in Amazonia, *Theor Appl Climatol*, *78*(1-3), 97–110, doi:10.1007/s00704-004-0046-7., 2004

Fu, R., L. Yin, W. Li, and P. A. Arias, Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection, 2013.

Fu, R., P. A. Arias, and H. Wang, The Connection Between the North and South American Monsoons, *The Monsoons and Climate Change*, 2016

Garstang, M., and D. R. Fitzjarrald, *Observations of surface to atmosphere interactions in the tropics*., 1999

Gatti, L.V., Gloor, M., Miller, J.B., Doughty, C.E., Malhi, Y., Domingues, L.G., Basso, L.S., Martinewski, A., Correia, C.S.C., Borges, V.F. and Freitas, S., Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements, *Nature*, *506*(7486), 76–80, doi:10.1038/nature12957, 2015.

Gentine, P., A. Garelli, S. B. Park, and J. Nie, Role of surface heat fluxes underneath cold pools, *Geo Res Letters*, *43*(2), 874–883, doi:10.1002/2015GL067262, 2016.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Gentine, P., A. Holtslag, and F. D'Andrea, Surface and atmospheric controls on the onset of moist convection over land, *J Hydrometeorol*, *14*(5), 1443–1462, doi:10.1175/JHM-D-12-0137.1, 2013.

Gentine, P., C. R. Ferguson, and A. A. M. Holtslag, Diagnosing evaporative fraction over land from boundary-layer clouds, *J Geophys Res-Atmos*, *118*(15), 8185–8196, doi:10.1002/jgrd.50416, 2013.

Gentine, P., D. Entekhabi, A. Chehbouni, G. Boulet, and B. Duchemin, Analysis of evaporative fraction diurnal behaviour, *Agr Forest Meteorol*, *143*, 13–29, doi:10.1016/j.agrformet.2006.11.002, 2007.

Gerken, T., Ruddell, B.L., Fuentes, J.D., Araújo, A., Brunsell, N.A., Maia, J., Manzi, A., Mercer, J., dos Santos, R.N., von Randow, C. and Stoy, P.C.,, Investigating the mechanisms responsible for the lack of surface energy balance closure in a central Amazonian tropical rainforest, *Agr Forest Meteorol*, 1–0, doi:10.1016/j.agrformet.2017.03.023, 2017.

Ghate, V. P., and P. Kollias, On the controls of daytime precipitation in the Amazonian dry season, *J Hydrometeorol*, JHM–D–16–0101.1–55, doi:10.1175/JHM-D-16-0101.1, 2016.

Giangrande, S. E. et al., Cloud Characteristics, Thermodynamic Controls and Radiative Impacts During the Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) Experiment, *Atmos. Chem. Phys. Discuss.*, 1–41, doi:10.5194/acp-2017-452, 2017.

Goulden, M. L., S. D. Miller, and H. R. da Rocha, Diel and seasonal patterns of tropical forest CO2 exchange, *Ecological , 2004*

Green, J. K., A. G. Konings, S. H. Alemohammad, J. Berry, D. Entekhabi, J. Kolassa, J.-E. Lee, and P. Gentine, Regionally strong feedbacks between the atmosphere and terrestrial biosphere, *Nat Geosci*, *48*, 1–12, doi:10.1038/ngeo2957, 2017.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Greve, P., B. Orlowsky, B. Mueller, J. Sheffield, M. Reichstein, and S. I. Seneviratne, Global assessment of trends in wetting and drying over land, *Nat Geosci*, *7*(10), 716–721, doi:10.1038/ngeo2247, 2014.

Guanter, L., Zhang, Y., Jung, M., Joiner, J., Voigt, M., Berry, J.A., Frankenberg, C., Huete, A.R., Zarco-Tejada, P., Lee, J.E. and Moran, Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence, *PNAS*, *111*(14), E1327–E1333, doi:10.1073/pnas.1320008111, 2014.

Guichard, F., Petch, J.C., Redelsperger, J.L., Bechtold, P., Chaboureau, J.P., Cheinet, S., Grabowski, W., Grenier, H., Jones, C.G., Köhler, M. and Piriou, J.M., Modelling the diurnal cycle of deep precipitating convection over land with cloud-resolving models and single-column models, *Q J Roy Meteor Soc*, *130*(604), 3139–3172, doi:10.1256/qj.03.145, 2004.

Guillod, B.P., Orlowsky, B., Miralles, D., Teuling, A.J., Blanken, P.D., Buchmann, N., Ciais, P., Ek, M., Findell, K.L., Gentine, P. and Lintner, B.R., Land-surface controls on afternoon precipitation diagnosed from observational data: uncertainties and confounding factors, *Atmos. Chem. Phys*, *14*(16), 8343–8367, doi:10.5194/acp-14-8343-2014-supplement, 2014.

Guillod, B. P., B. Orlowsky, D. G. Miralles, A. J. Teuling, and S. I. Seneviratne, Reconciling spatial and temporal soil moisture effects on afternoon rainfall, *Nat Comms*, *6*, 6443, doi:10.1038/ncomms7443, 2015.

H. G. Ouwersloot, M. Sikma, C. M. J. Jacobs, J. V.-G. de Arellano, X. Pedruzo-Bagazgoitia, M. Sikma, and C. C. van Heerwaarden, Direct and Diffuse Radiation in the Shallow Cumulus–Vegetation System: Enhanced and Decreased Evapotranspiration Regimes, *J Hydrometeorol*, *18*(6), 1731–1748, doi:10.1175/JHM-D-16-0279.1, 2017.

Hadden, D., and A. Grelle, Changing temperature response of respiration turns boreal forest from carbon sink into carbon source, *Agr Forest Meteorol*, *223*, 30–38, doi:10.1016/j.agrformet.2016.03.020, 2016.

Hydrology and Earth System Sciences
Open Access
Discussions

Hamada, J.-I., M. D. Yamanaka, S. Mori, Y. I. Tauhid, and T. Sribimawati, Differences of Rainfall Characteristics between Coastal and Interior Areas of Central Western Sumatera, Indonesia, *Journal of the Meteorological Society of Japan. Ser. II*, *86*(5), 593–611, doi:10.2151/jmsj.86.593, 2008.

Han, X., H.-J. H. Franssen, C. Montzka, and H. Vereecken, Soil moisture and soil properties estimation in the Community Land Model with synthetic brightness temperature observations, *Water resources Research*, n/a–n/a, doi:10.1002/2013WR014586, 2014.

Haverd, V., M. Cuntz, L. P. Nieradzik, and I. N. Harman, Improved representations of coupled soil-canopy processes in the CABLE land surface model, *Geosci. Model Dev. Discuss.*, 1–24, doi:10.5194/gmd-2016-37, 2016.

Grant, L. D., & van den Heever, S. C., Cold pool dissipation. *Journal of Geophysical Research: Atmospheres*, *121*(3), 1138-1155, 2016.

Heroult, A., Y. LIN, and A. Bourne, Optimal stomatal conductance in relation to photosynthesis in climatically contrasting Eucalyptus species under drought, *Plant Cell and Env*, doi:10.1111/j.1365-3040.2012.02570.x, 2013.

Hidayat, R., and S. Kizu, Influence of the Madden-Julian Oscillation on Indonesian rainfall variability in austral summer, *Int J Climatol*, *23*(12), n/a–n/a, doi:10.1002/joc.2005, 2009.

Hilker, T., A. I. Lyapustin, C. J. Tucker, F. G. Hall, R. B. Myneni, Y. Wang, J. Bi, Y. Mendes de Moura, and P. J. Sellers, Vegetation dynamics and rainfall sensitivity of the Amazon, *Proceedings of the National Academy of Sciences*, *111*(45), 16041–16046, doi:10.1073/pnas.1404870111, 2014.

Hohenegger, C., and C. S. Bretherton, Simulating deep convection with a shallow convection scheme, *Atmos. Chem. Phys*, *11*(20), 10389–10406, doi:10.5194/acp-11-10389-2011, 2011.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Horn, G. L., H. G. Ouwersloot, J. V.-G. de Arellano, and M. Sikma, Cloud Shading Effects on Characteristic Boundary-Layer Length Scales, *Bound-Lay Meteorol*, *157*(2), 237–263, doi:10.1007/s10546-015-0054-4, 2015.

Huang, R., and F. Sun, Impacts of the Tropical Western Pacific on the East Asian Summer Monsoon, *Journal of the Meteorological Society of Japan. Ser. II*, *70*(1B), 243–256, doi:10.2151/jmsj1965.70.1B_243, 1992.

Huete, A. R., K. Didan, Y. E. Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, and R. Myneni (2006), Amazon rainforests green-up with sunlight in dry season, *Geophys Res Lett*, *33*(6), L06405, doi:10.1029/2005GL025583, 2006.

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, Global precipitation at one-degree daily resolution from multisatellite observations, *J Hydrometeorol*, *2*(1), 36–50, doi:10.1175/1525-7541(2001)002<0036:GPAODD>2.0.CO;2, 2001.

Huijnen, V., M. J. Wooster, J. W. Kaiser, D. L. A. Gaveau, J. Flemming, M. Parrington, A. Inness, D. Murdiyarso, B. Main, and M. van Weele, Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997, *Sci. Rep.*, 1–8, doi:10.1038/srep26886, 2016.

Jardine, K., Chambers, J., Alves, E.G., Teixeira, A., Garcia, S., Holm, J., Higuchi, N., Manzi, A., Abrell, L., Fuentes, J.D. and Nielsen, L.K., Dynamic Balancing of Isoprene Carbon Sources Reflects Photosynthetic and Photorespiratory Responses to Temperature Stress, *Plant Physiol*, *166*(4), 2051–2064, doi:10.1104/pp.114.247494, 2014.

Jimenez, C., Prigent, C., Mueller, B., Seneviratne, S.I., McCabe, M.F., Wood, E.F., Rossow, W.B., Balsamo, G., Betts, A.K., Dirmeyer, P.A. and Fisher, J.B., Global intercomparison of 12 land surface heat flux estimates, *J Geophys Res*, *116*(D2), 1147–27, doi:10.1029/2010JD014545, 2011.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Joiner, J., A. P. Vasilkov, Y. Yoshida, L. A. Corp, and E. M. Middleton, First observations of global and seasonal terrestrial chlorophyll fluorescence from space, *Biogeosciences*, *8*(3), 637–651, doi:10.5194/bg-8-637-2011, 2011.

Joiner, J., L. Guanter, R. Lindstrot, M. Voigt, A. P. Vasilkov, E. M. Middleton, K. F. Huemmrich, Y. Yoshida, and C. Frankenberg, Global monitoring of terrestrial chlorophyll fluorescence from moderate-spectral-resolution near-infrared satellite measurements: methodology, simulations, and application to GOME-2, *Atmos Meas Tech*, *6*(10), 2803–2823, doi:10.5194/amt-6-2803-2013, 2013.

Juárez, R. I. N., M. G. Hodnett, R. Fu, M. L. Goulden, and C. von Randow, Control of Dry Season Evapotranspiration over the Amazonian Forest as Inferred from Observations at a Southern Amazon Forest Site, *J Climate*, *20*(12), 2827–2839, doi:10.1175/JCLI4184.1, 2007.

Jung, M., Reichstein, M., Schwalm, C.R., Huntingford, C., Sitch, S., Ahlström, A., Arneth, A., Camps-Valls, G., Ciais, P., Friedlingstein, P. and Gans, F., Compensatory water effects link yearly global land CO2 sink changes to temperature,, *541*(7638), 516–520, doi:10.1038/nature20780, 2017.

Kato, S., N. G. Loeb, F. G. Rose, D. R. Doelling, D. A. Rutan, T. E. Caldwell, L. Yu, and R. A. Weller, Surface Irradiances Consistent with CERES-Derived Top-of-Atmosphere Shortwave and Longwave Irradiances, *J Climate*, *26*(9), 2719–2740, doi:10.1175/JCLI-D-12-00436.1, 2013.

Keller, M., Alencar, A., Asner, G.P., Braswell, B., Bustamante, M., Davidson, E., Feldpausch, T., Fernandes, E., Goulden, M., Kabat, P. and Kruijt, B., Ecological Research in the Large-Scale Biosphere– Atmosphere Experiment in Amazonia: Early Results, *Ecol Appl*, *14*(sp4), 3–16, 2004.

Kennedy, D., P. Gentine, R. A. Fisher, and D. M. Lawrence, Implementation of plant hydraulics in the Community Land Model, *JAMES,* 2017.

Khairoutdinov, M., and D. Randall, High-resolution simulation of shallow-to-deep convection transition over land, *J Atmos Sci*, *63*(12), 3421–3436, 2006.

Khanna, J., D. Medvigy, S. Fueglistaler, and R. Walko, Regional dry-season climate changes due to three decades of Amazonian deforestation, *Nature Climate Change*, *7*(3), 200–204, doi:10.1038/nclimate3226, 2017.

Knox, R. G., M. Longo, A. L. S. Swann, K. Zhang, N. M. Levine, P. R. Moorcroft, and R. L. Bras, Hydrometeorological effects of historical land-conversion in an ecosystem-atmosphere model of Northern South America, *Hydrol Earth Syst Sc*, *19*(1), 241–273, doi:10.5194/hess-19-241-2015, 2015.

Konings, A. G., and P. Gentine, Global variations in ecosystem-scale isohydricity, *Global Change Biol*, doi:10.1111/gcb.13389, 2016.

Koren, I., Y. J. Kaufman, L. A. Remer, and J. V. Martins, Measurement of the effect of Amazon smoke on inhibition of cloud formation, *Science*, *303*(5662), 1342–1345, doi:10.1126/science.1089424, 2004.

Koster, R.D., Dirmeyer, P.A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C.T., Kanae, S., Kowalczyk, E., Lawrence, D. and Liu, P., Regions of strong coupling between soil moisture and precipitation, *Science*, *305*(5687), 1138–1140, 2004.

Koster, R.D., Dirmeyer, P.A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C.T., Kanae, S., Kowalczyk, E., Lawrence, D. and Liu, P., The Second Phase of the Global Land–Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill, *J Hydrometeorol*, *12*(5), 805–822, doi:10.1175/2011JHM1365.1, 2011.

Köppen, W., *The thermal zones of the Earth according to the duration of hot, moderate and cold periods and of the impact of heat on the organic world.(translated and …*, Meteorologische Zeitschrift, 1884.

Krakauer, N. Y., M. J. Puma, B. I. Cook, P. Gentine, and L. Nazarenko, Ocean-atmosphere interactions modulate irrigation's climate impacts,, 1–16, doi:10.5194/esd-2016-23, 2016.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Kuang, Z., Linear response functions of a cumulus ensemble to temperature and moisture perturbations and implications for the dynamics of convectively coupled waves, *J Atmos Sci,* 2010.

Kuang, Z., A Moisture-Stratiform Instability for Convectively Coupled Waves, *Journal of Atmospheric Sciences*, *65*(3), 834–854, doi:10.1175/2007JAS2444.1, 2008.

Laan-Luijkx, I.T., Velde, I.R., Krol, M.C., Gatti, L.V., Domingues, L.G., Correia, C.S.C., Miller, J.B., Gloor, M., Leeuwen, T.T., Kaiser, J.W. and Wiedinmyer, C., Response of the Amazon carbon balance to the 2010 drought derived with CarbonTracker South America, *Global Biogeochem Cy*, *29*(7), 1092–1108, doi:10.1002/2014GB005082, 2015.

Laurent, H., L. Machado, and C. A. Morales, Characteristics of the Amazonian mesoscale convective systems observed from satellite and radar during the WETAMC/LBA experiment, *J of Climate,* 2002.

Lawrence, D. M., K. W. Oleson, and M. G. Flanner, Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, *JAMES,* 2011

Lawrence, D., and K. Vandecar, Effects of tropical deforestation on climate and agriculture, *Nature Climate Change*, *5*(1), 27–36, doi:10.1038/nclimate2430, 2015.

Lawton, R. O., U. S. Nair, R. A. Pielke Sr, and R. M. Welch, Climatic Impact of Tropical Lowland Deforestation on Nearby Montane Cloud Forests, *Science*, *294*, 584–587, 2001.

Lebel, T., Cappelaere, B., Galle, S., Hanan, N., Kergoat, L., Levis, S., Vieux, B., Descroix, L., Gosset, M., Mougin, E. and Peugeot, C., AMMA-CATCH studies in the Sahelian region of West-Africa: An overview, *Journal of Hydrology*, *375*(1-2), 3–13, doi:10.1016/j.jhydrol.2009.03.020, 2009.

Lee, J. E., R. S. Oliveira, T. E. Dawson, and I. Fung, Root functioning modifies seasonal climate, *P Natl Acad Sci Usa*, *102*(49), 17576–17581, 2005.

Lee, J.-E., J. A. Berry, C. van der Tol, X. Yang, L. Guanter, A. Damm, I. Baker, and C. Frankenberg, Simulations of chlorophyll fluorescence incorporated into the Community Land Model version 4, *Global Change Biol*, n/a–n/a, doi:10.1111/gcb.12948, 2015.

Lemordant, L., Modification of land-atmosphere interactions by CO_2 effects: Implications for summer dryness and heat wave amplitude, *Geo Res Letters*, *43*(19), 10–240–10–248, doi:10.1002/2016GL069896, 2016.

Leuning, R., A critical appraisal of a combined stomatal-photosynthesis model for C3 plants, *Plant Cell and Env*, 1995.

Leuning, R., F. M. Kelliher, D. G. G. PURY, and E. D. Schulze, Leaf nitrogen, photosynthesis, conductance and transpiration: scaling from leaves to canopies, *Plant Cell Environ*, *18*(10), 1183–1200, doi:10.1111/j.1365-3040.1995.tb00628.x, 1995.

Levy, M. C., A. Cohn, A. V. Lopes, and S. E. Thompson, Addressing rainfall data selection uncertainty using connections between rainfall and streamflow, *Sci. Rep.*, *7*(1), 1–12, doi:10.1038/s41598-017-00128-5, 2017.

Li, W., R. Fu, and R. E. Dickinson, Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4, *Journal of Geophysical Research*, 2006.

Liebmann, B., and J. A. Marengo, Interannual variability of the rainy season and rainfall in the Brazilian Amazon basin, *J Climate*, *14*(22), 4308–4318, 2001.

Lintner, B. R., and J. Chiang, Reorganization of tropical climate during El Nino: A weak temperature gradient approach, *J Climate*, *18*(24), 5312–5329, 2005.

Lintner, B. R., and J. D. Neelin, A prototype for convective margin shifts, *Geophys Res Lett*, *34*(5), L05812, doi:10.1029/2006GL027305, 2007.

Lintner, B. R., and J. D. Neelin, Soil Moisture Impacts on Convective Margins, *J Hydrometeorol*, *10*(4), 1026–1039, doi:10.1175/2009JHM1094.1, 2009.

Lintner, B. R., P. Gentine, K. L. Findell, and G. D. Salvucci, The Budyko and complementary relationships in an idealized model of large-scale land–atmosphere coupling, *Hydrol Earth Syst Sc*, *19*(5), 2119–2131, doi:10.5194/hess-19-2119-2015, 2015.

Lintner, B. R., P. Gentine, K. L. Findell, F. D'Andrea, A. H. Sobel, and G. D. Salvucci, An idealized prototype for large-scale land-atmosphere coupling, *J Climate*, *26*(7), 2379–2389, doi:10.1175/JCLI-D-11-00561.1, 2013.

Liu, L., L. Guan, and X. Liu, Directly estimating diurnal changes in GPP for C3 and C4 crops using far-red sun-induced chlorophyll fluorescence, *Agr Forest Meteorol*, *232*, 1–9, doi:10.1016/j.agrformet.2016.06.014, 2017.

Lohou, F., F. Said, M. Lothon, P. Durand, and D. Serça, Impact of Boundary-Layer Processes on Near-Surface Turbulence Within the West African Monsoon, *Bound-Lay Meteorol*, *136*(1), 1–23, doi:10.1007/s10546-010-9493-0, 2010.

Lopes, A. P., B. W. Nelson, J. Wu, P. M. L. de Alencastro Graça, J. V. Tavares, N. Prohaska, G. A. Martins, and S. R. Saleska, Leaf flush drives dry season green-up of the Central Amazon, *Remote Sensing of Environment*, *182*(C), 90–98, doi:10.1016/j.rse.2016.05.009, 2016.

Machado, L.A., Silva Dias, M.A., Morales, C., Fisch, G., Vila, D., Albrecht, R., Goodman, S.J., Calheiros, A.J., Biscaro, T., Kummerow, C. and Cohen, J.. The CHUVA project: How does convection vary across Brazil?. *Bulletin of the American Meteorological Society*, *95*(9), 1365-1380, 2014.

Machado, L., and H. Laurent, Diurnal march of the convection observed during TRMM-WETAMC/LBA, *J Geo Res: Atmo*, 2002.

Mahecha, M. D. et al., Global convergence in the temperature sensitivity of respiration at ecosystem level, *Science*, *329*(5993), 838–840, doi:10.1126/science.1189587, 2010.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Marengo, J. A., J. Tomasella, L. M. Alves, W. R. Soares, and D. A. Rodriguez, The drought of 2010 in the context of historical droughts in the Amazon region, *Geophys Res Lett*, *38*(12), n/a–n/a, doi:10.1029/2011GL047436, 2011.

Martin, S.T., Artaxo, P., Machado, L.A.T., Manzi, A.O., Souza, R.A.F., Schumacher, C., Wang, J., Andreae, M.O., Barbosa, H.M.J., Fan, J. and Fisch, G., Introduction: Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5), *Atmos. Chem. Phys*, *16*(8), 4785–4797, doi:10.5194/acp-16-4785-2016, 2016.

Martin, S. T. et al., The Green Ocean Amazon Experiment (GoAmazon2014/5) Observes Pollution Affecting Gases, Aerosols, Clouds, and Rainfall over the Rain Forest, *Bull. Amer. Meteor. Soc.*, *98*(5), 981–997, doi:10.1175/BAMS-D-15-00221.1, 2017.

Martinez-Vilalta, J., and N. Garcia-Forner, Water potential regulation, stomatal behaviour and hydraulic transport under drought: deconstructing the iso/anisohydric concept, *Plant Cell Environ*, *40*(6), 962–976, doi:10.1111/pce.12846, 2016.

Martinez-Vilalta, J., R. Poyatos, D. Aguadé, J. Retana, and M. Mencuccini, A new look at water transport regulation in plants, *New Phytologist*, doi:10.1111/nph.12912, 2014.

Medlyn, B. E., R. A. Duursma, D. Eamus, D. S. Ellsworth, I. C. Prentice, C. V. M. Barton, K. Y. Crous, P. De Angelis, M. Freeman, and L. Wingate, Reconciling the optimal and empirical approaches to modelling stomatal conductance, *Global Change Biol*, *17*(6), 2134–2144, doi:10.1111/j.1365-2486.2010.02375.x, 2011.

Medlyn, B. E., R. A. Duursma, D. Eamus, D. S. Ellsworth, I. Colin Prentice, C. V. M. Barton, K. Y. Crous, P. Angelis, M. Freeman, and L. Wingate, Reconciling the optimal and empirical approaches to modelling stomatal conductance, *Global Change Biol*, *18*(11), 3476–3476, doi:10.1111/j.1365-2486.2012.02790.x, 2012.

Medvigy, D., R. L. Walko, and R. Avissar, Effects of Deforestation on Spatiotemporal Distributions of Precipitation in South America, *J Climate*, *24*, 2147–2163, 2011.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Miralles, D. G., J. H. Gash, T. R. H. Holmes, R. A. M. de Jeu, and A. J. Dolman, Global canopy interception from satellite observations, *J Geophys Res*, *115*(D16), 237, doi:10.1029/2009JD013530, 2010.

Morton, D. C., and B. D. Cook, Amazon forest structure generates diurnal and seasonal variability in light utilization, *Biogeosciences*, *13*(7), 2195–2206, doi:10.5194/bg-13-2195-2016, 2016.

Morton, D. C., J. Nagol, C. C. Carabajal, J. Rosette, M. Palace, B. D. Cook, E. F. Vermote, D. J. Harding, and P. R. J. North, Amazon forests maintain consistent canopy structure and greenness during the dry season, *Nature*, *506*(7487), 221–224, doi:10.1038/nature13006, 2014.

Mueller, B., Seneviratne, S.I., Jimenez, C., Corti, T., Hirschi, M., Balsamo, G., Ciais, P., Dirmeyer, P., Fisher, J.B., Guo, Z. and Jung, M., Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations, *Geophys Res Lett*, *38*, –, doi:10.1029/2010GL046230, 2011.

Munger, J. W., J. B. McManus, D. D. Nelson, M. S. Zahniser, E. A. Davidson, S. C. Wofsy, R. Wehr, and S. R. Saleska, Seasonality of temperate forest photosynthesis and daytime respiration, *Nature*, *534*(7609), 680–683, doi:10.1038/nature17966, 2016.

Nakicenovic, N., IPCC Special Report on Emissions Scenarios, 2000

Naudts, K., Ryder, J., McGrath, M.J., Otto, J., Chen, Y., Valade, A., Bellasen, V., Berhongaray, G., Bönisch, G., Campioli, M. and Ghattas, J., A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes, *Geosci. Model Dev. Discuss.*, *7*(6), 8565–8647, doi:10.5194/gmdd-7-8565-2014, 2014.

Ngo-Duc, T., K. Laval, G. Ramillien, J. Polcher, and A. Cazenave, Validation of the land water storage simulated by Organising Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) with Gravity Recovery and Climate Experiment

(GRACE) data, *Water resources Research*, *43*(4), –, doi:10.1029/2006WR004941, 2007.

Nicholson, S., Land surface processes and Sahel climate, *Rev Geophys*, *38*(1), 117–139, 2000.

Nitta, T., Convective Activities in the Tropical Western Pacific and Their Impact on the Northern Hemisphere Summer Circulation, *Journal of the Meteorological Society of Japan. Ser. II*, *65*(3), 373–390, doi:10.2151/jmsj1965.65.3_373, 1987.

Naudts, K., Ryder, J., McGrath, M.J., Otto, J., Chen, Y., Valade, A., Bellasen, V., Berhongaray, G., Bönisch, G., Campioli, M. and Ghattas, J., The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements, *J Geophys Res-Atmos*, *116*, –, doi:10.1029/2010JD015139, 2011.

Noilhan, J., and S. Planton, A simple parameterization of land surface processes for meteorological models, *Mon Wea Rev*, 1989.

Oleson, K.W., Niu, G.Y., Yang, Z.L., Lawrence, D.M., Thornton, P.E., Lawrence, P.J., Stöckli, R., Dickinson, R.E., Bonan, G.B., Levis, S. and Dai, A., Improvements to the Community Land Model and their impact on the hydrological cycle, *J Geophys Res-Biogeo*, *113*, –, doi:10.1029/2007JG000563, 2008.

Oliveira, R. S., T. E. Dawson, S. S. O. Burgess, and D. C. Nepstad, Hydraulic redistribution in three Amazonian trees, *Oecologia*, *145*(3), 354–363, doi:10.1007/s00442-005-0108-2, 2005.

Ouwersloot, H. G., J. V.-G. de Arellano, B. J. H. van Stratum, M. C. Krol, and J. Lelieveld, Quantifying the transport of sub-cloud layer reactants by shallow cumulus clouds over the Amazon, *J Geophys Res-Atmos*, n/a–n/a, doi:10.1002/2013JD020431, 2013.

Park, S., and C. S. Bretherton, The University of Washington Shallow Convection and Moist Turbulence Schemes and Their Impact on Climate Simulations with the

Community Atmosphere Model, *J Climate*, *22*(12), 3449–3469, doi:10.1175/2008JCLI2557.1, 2009.

Park, S.-B., S. Boeing, and P. Gentine, Role of shear on shallow convection (in press), *J Atmos Science*, 2018.

Peterhansel, C., and V. G. Maurino, Photorespiration Redesigned, *Plant Physiol*, *155*(1), 49–55, doi:10.1104/pp.110.165019, 2011.

Phillips, N. G., R. Oren, J. Licata, and S. Linder, Time series diagnosis of tree hydraulic characteristics, *Tree Physiol*, 879–890, 2004.

Phillips, N. G., T. N. Buckley, and D. T. Tissue, Capacity of Old Trees to Respond to Environmental Change, *Journal of Integrative Plant Biology*, *50*(11), 1355–1364, doi:10.1111/j.1744-7909.2008.00746.x, 2008.

Phillips, N., A. Nagchaudhuri, R. Oren, and G. Katul, Time constant for water transport in loblolly pine trees estimated from time series of evaporative demand and stem sapflow, *Trees*, *11*(7), 412–419, 1997.

Pielke Sr, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R., Fall, S. and Reichstein, M., Land use/land cover changes and climate: modeling analysis and observational evidence, *Wires Clim Change*, *2*(6), 828–850, doi:10.1002/wcc.144, 2011.

Pielke, R. A., Sr, R. Mahmood, and C. McAlpine, Land's complex role in climate change, *Physics Today*, *69*(11), 40–46, doi:10.1063/PT.3.3364, 2016.

Pielke, R., and R. Avissar, Influence of landscape structure on local and regional climate, *Landscape Ecology*, *4*(2/3), 133–155, 1990.

Pielke, R., G. DALU, J. SNOOK, T. LEE, and T. KITTEL, Nonlinear Influence of Mesoscale Land-Use on Weather and Climate, *J Climate*, *4*(11), 1053–1069, 1991.

Pons, T. L., and R. Welschen, Midday depression of net photosynthesis in the tropical rainforest tree Eperua grandiflora: contributions of stomatal and internal conductances, respiration and Rubisco functioning, *Tree Physiol*, *23*(14), 937–947, 2003.

Poulter, B., Frank, D., Ciais, P., Myneni, R.B., Andela, N., Bi, J., Broquet, G., Canadell, J.G., Chevallier, F., Liu, Y.Y. and Running, S.W., Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, *Nature*, *509*(7502), 600–603, doi:10.1038/nature13376, 2014.

Powell, T.L., Galbraith, D.R., Christoffersen, B.O., Harper, A., Imbuzeiro, H.M., Rowland, L., Almeida, S., Brando, P.M., da Costa, A.C.L., Costa, M.H. and Levine, N.M., Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought, *New Phytologist*, *200*(2), 350–365, doi:10.1111/nph.12390, 2013.

Pradipta, P., A. Giannini, P. Gentine, and U. Lall, Resolving Contrasting Regional Rainfall Responses to El Niño over Tropical Africa, *J Climate*, *29*(4), 1461–1476, doi:10.1175/JCLI-D-15-0071.1, 2016.

Prieto, I., and R. J. Ryel, Internal hydraulic redistribution prevents the loss of root conductivity during drought, *Tree Physiol*, *34*(1), 39–48, doi:10.1093/treephys/tpt115, 2014.

Ray, D. K., U. S. Nair, R. O. Lawton, R. M. Welch, and R. A. Pielke Sr. Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of orographic cloud formation to deforestation in the plains, *J Geophys Res*, *111*(D2), D02108, doi:10.1029/2005JD006096, 2006.

Raymond, D. J., and X. Zeng, Modelling tropical atmospheric convection in the context of the weak temperature gradient approximation, *Q J Roy Meteor Soc*, *131*(608), 1301–1320, doi:10.1256/qj.03.97, 2005.

Redelsperger, J.-L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher African monsoon multidisciplinary analysis - An international research project and field campaign, *Bull. Amer. Meteor. Soc.*, *87*(12), 1739–+, doi:10.1175/BAMS-87-12-1739, 2006.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Restrepo-Coupe, N., da Rocha, H.R., Hutyra, L.R., da Araujo, A.C., Borma, L.S., Christoffersen, B., Cabral, O.M., de Camargo, P.B., Cardoso, F.L., da Costa, A.C.L. and Fitzjarrald, D.R., What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network, *Agr Forest Meteorol*, *182-183*, 128–144, doi:10.1016/j.agrformet.2013.04.031, 2013.

Rieck, M., C. Hohenegger, and C. C. van Heerwaarden, The influence of land surface heterogeneities on cloud size development, *Mon Wea Rev*, 140611124045000, doi:10.1175/MWR-D-13-00354.1, 2014.

Rieck, M., C. Hohenegger, and P. Gentine, The effect of moist convection on thermally induced mesoscale circulations, *Q J Roy Meteor Soc*, *141*(691), 2418–2428, doi:10.1002/qj.2532, 2015.

Rio, C., F. Hourdin, J. Y. Grandpeix, and J. P. Lafore, Shifting the diurnal cycle of parameterized deep convection over land, *Geophys Res Lett*, *36*, –, doi:10.1029/2008GL036779, 2009.

Rochetin, N., F. Couvreux, J.-Y. Grandpeix, and C. Rio, Deep Convection Triggering by Boundary Layer Thermals. Part I: LES Analysis and Stochastic Triggering Formulation, *J Atmos Sci*, *71*(2), 496–514, doi:10.1175/JAS-D-12-0336.1, 2014.

Rochetin, N., J.-Y. Grandpeix, C. Rio, and F. Couvreux, Deep Convection Triggering by Boundary Layer Thermals. Part II: Stochastic Triggering Parameterization for the LMDZ GCM, *J Atmos Sci*, *71*(2), 515–538, doi:10.1175/JAS-D-12-0337.1, 2014.

Romps, D. M., Numerical tests of the weak pressure gradient approximation, *J Atmos Sci*, *69*(9), 2846–2856, doi:10.1175/JAS-D-11-0337.1, 2012.

Romps, D. M., Weak Pressure Gradient Approximation and Its Analytical Solutions, *J Atmos Sci*, *69*(9), 2835–2845, doi:10.1175/JAS-D-11-0336.1, 2012.

Roy, S., C. Weaver, D. Nolan, and R. Avissar, A preferred scale for landscape forced mesoscale circulations? *J Geophys Res-Atmos*, *108*(D22), 8854, doi:10.1029/2002JD003097, 2003.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L. E. O. C. Aragao, L. O. Anderson, R. B. Myneni, and R. Nemani, Persistent effects of a severe drought on Amazonian forest canopy, *PNAS*, *110*(2), 565–570, doi:10.1073/pnas.1204651110, 2013.

Saleska, S. R., J. Wu, K. Guan, A. C. Araujo, and A. Huete, Dry-season greening of Amazon forests, *Nature*, doi:10.1038/nature16457, 2016.

Schaefli, B., R. J. van der Ent, R. Woods, and H. H. G. Savenije, An analytical model for soil-atmosphere feedback, *Hydrol Earth Syst Sc*, *16*(7), 1863–1878, doi:10.5194/hess-16-1863-2012, 2012.

Schiro, K. A., J. D. Neelin, D. K. Adams, and B. R. Lintner, Deep Convection and Column Water Vapor over Tropical Land versus Tropical Ocean: A Comparison between the Amazon and the Tropical Western Pacific, *Journal of Atmospheric Sciences*, *73*(10), 4043–4063, doi:10.1175/JAS-D-16-0119.1, 2016.

Scholz, F., N. Phillips, and S. Bucci, Hydraulic capacitance: biophysics and functional significance of internal water sources in relation to tree size, *Size- and Age-Related Changes in Tree Structure*, 341–361, 2011.

Scott, R., D. Entekhabi, R. D. Koster, and M. Suarez, Timescales of land surface evapotranspiration response, *J Climate*, *10*(4), 559–566, 1997.

Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Los, C. O. Justice, D. A. Dazlich, and D. A. Randall, A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMS. Part II: The Generation of Global Fields of Terrestrial Biophysical Parameters from Satellite Data, *J Climate*, *9*(4), 706–737, doi:10.1175/1520-0442(1996)009<0706:ARLSPF>2.0.CO;2, 1996.

Sellers, P., D. A. Randall, G. Collatz, J. Berry, C. Field, D. Dazlich, C. Zhang, G. Collelo, and L. Bounoua, A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMS. Part I: Model Formulation, *J Climate*, *9*(4), 676–705, 1996.

Seneviratne, S., Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment, *Geophys Res Lett*, *40*(19), 5212–5217, doi:10.1002/grl.50956, 2013.

Sentić, S., and S. L. Sessions, Idealized modeling of convective organization with Changing Sea surface temperatures using multiple equilibria in weak temperature gradient simulations, *J. Adv. Model. Earth Syst.*, 1–65, doi:10.1002/2016MS000873, 2017.

Sobel, A. H., and C. S. Bretherton, Large-scale waves interacting with deep convection in idealized mesoscale model simulations, *Tellus Series A-Dynamic Meteorology And Oceanography*, *55*(1), 45–60, doi:10.1034/j.1600-0870.2003.201421.x, 2003.

Sobel, A. H., G. Bellon, and J. Bacmeister, Multiple equilibria in a single-column model of the tropical atmosphere, *Geophys Res Lett*, *34*(22), L22804, doi:10.1029/2007GL031320, 2007.

Sobel, A. H., J. Nilsson, and L. Polvani, The weak temperature gradient approximation and balanced tropical moisture waves, *J Atmos Sci*, *58*(23), 3650–3665, 2001.

Spracklen, D. V., S. R. Arnold, and C. M. Taylor, Observations of increased tropical rainfall preceded by air passage over forests, *Nature*, *489*(7415), 282–285, doi:10.1038/nature11390, 2012.

Stevens, B., and S. Bony, What Are Climate Models Missing? *Science*, *340*(6136), 1053–1054, doi:10.1126/science.1237554, 2013.

Stoeckli, R., D. M. Lawrence, G. Y. Niu, K. W. Oleson, P. E. Thornton, Z. L. Yang, G. B. Bonan, A. S. Denning, and S. W. Running, Use of FLUXNET in the Community Land Model development, *J Geophys Res*, *113*(G1), G01025, doi:10.1029/2007JG000562, 2008.

Sutanto, S. J., J. Wenninger, A. M. J. Coenders-Gerrits, and S. Uhlenbrook, Partitioning of evaporation into transpiration, soil evaporation and interception: a comparison between isotope measurements and a HYDRUS-1D model, *Hydrol Earth Syst Sc*, *16*(8), 2605–2616, doi:10.5194/hess-16-2605-2012, 2012.

Swann, A. L. S., M. Longo, R. G. Knox, E. Lee, and P. R. Moorcroft, Future deforestation in the Amazon and consequences for South American climate, *Agr Forest Meteorol*, *214-215*, 12–24, doi:10.1016/j.agrformet.2015.07.006, 2015.

Hydrology and Earth System Sciences
Open Access
Discussions

Tang, S., Xie, S., Zhang, Y., Zhang, M., Schumacher, C., Upton, H., Jensen, M.P., Johnson, K.L., Wang, M., Ahlgrimm, M. and Feng, Z., Large-scale vertical velocity, diabatic heating and drying profiles associated with seasonal and diurnal variations of convective systems observed in the GoAmazon2014/5 experiment, *Atmos. Chem. Phys*, *16*(22), 14249–14264, doi:10.5194/acp-16-14249-2016, 2016.

Taylor, C. M., C. E. Birch, D. J. Parker, N. Dixon, F. Guichard, G. Nikulin, and G. M. S. Lister, New perspectives on land-atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis, *Atmos Sci Lett*, *12*(1), 38–44, doi:10.1002/asl.336, 2011.

Taylor, C. M., C. E. Birch, D. J. Parker, N. Dixon, F. Guichard, G. Nikulin, and G. M. S. Lister, Modelling soil moisture - precipitation feedbacks in the Sahel: importance of spatial scale versus convective parameterization, *Geophys Res Lett*, *40*(23), 6213–6218, doi:10.1002/2013GL058511, 2013.

Taylor, C. M., D. J. Parker, and P. P. Harris, An observational case study of mesoscale atmospheric circulations induced by soil moisture, *Geophys Res Lett*, *34*(15), L15801, doi:10.1029/2007GL030572, 2007.

Taylor, C. M., P. P. Harris, and D. J. Parker, Impact of soil moisture on the development of a Sahelian mesoscale convective system: a case-study from the AMMA Special Observing Period, *Q J Roy Meteor Soc*, *136*(S1), 456–470, doi:10.1002/qj.465, 2009.

Thiery, W., E. L. Davin, D. M. Lawrence, A. L. Hirsch, M. Hauser, and S. I. Seneviratne, Present-day irrigation mitigates heat extremes, *J Geophys Res-Atmos*, *122*(3), 1403–1422, doi:10.1002/2016JD025740, 2017.

Thornley, J. H. M., Plant growth and respiration re-visited: maintenance respiration defined - it is an emergent property of, not a separate process within, the system - and why the respiration : photosynthesis ratio is conservative, *Annals of Botany*, *108*(7), 1365–1380, doi:10.1093/aob/mcr238, 2011.

Thum, T., Zaehle, S., Köhler, P., Aalto, T., Aurela, M., Guanter, L., Kolari, P., Laurila, T., Lohila, A., Magnani, F. and Tol, C.V.D., Modelling sun-induced fluorescence and photosynthesis with a land surface model at local and regional scales in northern Europe, *Biogeosciences*, *14*(7), 1969–1987, doi:10.5194/bg-14-1969-2017, 2017.

Torri, G., Z. Kuang, and Y. Tian, Mechanisms for convection triggering by cold pools, *Geophys Res Lett*, *42*(6), 1943–1950, doi:10.1002/2015GL063227, 2015.

van der Ent, R. J., and O. A. Tuinenburg, The residence time of water in the atmosphere revisited, *Hydrol Earth Syst Sc*, *21*(2), 779–790, doi:10.5194/hess-21-779-2017, 2017.

van der Ent, R. J., H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne, Origin and fate of atmospheric moisture over continents, *Water resources Research*, *46*(9), n/a–n/a, doi:10.1029/2010WR009127, 2010.

van Dijk, A.I., Gash, J.H., van Gorsel, E., Blanken, P.D., Cescatti, A., Emmel, C., Gielen, B., Harman, I.N., Kiely, G., Merbold, L. and Montagnani, L., Rainfall interception and the coupled surface water and energy balance, *Agr Forest Meteorol*, *214-215*, 402–415, doi:10.1016/j.agrformet.2015.09.006, 2015.

Vila-Guerau de Arellano, J., E. G. Patton, T. Karl, K. van den Dries, M. C. Barth, and J. J. Orlando, The role of boundary layer dynamics on the diurnal evolution of isoprene and the hydroxyl radical over tropical forests, *J Geophys Res-Atmos*, *116*(D7), 8032, doi:10.1029/2010JD014857, 2011.

Vogel, M. M., R. Orth, F. Cheruy, S. Hagemann, R. Lorenz, B. J. J. M. van den Hurk, and S. I. Seneviratne, Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks, *Geophys Res Lett*, *44*(3), 1511–1519, doi:10.1002/2016GL071235, 2017.

Wang, J., F. J. F. Chagnon, E. R. Williams, A. K. Betts, N. O. Renno, L. A. T. Machado, G. Bisht, R. Knox, and R. L. Bras, Impact of deforestation in the Amazon basin on cloud climatology, *PNAS*, *106*(10), 3670–3674, doi:10.1073/pnas.0810156106, 2009.

Wang, J., R. L. Bras, and E. Eltahir, The impact of observed deforestation on the mesoscale distribution of rainfall and clouds in Amazonia, *J Hydrometeorol*, *1*(3), 267–286, 2000.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Wang, S., A. H. Sobel, and Z. Kuang, Cloud-resolving simulation of TOGA-COARE using parameterized large-scale dynamics, *J Geophys Res-Atmos*, *118*(12), 6290–6301, doi:10.1002/jgrd.50510, 2013.

Wang, Y. P., and R. Leuning, A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I:, *Agr Forest Meteorol*, *91*(1-2), 89–111, doi:10.1016/S0168-1923(98)00061-6, 1998.

Washington, R., R. James, H. Pearce, W. M. Pokam, and W. Moufouma-Okia, Congo Basin rainfall climatology: can we believe the climate models? *Philos T R Soc B*, *368*(1625), 20120296–20120296, doi:10.1098/rstb.2012.0296, 2013.

Wehr, R., R. Commane, J. W. Munger, J. B. McManus, D. D. Nelson, M. S. Zahniser, S. R. Saleska, and S. C. Wofsy, Dynamics of canopy stomatal conductance, transpiration, and evaporation in a temperate deciduous forest, validated by carbonyl sulfide uptake,, 1–17, doi:10.5194/bg-2016-365, 2016.

Werth, D., and R. Avissar, The local and global effects of Amazon deforestation, *J Geophys Res-Atmos*, *107*(D20), 8087, doi:10.1029/2001JD000717, 2002.

Wills, R. C., M. P. Byrne, and T. Schneider, Thermodynamic and dynamic controls on changes in the zonally anomalous hydrological cycle, *Geo Res Letters*, *43*(9), 4640–4649, doi:10.1002/2016GL068418, 2016.

Wright, J. S., R. Fu, J. R. Worden, S. Chakraborty, N. E. Clinton, C. Risi, Y. Sun, and L. Yin, Rainforest-initiated wet season onset over the southern Amazon, *PNAS*, *114*(32), 8481–8486, doi:10.1073/pnas.1621516114, 2017.

Wu, C.-M., B. Stevens, and A. Arakawa, What Controls the Transition from Shallow to Deep Convection? *J Atmos Sci*, *66*(6), 1793–1806, doi:10.1175/2008JAS2945.1, 2009.

Xu, X., D. Medvigy, J. S. Powers, J. M. Becknell, and K. Guan, Diversity in plant hydraulic traits explains seasonal and inter-annual variations of vegetation dynamics in seasonally dry tropical forests, *New Phytologist*, 1–16, doi:10.1111/nph.14009, 2016.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Yano, J. I., and R. S. Plant, Convective quasi-equilibrium, *Rev Geophys*, *50*(4), RG4004, doi:10.1029/2011RG000378, 2012.

Yin, L., R. Fu, E. Shevliakova, and R. E. Dickinson, How well can CMIP5 simulate precipitation and its controlling processes over tropical South America? *Climate dynamics*, *41*(11-12), 3127–3143, doi:10.1007/s00382-012-1582-y, 2013.

Yu, H., L. A. Remer, M. Chin, H. Bian, R. G. Kleidman, and T. Diehl, A satellite-based assessment of transpacific transport of pollution aerosol, *J Geophys Res-Atmos*, *113*(D14), doi:10.1029/2007JD009349, 2008.

Zahn, E., N. L. Dias, A. Araújo, L. D. A. Sá, M. Sörgel, I. Trebs, S. Wolff, and A. Manzi, Scalar turbulent behavior in the roughness sublayer of an Amazonian forest, *Atmos. Chem. Phys*, *16*(17), 11349–11366, doi:10.5194/acp-16-11349-2016, 2016.

Zeng, N., and J. D. Neelin, A land-atmosphere interaction theory for the tropical deforestation problem, *J Climate*, *12*(2-3), 857–872, 1999.

Zeng, N., J. Neelin, K. Lau, and C. Tucker, Enhancement of Interdecadal Climate Variability in the Sahel by Vegetation Interaction, *Science*, *286*(5444), 1537–1540, 1999.

Zeppel, M. J. B., J. D. Lewis, N. G. Phillips, and D. T. Tissue, Consequences of nocturnal water loss: a synthesis of regulating factors and implications for capacitance, embolism and use in models, *Tree Physiol*, *34*(10), 1047–1055, doi:10.1093/treephys/tpu089, 2014.

Zhang, K., de Almeida Castanho, A.D., Galbraith, D.R., Moghim, S., Levine, N.M., Bras, R.L., Coe, M.T., Costa, M.H., Malhi, Y., Longo, M. and Knox, R.G., The fate of Amazonian ecosystems over the coming century arising from changes in climate, atmospheric CO 2,and land use, *Global Change Biol*, *21*(7), 2569–2587, doi:10.1111/gcb.12903, 2015.

Zhang, Y. J., F. C. Meinzer, and J. Qi, Midday stomatal conductance is more related to stem rather than leaf water status in subtropical deciduous and evergreen broadleaf trees, *Plant Cell and Env*, *36*(1), 149–158, doi:10.1111/j.1365-3040.2012.02563.x, 2013.

Zhang, Y., R. Fu, H. Yu, R. E. Dickinson, R. N. Juarez, M. Chin, and H. Wang, A regional climate model study of how biomass burning aerosol impacts land-atmosphere interactions over the Amazon, *Journal of Geophysical Research: Atmospheres (1984–2012)*, *113*(D14), 1042, doi:10.1029/2007JD009449, 2008.

Zhang, Y., R. Fu, H. Yu, Y. Qian, R. Dickinson, M. A. F. Silva Dias, P. L. da Silva Dias, and K. Fernandes, Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia, *Geophys Res Lett*, *36*(10), 1509, doi:10.1029/2009GL037180, 2009.

Zhuang, Y., R. Fu, and J. A. Marengo, Seasonal variation of shallow-to-deep convection transition and its link to the environmental conditions over the Central Amazon, *J Geo Res: Atmo*, doi:10.1002/(ISSN)2169-8996, 2017.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Table 1. The surface friction velocity, subcloud layer height (where the minimum of virtual potential temperature flux occurs), ratio of subcloud layer height and Obukhov length, ratio of surface friction velocity and Deardorff convective velocity scale, and the total number of identified clouds for 12 time instants in each case.

Case	S3	S2	S1	CTL	R1	R2	R3
u_* u_* [m s^{-1}]	0.07	0.14	0.21	0.28	0.35	0.42	0.56
z_i [m]	590	590	590	590	590	610	630
z_i / L	392.1	49.0	14.5	6.1	3.1	1.9	0.8
u_*/ w_* u_*/ w_*	0.10	0.20	0.30	0.40	0.50	0.60	0.79
N_{cloud}	2248	2229	2283	2302	2250	2703	2776

List of Figures

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Discussions

Figure 1: Snapshot of cloud cover over the Amazon basin (courtesy NASA, MODIS visible bands) in the dry season. Small clouds are shallow convective clouds, highlighting surface Bowen ratio changes between the river and the forest. At the bottom right, the deep convective cells, does not follow the surface heterogeneity (and is much larger in scale).Figure 1: Snapshot of cloud cover over the Amazon basin (courtesy NASA, MODIS visible bands) in the dry season. Small clouds are shallow convective clouds, highlighting surface Bowen ratio changes between the river and the forest. At the bottom right, the deep convective cells, does not follow the surface heterogeneity (and is much larger in scale).

Figure 2: Diurnal cycle in local hour of dry (red) and wet (blue) season observations of precipitation at K34, near Manaus, along with their standard deviation averaged across years 2010-2014.

Figure 3: Response of tropically-averaged free tropospheric temperature between 700mb and 200mb to El Niño Southern Oscillation (choosing the ENSO 3.4 index)

Figure 4: Seasonal variations in Evapotranspiration (ET) from WECANN, Precipitation (Precip) based on GPCP, Net Radiation (Rn) from CERES and Gross Primary Production (GPP) based on WECANN informed by Solar-Induced Fluorescence (SIF) over the wet part of the Amazon (top left), the Savanna region of Brazil (top right), over Indonesia (bottom left) and over the Congo basin (bottom right).

Figure 5: Seasonality of Precipitation based on GPCP in the tropics in December-January-February (a), March-April-May (b), June-July-August (c), and September-October-November (SON) and its latitudinal average (e).

Figure 6: same as Figure 5 but for Gross Primary Production (GPP)

Figure 7: same as Figure 5 for latent heat flux LE

Figure 8: same as Figure 5 for sensible heat flux H

Figure 9: same as Figure 5 for evaporative fraction (EF), the ratio of LE to H+LE.

Figure 10: same as Figure 5 for sea-level surface moist static energy flux, the sum of sensible heat flux H and latent heat flux

Figure 11: Schematic showing the vertical structure of light and water limitations in a tropical forest.

Hydrology and Earth System Sciences
Open Access
Discussions

Figure 12: Climatology of the diurnal cycle of leaf water potential and top soil water potential in the dry and wet seasons in Caxiuana, Brazil simulated by the Community Land Model (CLM) with plant hydraulics.

Figure 13: Mesoscale heterogeneity impact on cloud generation. a) Typical perspective regarding the impact of deforestation and clearings generating deep convective clouds and b) more realistic impact, in terms of mostly a modification of shallow convection cloud cover, impacting radiation more than precipitation.

Figure 15: (a) Schematic of the key elements of the convective margins framework as applied along an inflow path across northeastern South America. The solid blue and black lines are precipitation and vertically-integrated moisture, while dashed blue line corresponds to precipitation smeared out by transients. Adapted from Figure 2 of Lintner and Neelin (2009). (b) Rainfall longitudinal transects from the Climate Anomaly Monitoring System (CAMS) raingauge-derived precipitation data for September-October-November for the period 1950-2000 for El Niño (red), La Niña (blue), and all (black) years, averaged over 3.75°S-1.75°S. From Figure 4b of Lintner and Neelin (2007).

Figure 16: adapted from Schäfli et al. (2012)

Figure 18: Land-atmosphere feedback strength (change in the variance due to the feedback) between Precipitation and ET (top) and Photosynthetically Active Radiation (PAR) (bottom) based on recent metric developed by Green et al. [2017] using a multivariate Granger causality approach.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

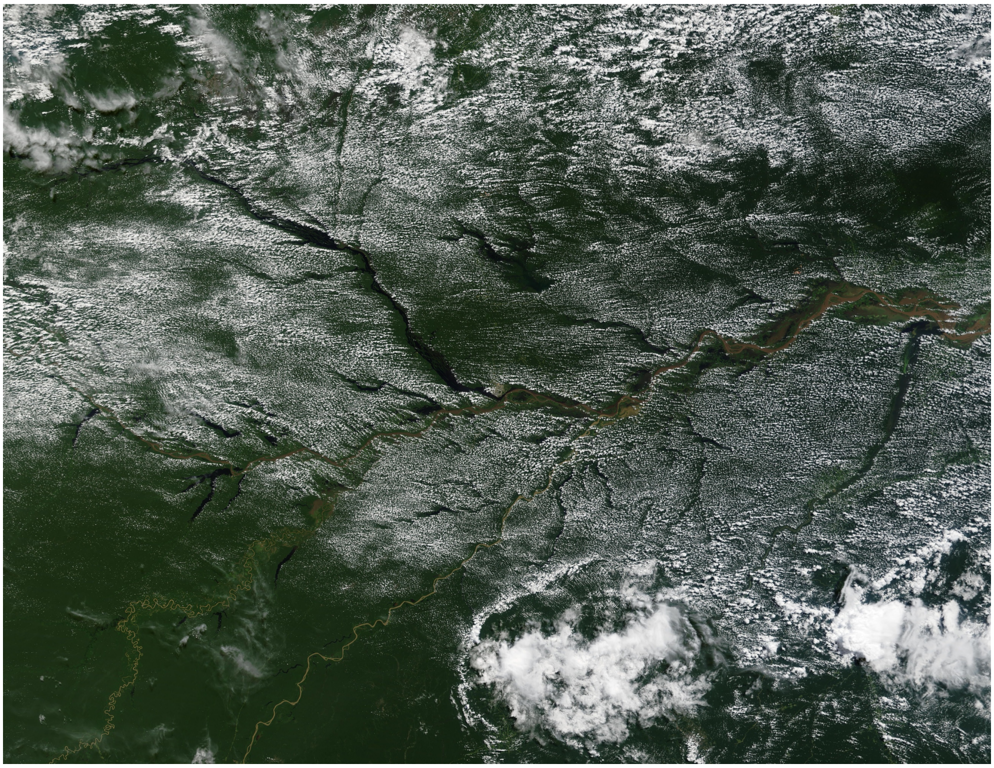
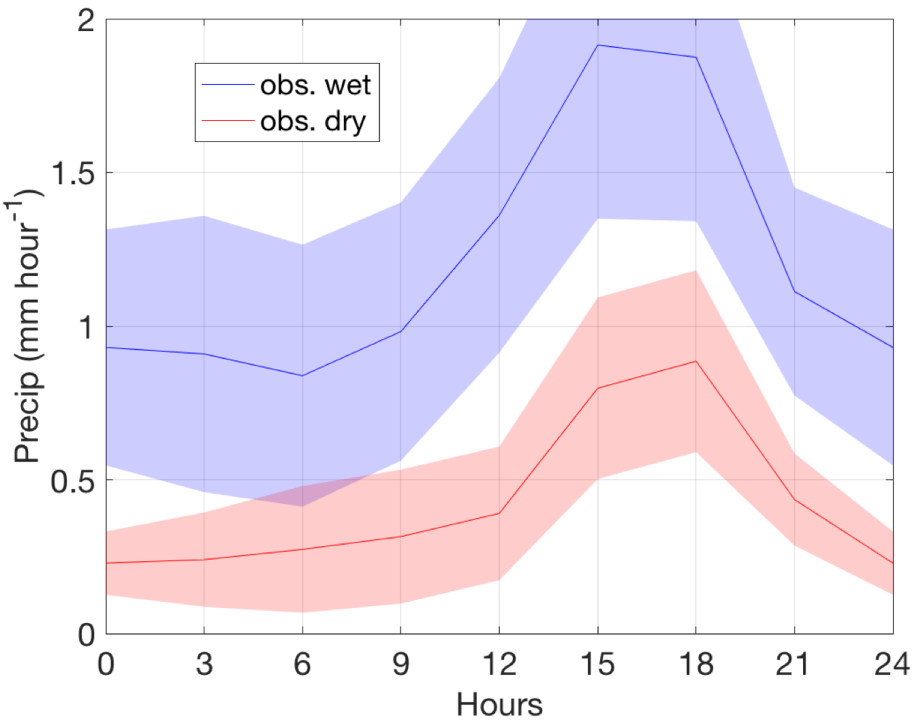


Figure 1: Snapshot of cloud cover over the Amazon basin (courtesy NASA, MODIS visible bands) in the dry season. Small clouds are shallow convective clouds, highlighting surface Bowen ratio changes between the river and the forest. At the bottom right, the deep convective cells, does not follow the surface heterogeneity (and is much larger in scale).



1806

1807 Figure 2: Diurnal cycle in local hour of dry (red) and wet (blue) season observations of
1808 precipitation at K34, near Manaus, along with their standard deviation averaged across years
1809 2010-2014.

1810

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

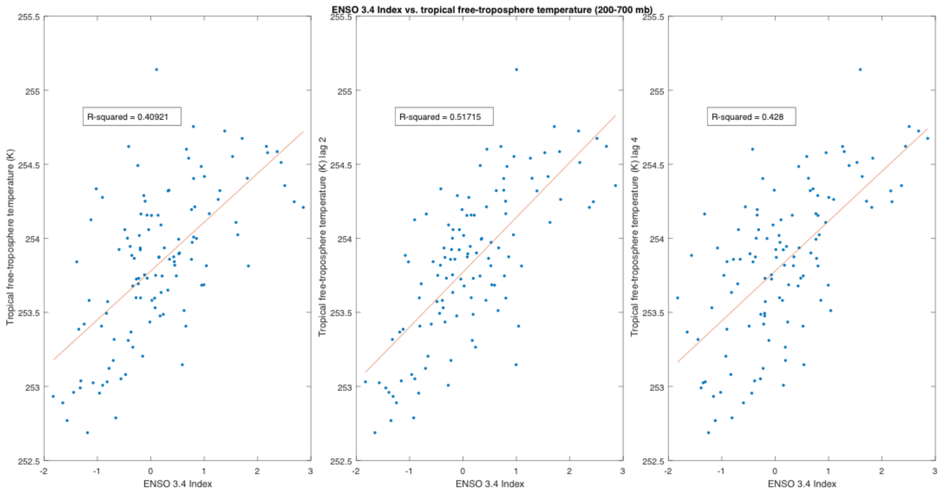


Figure 3: Response of tropically-averaged free tropospheric temperature between 700mb and 200mb to El Niño Southern Oscillation (choosing the ENSO 3.4 index) with either no lag (left) or 2-month lag (middle) or 4-month lag (right)

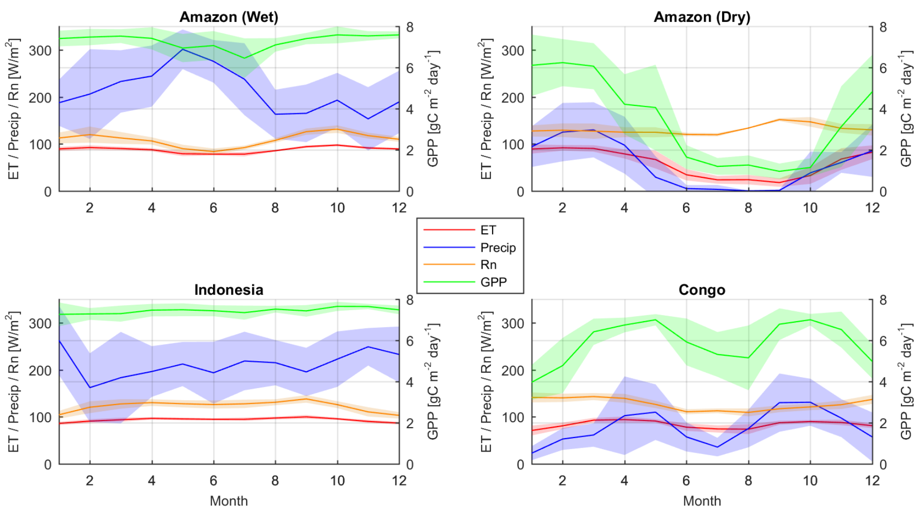


Figure 4: Seasonal variations in Evapotranspiration (ET) from WECANN, Precipitation (Precip) based on GPCP, Net Radiation (Rn) from CERES and Gross Primary Production (GPP) based on WECANN informed by Solar-Induced Fluorescence (SIF) over the wet part of the Amazon (top left), the Savanna region of Brazil (top right), over Indonesia (bottom left) and over

the Congo basin (bottom right).

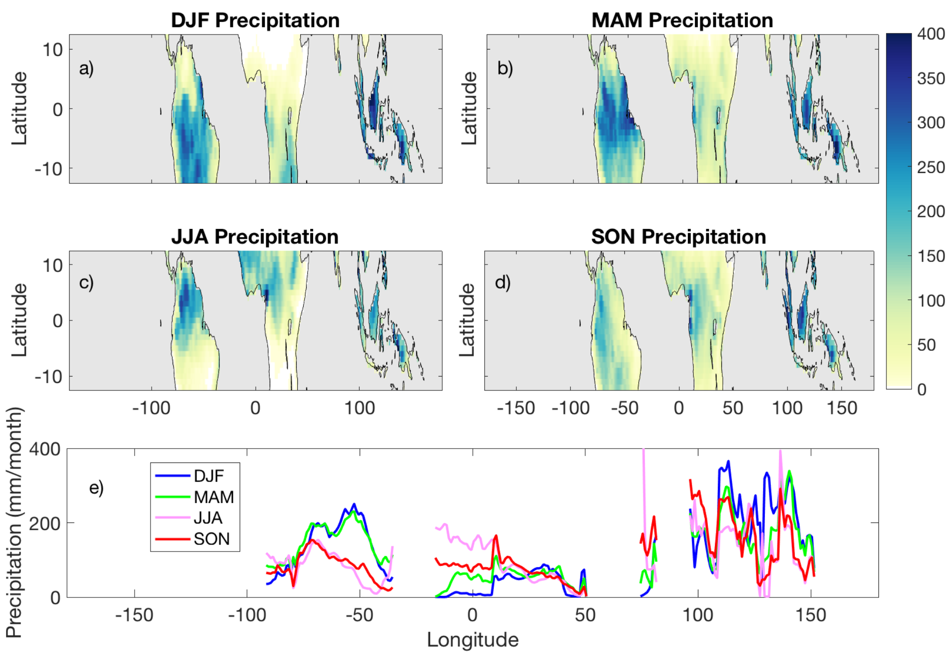


Figure 5: Seasonality of Precipitation based on GPCP in the tropics in December-January-February (a), March-April-May (b), June-July-August (c), and September-October-November (SON) and its latitudinal average (e).

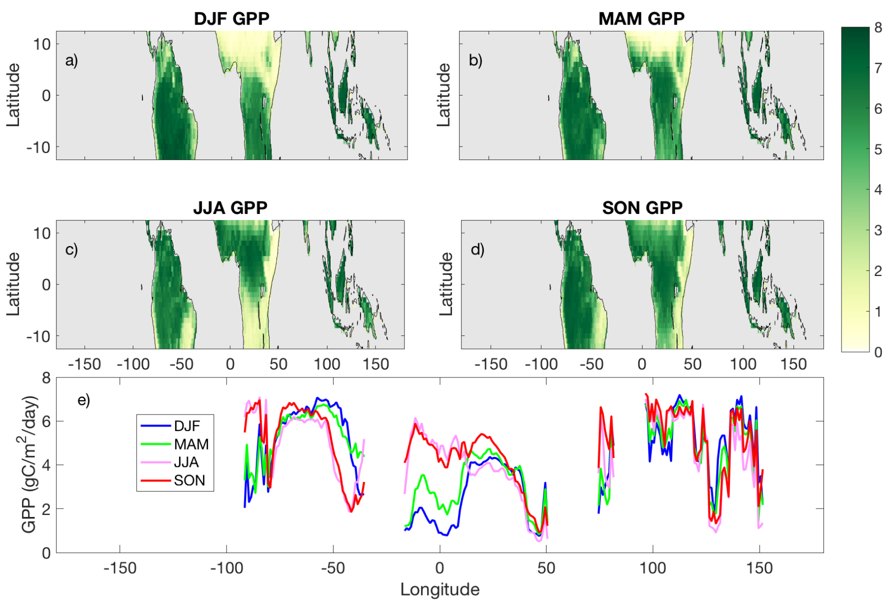


Figure 6: same as Figure 5 but for Gross Primary Production (GPP)

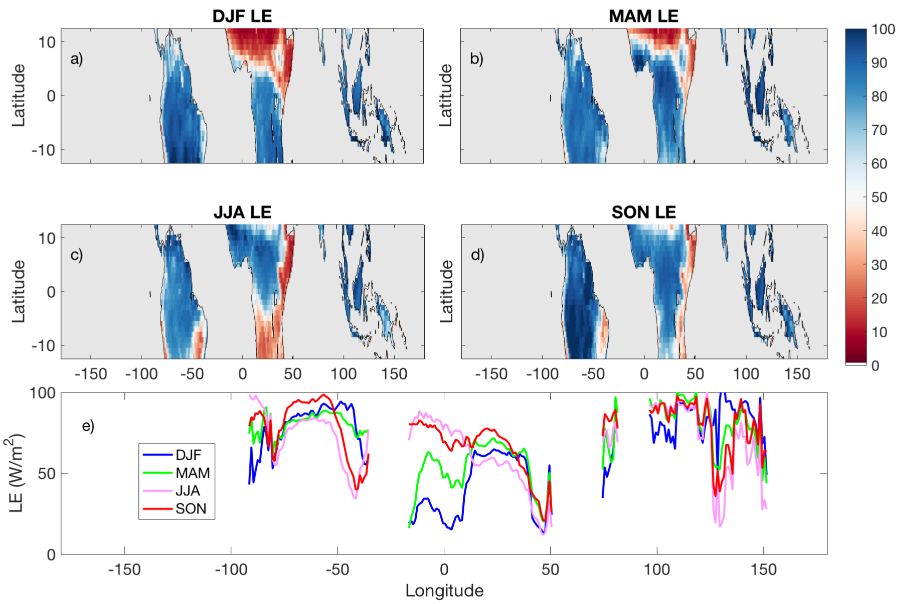


Figure 7: same as Figure 5 for latent heat flux LE

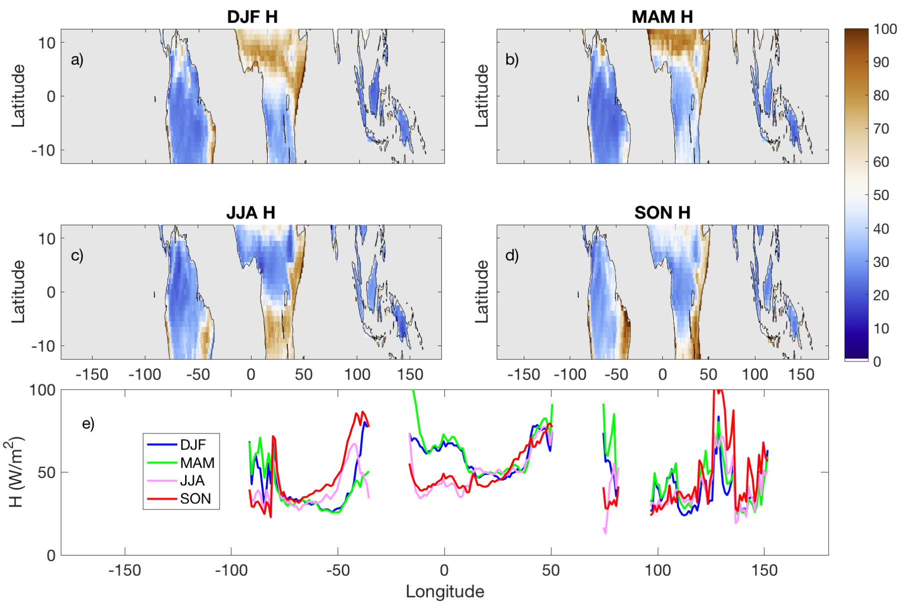


Figure 8: same as Figure 5 for sensible heat flux H

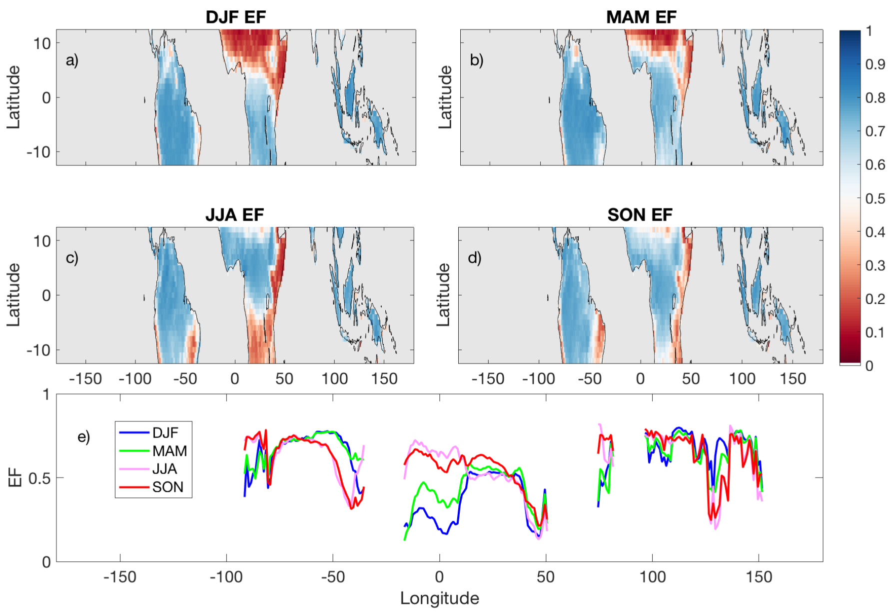


Figure 9: same as Figure 5 for evaporative fraction (EF), the ratio of LE to H+LE.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

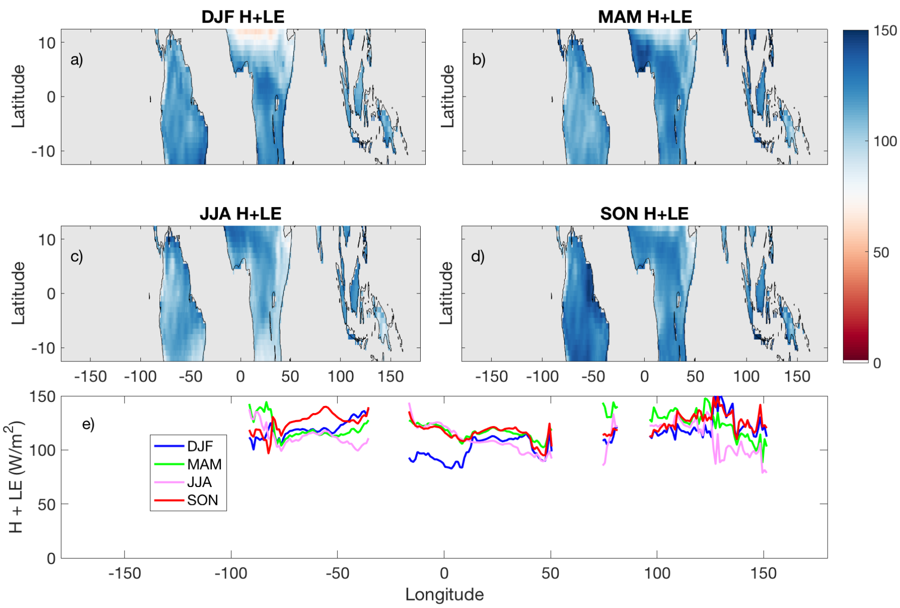
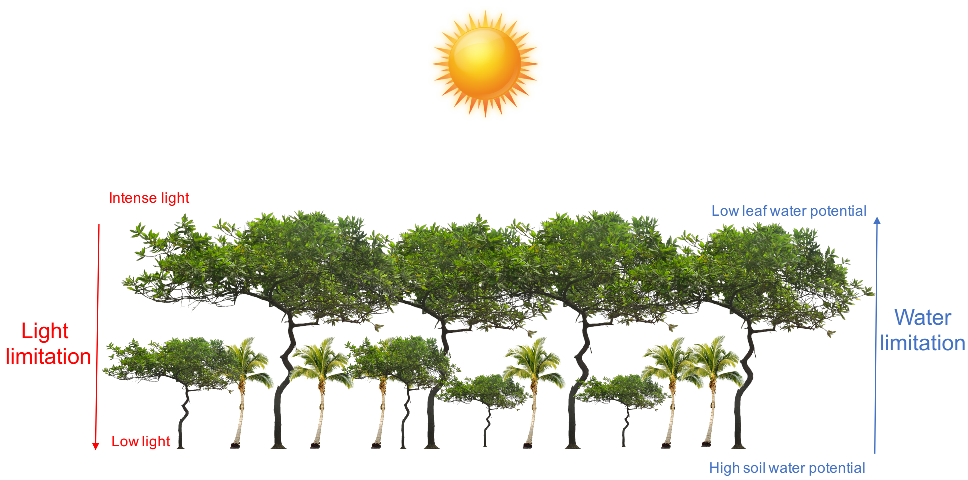


Figure 10: same as Figure 5 for sea-level surface moist static energy flux, the sum of sensible heat flux H and latent heat flux



Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Figure 11: Schematic showing the vertical structure of light and water limitations in a tropical forest.

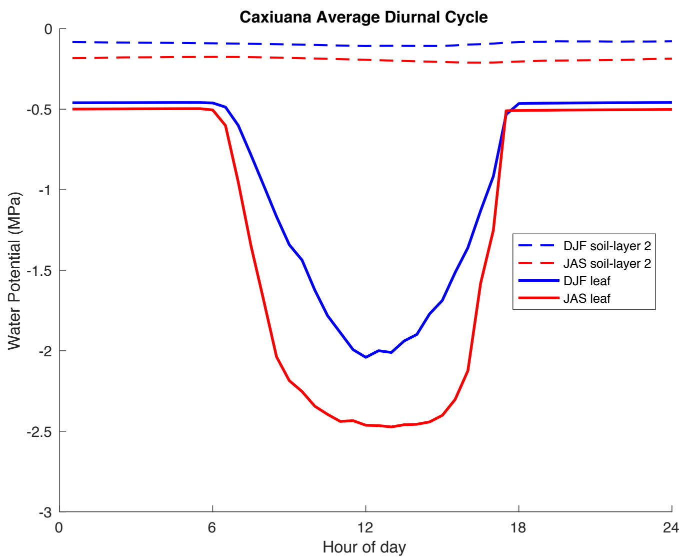


Figure 12: Climatology of the diurnal cycle of leaf water potential and top soil water potential in the dry and wet seasons in Caxiuana, Brazil simulated by the Community Land Model (CLM) with plant hydraulics.

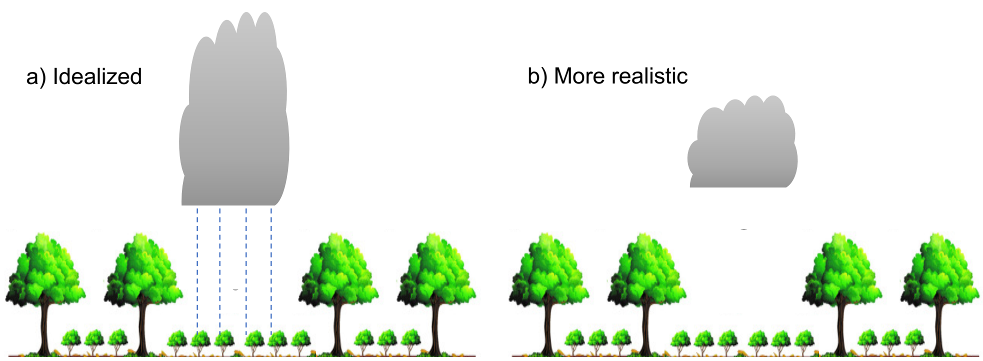


Figure 13: Mesoscale heterogeneity impact on cloud generation. a) Typical perspective regarding the impact of deforestation and clearings generating deep convective clouds and b) more realistic impact, in terms of mostly a modification of shallow convection cloud cover, impacting radiation more than precipitation.

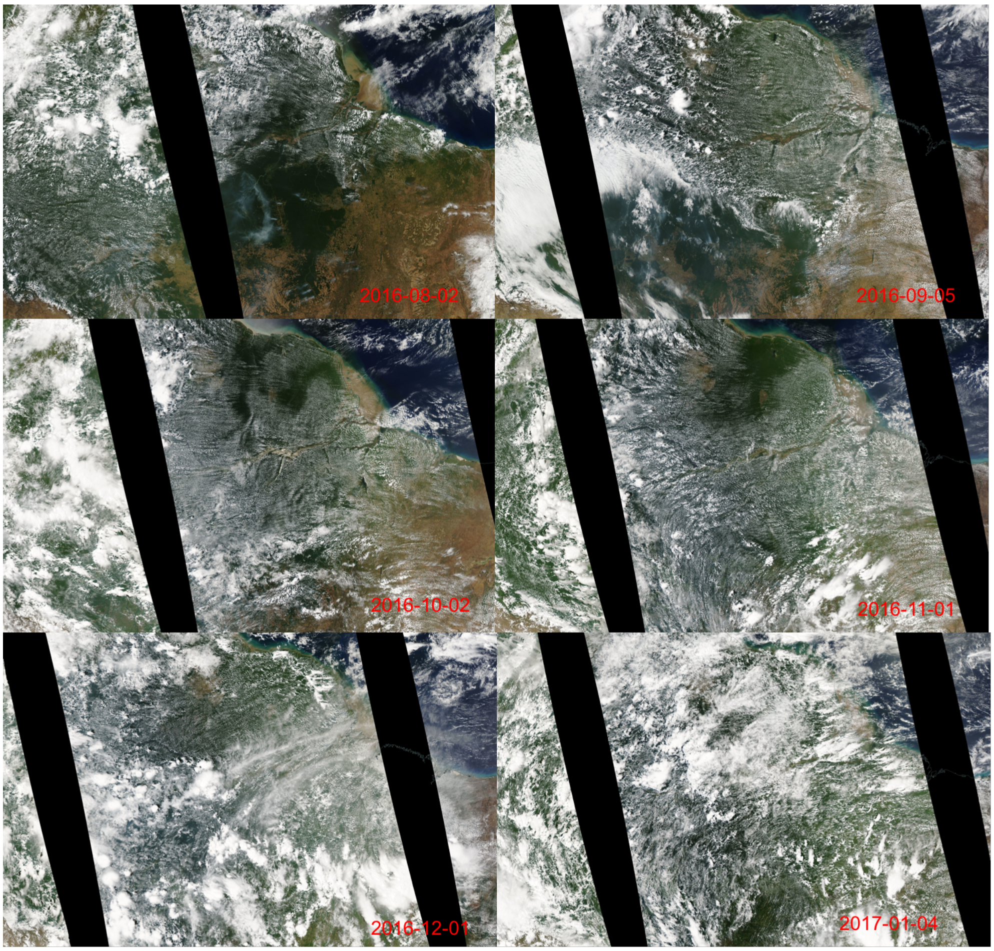


Figure 14: MODIS visible image of the Northwestern Amazon as the basin transition into the wet season. In the dry season surface heterogeneity whether due to rivers, forest-deforested patches or land-ocean contrast are very clear. In the wet season those sharp gradients disappear as cloud cover mostly dominated by deep convection starts organizing at scales independent from the surface heterogeneity.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

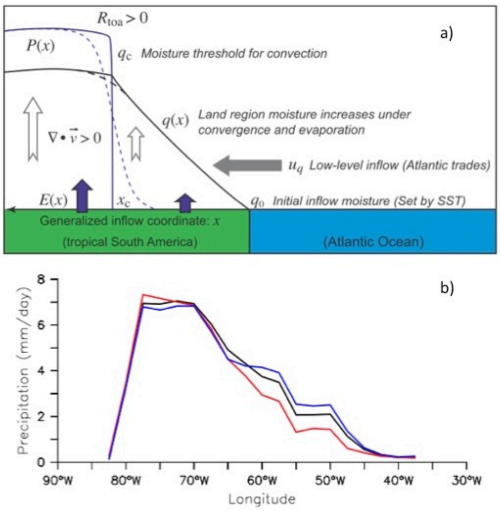
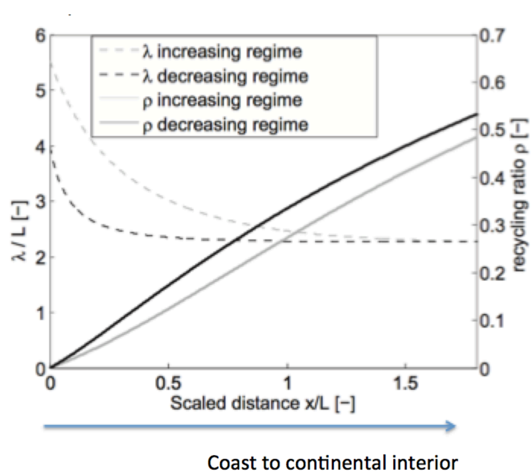


Figure 15: (a) Schematic of the key elements of the convective margins framework as applied along an inflow path across northeastern South America. The solid blue and black lines are precipitation and vertically-integrated moisture, while dashed blue line corresponds to precipitation smeared out by transients. Adapted from Figure 2 of Lintner and Neelin (2009). (b) Rainfall longitudinal transects from the Climate Anomaly Monitoring System (CAMS) raingauge-derived precipitation data for September-October-November for the period 1950-2000 for El Niño (red), La Niña (blue), and all (black) years, averaged over 3.75°S-1.75°S. From Figure 4b of Lintner and Neelin (2007).



$$\rho(x) = 1 - \exp\left(-\int_{x_0}^{x} \frac{E(x')}{C(x')u_x} dx'\right) = 1 - \exp\left(-\frac{x}{\lambda(x)}\right),$$

Figure 16: adapted from Schäfli et al. (2012)

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-12
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 18 February 2019

Hydrology and Earth System Sciences
Open Access
Discussions

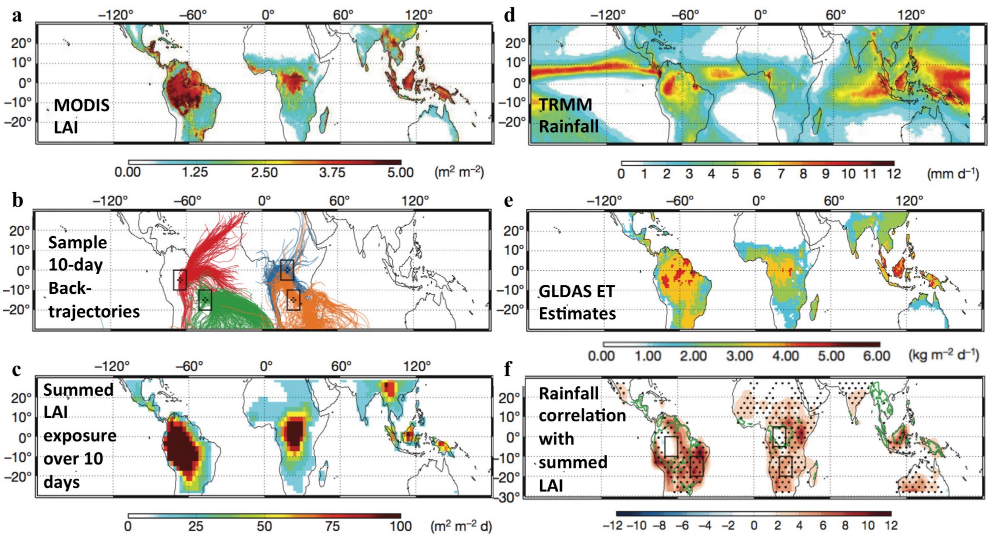


Figure 17: 10 day-backtrajectory analysis over several continental regions of the continental tropics, along with LAI, mean TRMM estimated rainfall, and GLDAS ET estimates.

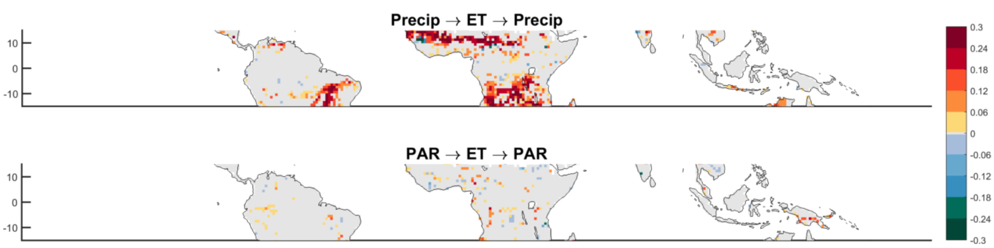


Figure 18: Land-atmosphere feedback strength (change in the variance due to the feedback) between Precipitation and ET (top) and Photosynthetically Active Radiation (PAR) (bottom) based on recent metric developed by Green et al. [2017] using a multivariate Granger causality approach.