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An Atlantic influence on evapotranspiration in the Orinoco and Amazon basins

Nicolás Duque-Gardeazabal[1,2], **Andrew R. Friedman**[1,2,a], **and Stefan Brönnimann**[1,2]

[1]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]Institute of Geography, University of Bern, Bern, Switzerland
[a]now at: Laboratoire de Météorologie Dynamique, Institute Pierre-Simon Laplace, Paris, France

Correspondence: Nicolás Duque-Gardeazabal (nicolas.duque@unibe.ch)

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Abstract. Tropical South America's hydroclimate is influenced by ocean–atmospheric variability modes (drivers of climate variability). It is still not known which physical mechanisms teleconnect the Atlantic modes of variability with South America's soil moisture, net radiation, and terrestrial evaporation (evapotranspiration). Understanding these mechanisms is essential to predict the response of ecosystems. This study uses composites of reanalysis and satellite data to identify the processes linking land–surface anomalies and ocean–atmospheric modes. It estimates the control soil moisture and net radiation impose on evapotranspiration (categorised as water- or energy-limited regimes). It shows that these two local controllers of evapotranspiration are influenced by the position of the Intertropical Convergence Zone (ITCZ). However, the evapotranspiration anomalies are driven by the phase of each climate mode, which alter water and radiation availability. The Atlantic Meridional Mode (AMM) generates cross-equatorial wind anomalies that affect moisture convergence, which in turn modify the cloud cover, precipitation, soil moisture, radiation availability, and hence evapotranspiration. The anomalies have important geographical differences depending on the season analysed; they migrate from the east in austral autumn towards the central Amazon and western Orinoco in austral spring. The Atlantic Niño Equatorial mode (Atl3) affects evapotranspiration in the Guianas and eastern Orinoco by means of pressure and trade wind variability, which in turn affect local hydrometeorological conditions and evapotranspiration. Both Atlantic modes mainly impact regions different from those impacted by El Niño–Southern Oscillation (ENSO), although northeast Brazil and the Guianas might experience overlapping effects. Therefore, these ocean–atmospheric modes impact the water, energy, and carbon cycles; they might influence regional climate extremes (e.g. droughts and floods); and they are critical for achieving sustainable development goals (SDGs).

1 Introduction

The hydroclimate of tropical South America is strongly influenced by ocean–atmospheric variability modes (climate drivers), for instance, El Niño–Southern Oscillation (ENSO) (Cai et al., 2020; Garreaud et al., 2009; Grimm and Zilli, 2009). Other sources of seasonal variability stem from other ocean basins (e.g. the Atlantic, Indian Ocean) and at other temporal scales, from the Madden–Julian Oscillation, or from local features like topography or land–atmosphere interactions (Pabón and Dorado, 2008; Cai et al., 2019). The modes cause impacts through atmospheric circulation anomalies and thus drive local atmospheric conditions; the latter enforces hydrological variability, which is evidenced by anomalies of precipitation, soil moisture (SM), surface temperature, evapotranspiration, and streamflow. The atmospheric anomalies might also influence extreme events (e.g. droughts and floods) (Merz et al., 2021; Mishra and Singh, 2010), and their consideration in long-term planning is critical for achieving sustainable development.

Among the hydrological fluxes, terrestrial evaporation is key to the water, energy, and carbon cycles (Wang and Dickinson, 2012). This flux mainly consists of evaporation from soil, interception, and plant transpiration (hereafter all jointly

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referred as evapotranspiration – ET). Limitations of ET influence growth processes and hence carbon uptake; previous studies have linked net primary or biome production variability to SM–atmosphere feedbacks and climate/earth system drivers, e.g. through climate-driven droughts (Nemani et al., 2003; Humphrey et al., 2021; Zhao and Running, 2010). There is evidence that individual extreme-weather events can coerce plant phenology, for instance, flowering, leaf senescence, and plant growth (Ummenhofer and Meehl, 2017). Therefore, to predict ecosystem activity, it is essential to identify the mechanisms of internal climate variability drivers that cause a response in ET. Moreover, estimating the response of ET to climate variability drivers is also necessary to unravel the effects of climate change on hydrology (IPCC, 2021) and to estimate irrigation requirements (Kaune et al., 2019).

In the following, we consider oceanic variability modes in the Pacific and Atlantic as drivers of the climate variability in the Amazon and Orinoco basins (Lübbecke et al., 2018). Some studies statistically looked at the Pacific and Atlantic joint effects on precipitation (Gu and Adler, 2009; Ronchail et al., 2002). Others studied the interannual changes in moisture transport dynamics – imposed by oceanic climatic drivers – and their associated rainfall anomalies over South America (Hoyos et al., 2019; Ruiz-Vásquez et al., 2024). Atlantic trade wind strength and the precipitation anomalies are related to ocean variability modes such as the Tropical North Atlantic mode (TNA) (Arias et al., 2015, 2020; Enfield, 1996), the Atlantic Meridional Mode (AMM) (Chiang et al., 2002; Fernandes et al., 2015; Rodrigues and McPhaden, 2014; Paccini et al., 2021; Drumond et al., 2014), and the Atlantic Niño Equatorial mode (Atl3) (Ruiz-Barradas et al., 2000; Torralba et al., 2015; Vallès-Casanova et al., 2020). The Atlantic modes tend to be active and peak between the austral autumn and spring – MAM, JJA, and SON (the initial letters of the months) – contrary to ENSO, which peaks at the end of the year (SON and D(0)JF(+1)). These Atlantic modes might have contributed to northeast Brazil droughts and the Magdalena River floods in 2011–2012, as well as the Amazon droughts in 2005 and 2010 (Lopes et al., 2016; Marengo and Espinoza, 2016). Although the Atlantic modes are associated with ENSO through atmospheric bridges or extratropical pathways (Compo and Sardeshmukh, 2010; Martín-Rey et al., 2014; García-Serrano et al., 2017; Casselman et al., 2023), each of them has specific regional impacts on sea level pressure (SLP) and hence on atmospheric circulation.

However, the variability in evapotranspiration has received less attention than precipitation. Previous research has established SM and net radiation (Rn) as the primary local controllers of ET (Seneviratne et al., 2010; Hirschi et al., 2014); consequently, ET is classified into two regimes: water limited or energy limited. The annual cycle and the location of the regimes are not known in South America and are important to understand ET variability. Some studies have statistically investigated the teleconnections of ENSO (Moura et al., 2019; Le and Bae, 2020; Miralles et al., 2014) or other climate drivers with the ET around the world (Martens et al., 2018), but the physical causes of these connections are not known. Specifically, it is not known how the interannual changes in moisture transport impact net radiation. In our paper, we focus on the Atlantic modes, which have received less attention in the literature. Moisture recycling is another factor that can impact surface radiation, but previous studies have focused on its impact on regional and distant precipitation rather than on radiation (Staal et al., 2018; Wang-Erlandsson et al., 2018; Zemp et al., 2014; van der Ent and Savenije, 2011). Other research has looked at the influence of Amazon soil moisture memory on ET (Zanin et al., 2024) or how anomalous moisture transport from the TNA affects SM and vegetation indices (Arias et al., 2020), but other Atlantic modes have been overlooked.

Consequently, it is still not known how the variations in regional atmospheric circulation – driven by the Atlantic modes – alter local continental atmospheric conditions and afterwards affect net surface radiation and soil moisture, the two key local controllers of ET. We refer to the latter as the physical mechanisms of the teleconnection, which consist of a chain of progressive physical processes. Ecological processes respond to the variability in hydrometeorological conditions (Eagleson, 2013); by understanding the mechanisms leading to that variability, the community can increase the potential predictability of ecosystem activity. Therefore, this study aims to investigate the physical causes of the link of the AMM and Atl3 with ET in tropical South America at seasonal scale. Other drivers (the Indian Ocean Dipole mode, the Atlantic Multidecadal Oscillation (AMO), etc.) are excluded from our study (see Sects. 3 and 5). Moisture recycling is only briefly discussed in Sect. 5. We aim to answer the following questions:

1. Where and in which season is the evapotranspiration dominated by a water- or energy-limited regime?

2. How do the Atlantic modes drive anomalous atmospheric circulation and influence the variability in local atmospheric conditions, and how do they then affect the local controllers and thus affect evapotranspiration?

3. Where do the dynamics and, thus, the impacts of the Atlantic modes overlap with those of ENSO in time and space?

2 Data

This study uses net radiation, soil moisture (SM), and ET, as well as atmospheric circulation variables, such as SLP, winds, moisture transport, convergence, and rainfall. We use those atmospheric variables because ocean–atmospheric modes drive the regional atmospheric circulation, which afterwards influences the local ET controllers. Sea surface temperature anomalies (SSTAs) are used to identify the ocean–atmospheric modes (Sect. 3). All datasets are downloaded at the monthly timescale and used between December 1979 and November 2020 (except for satellite-based soil moisture; details are in Sect. 2.2); they are aggregated at the seasonal scale and are analysed for each season individually and synchronously. The aggregation method for all variables is the average of the three monthly values, except for precipitation and ET, where we use the sums (Duque-Gardeazabal, 2025).

Satellite and reanalysis data sources each have strengths and limitations. Satellite data can provide some of the needed data, mainly over land, but moisture transport is not available from this source. Reanalysis data are considered physically based interpolations of observations and provide atmospheric variables that satellites do not directly acquire. Satellite-based datasets have difficulties measuring soil moisture over densely forested canopies (Beck et al., 2021). Errors in the root zone SM compromise the estimation of plant water stress and, thus, the skill of the ET estimate. On the other hand, simulations of ET that ingest reanalysis outputs might inherit their biases (Gebrechorkos et al., 2024; Valencia et al., 2023). Although the performance of both data sources has improved in recent years (Beck et al., 2021; Xie et al., 2024), their estimates remain uncertain, and confidence in their inter-annual dynamics rests on the fact that the analysed signals are evident in independent datasets. Therefore, we look for consistency in the dynamics of both sources of information; we do not regrid and do not merge any datasets because we do not perform operations between them. We display the datasets conjointly when necessary and analyse the dynamics unfolding in both data sources (Table 1).

We use SSTAs from the Extended Reconstructed SST version 5 (Huang et al., 2017) – which is used as the primary dataset – and the Hadley Center Sea Ice and SST version 4.0.1 (Kennedy et al., 2019). ERSST is at a 2°, and HadSST is at a 5° resolution.

2.1 Reanalysis

The European Centre for Medium-range Weather Forecasting (ECMWF) ERA5 reanalysis provides information on atmospheric variables that influence the local controllers of evapotranspiration and also relate to the dynamics of the coupled ocean–atmospheric modes (Hersbach et al., 2020). Monthly time series of winds, vertically integrated water vapour flux (VIMF), mean SLP, and vertically integrated moisture flux divergence (MDiv) are taken from it. All atmospheric variables from ERA5 have a 0.25° spatial resolution.

ERA5-Land is a land–surface simulation operationally forced by ERA5, which includes detailed modules on infiltration, four-layer physically based soil water storage, plant water uptake, phenology and transpiration, and evaporation from soil and canopy interception (Muñoz-Sabater et al., 2021; ECMWF, 2023). From it, we download or derive the net surface radiation (Rn), the volumetric soil water content in the first soil layer (hereafter soil moisture – SM), and the total evaporation (hereafter also referred to as evapotranspiration – ET). All variables from ERA5-Land have a 0.1° resolution.

2.2 Satellite

This research uses the Multi-Source Weighted-Ensemble Precipitation v2.8 (MSWEP) (Beck et al., 2019) with a spatial resolution of 0.1°. The dataset is created using rain gauge, satellite, and reanalysis data. MSWEP uses ERA5 rainfall estimates mainly in the extratropics, whereas the ingested satellite data are given stronger weight in the tropics.

In addition, we use three satellite-based datasets: the European Space Agency Climate Change Initiative for Soil Moisture v08.1 (ESA-CCI-SM) (Gruber et al., 2019), total evaporation from the Global Land Evaporation Amsterdam Model v3.8a (GLEAM) (Martens et al., 2017), and the EUMETSAT CLARA-A3 cloud area fraction as a proxy for net radiation (Karlsson et al., 2023), all of them at a 0.25° resolution. ESA-CCI-SM was downloaded at a daily resolution and transformed to monthly values by averaging the days within each month as long as the month had at least four values; the remaining spatial gaps were not filled and were excluded from calculations. GLEAM uses a three-layer conceptual root zone soil module from which vegetation can access water (which considers ESA-CCI-SM assimilation where available). It includes a module for plant stress based on SM and vegetation phenology, and it also provides evaporation from interception and bare soil. GLEAM uses the ERA5 radiation as forcing.

Some eddy-covariance towers are located in the Amazon and other places in South America; their measurements are – in general – after 2000. Baker et al. (2021) managed to use records from one tower with 19 years of data (1999–2017) but highlighted the fact that the data from the other towers were only available for a few years (mainly between 1999 and 2006). Other global products based on FLUXNET towers, such as FLUXCOM (Jung et al., 2019), also have data after 2001. The short time series constrains the possibility of registering several events to analyse the effect of the climate modes (few degrees of freedom). The performance of GLEAM and ERA5-Land ET has been evaluated against eddy-covariance towers and has found correlations of around 0.6 and 0.7 for the evergreen broadleaf forest ecoregion (Muñoz-Sabater et al., 2021; Xie et al., 2024). Therefore, we choose not to analyse eddy-covariance data and assume fair performance of the other two sources.

Table 1. Overview of the datasets used in this study. ERA5 is described in Hersbach et al. (2020), and ERA5-Land is in Muñoz-Sabater et al. (2021) and ECMWF (2023).

	Reanalysis			Satellite		
Variable	Dataset	Spatial resolution	Temporal resolution	Dataset	Spatial resolution	Temporal resolution
Sea level pressure	ERA5	0.25°	Monthly	–	–	–
Winds at 850 hPa	ERA5	0.25°	Monthly	–	–	–
Vertically integrated water vapour flux (VIMF)	ERA5	0.25°	Monthly	–	–	–
Moisture divergence (MDiv)	ERA5	0.25°	Monthly	–	–	–
Precipitation	–	–	–	MSWEP v2.8 (Beck et al., 2019)	0.1°	Monthly
Net surface thermal radiation	ERA5-Land	0.1°	Monthly	CLARA-A3 cloud area fraction (Karlsson et al., 2023)	0.25°	Monthly
Net surface solar radiation	ERA5-Land	0.1°	Monthly	(Karlsson et al., 2023)		
Soil moisture (volumetric water content in the first soil layer)	ERA5-Land	0.1°	Monthly	ESA-CCI-SM v08.1 (Gruber et al., 2019)	0.25°	Daily (aggregated to monthly)
Total evaporation	ERA5-Land	0.1°	Monthly	GLEAM v3.8a (Martens et al., 2017)	0.25°	Monthly
Sea surface	ERSST v5 (Huang et al., 2017)				2°	Monthly
Temperature anomalies	HadSST v4.0.1 (Kennedy et al., 2019)				5°	Monthly

3 Methods

Climate modes and their atmospheric circulation anomalies are expected to impact evapotranspiration through a chain of progressive physical processes. The processes start with anomalies in atmospheric circulation (coupled with SSTAs) and moisture transport (VIMF). Then, the latter changes moisture flux divergence (MDiv), affecting cloud formation, which simultaneously influences precipitation and radiation availability. Precipitation then affects soil moisture, and afterwards, the two local controllers impact evapotranspiration. However, the impacts of the chain are also mediated by the climatological cycle of the ET regime (water limited or energy limited). Consequently, our research starts by determining the annual cycle of the ET regime and of the local controllers (Sect. 3.1). Then, we use composites to show how the chain unfolds, with its final impacts on ET (Sect. 3.2). Finally, we study the joint effects of the Atlantic modes and ENSO (Sect. 3.3) (Duque-Gardeazabal, 2025). Moisture recycling is discussed in Sect. 5.

3.1 Determining the location and annual cycle of local ET controllers

This study explores the two main local controllers of ET (soil moisture and net radiation) (Seneviratne et al., 2010) to afterwards search for the ocean–atmospheric modes that drive those controllers. SM and net radiation are classified by the slope of their multi-linear regression against evapotranspiration, using their seasonally standardised anomalies. This analysis can suggest whether the ET anomalies are associated with water availability or a radiation anomaly (ET regime). The multiple linear regression is then expressed as

$$\mathrm{ET}_{ij} = a_{ij} \times \mathrm{SM}_{ij} + b_{ij} \times \mathrm{Rn}_{ij} + C, \quad (1)$$

where ET is the total evaporation, SM is the volumetric soil water content in the first layer, Rn is the surface net radiation, i refers to a specific longitude, and j refers to a specific latitude. a and b are then the regression slope coefficients and C the intercept.

3.2 Composites

This study uses composite analysis to exemplify the state of the atmosphere and the land surface during the active phase of the Atlantic modes. The composites reveal the physical processes/mechanisms that connect the variables.

Coupled ocean–atmospheric modes are identified by SSTA indices. The SSTAs are first detrended to exclude the effect of climate change from the analysis, using a regression with de-seasonalised CO_2 ($R^2 = 0.92$, $p < 0.001$) (Thoning et al., 1989); the CO_2 concentration is used to consider its continuous change in the 20th and 21st century and to avoid subtracting the internal variability. We performed principal component analysis over the detrended Atlantic SSTAs, and the resulting loadings were compared with the literature review (Fernandes et al., 2015; Vallès-Casanova et al., 2020; Ruiz-Barradas et al., 2000) (Supplement Fig. S8). Correlation analysis between the principal components and hydrological variables revealed which modes possibly have an impact on South America (not shown). Other climate modes, such as the Indian Ocean Dipole or the AMO, unfold over basins that are not close to our study area, and hence, they do not alter tropical South America's atmospheric circulation. Consequently, we discard them from our analysis. We define the Atlantic indices based on SSTA area-average boxes similar to the principal component loadings of the Atlantic SSTs (Fig. S8).

- The AMM monthly index is defined as the difference between the spatially averaged Tropical North Atlantic (TNA) SSTAs (5–25° N, 70–15° W) and those of the Tropical South Atlantic (TSA) (25–5° S, 40–0° W); the spatial definition of the AMM comprises the TNA.
- The Atl3 monthly index is identified as the spatial average of eastern equatorial Atlantic SSTAs (3° S–3° N, 20° W–0°).

To define the composite time steps, the phases of each mode are established based on the indices. The positive and negative phases are identified when their indices are above or below ±1 standard deviation, respectively, and otherwise are defined as neutral phase. The latter is defined individually for each season (index time series in Fig. S8). The asymmetric impacts of the modes are assessed by adding both extreme phases (positive plus negative), allowing recognition of the different impacts exerted by each phase. The composite's statistical significance is assessed with the two-sample Student two-tailed t test, testing the positive or negative phase against the neutral. Regarding precipitation, half of the cell's time series has skewed distributions (Shapiro–Wilk test, not shown). Thus, the Mann–Whitney U test is used instead. We did not find a significant correlation between evapotranspiration and CO_2. Nevertheless, ET time series are detrended with a linear trend to also exclude global warming (Zhang et al., 2016) before being used in the composites.

ENSO develops in the second semester, and its peak season is DJF. On the other hand, the AMM is more active from February onwards but might last until SON (Yoon and Zeng, 2010), and the Atl3 is more active in JJA (Vallès-Casanova et al., 2020). In DJF, the AMM-associated anomalies are evident over the Atlantic, but its effect over the continent is diluted (not shown). Therefore, we analyse the influence of the Atlantic modes from March to September.

3.3 Conjoint effect with ENSO

We also perform a grid-wise partial correlation analysis between the two Atlantic indices, the El Niño Longitude Index (ELI) (Williams and Patricola, 2018), and evapotranspiration. The ELI considers the type of ENSO event (east or central Pacific). The purpose of this analysis is to find those regions that are driven by an Atlantic mode but might also have impacts from another mode when it is also active (i.e. simultaneously controlling the analysis by the effect of ENSO and the other Atlantic mode).

4 Results

4.1 Key local evapotranspiration controllers

The classification of the ET regime follows the migration of the Intertropical Convergence Zone (ITCZ, located in the southern Amazon in DJF and over northern Orinoco in JJA) (Fig. 1). The reason is associated with the heavy rainfall in the ITCZ, which saturates the soils and influences the locations of the energy-limited regime. Panels (a) to (h) in Fig. 1 show the slope coefficients of the regressions, which are then ranked in panels (i) to (l). Values below 0 indicate that the other independent variable is the main controller of ET. In MAM (Fig. 1a, e, i), the northeasterly winds bring moisture from the Atlantic and produce convergence and rainfall over the Amazon in such amounts that the soil saturates (and thus is above the soil's water field capacity), giving the conditions for energy-limited ET. However, the north of the Orinoco basin still behaves like a water-limited environment. As the ITCZ moves northward in JJA (Fig. 1b, f, j), the rainfall recharges SM, changing Orinoco's behaviour to an energy-limited regime, whereas other regions transform from energy- to water-limited regimes, such as northeast Brazil and the southern Amazon. The core of the Amazon rainforest is energy limited throughout the year. In SON (Fig. 1c, g, k), the ITCZ begins to move southward, but the energy-limited regime is concentrated in the west of the Amazon. The east and southeast basins are still in a water-limited regime. The Orinoco still behaves in an energy-limited way even though this is the transition season from wet to dry. In DJF (Fig. 1d, h, l), the ET in the southern Amazon depends on the available energy, as the ITCZ has reached its southern continental location; above-average net radiation (Rn) would produce more ET. The energy-limited regions correspond to those where SM is above the soil's field capacity (ECMWF, 2023) (not shown), and not all of the continent is primarily controlled by variations in energy supply.

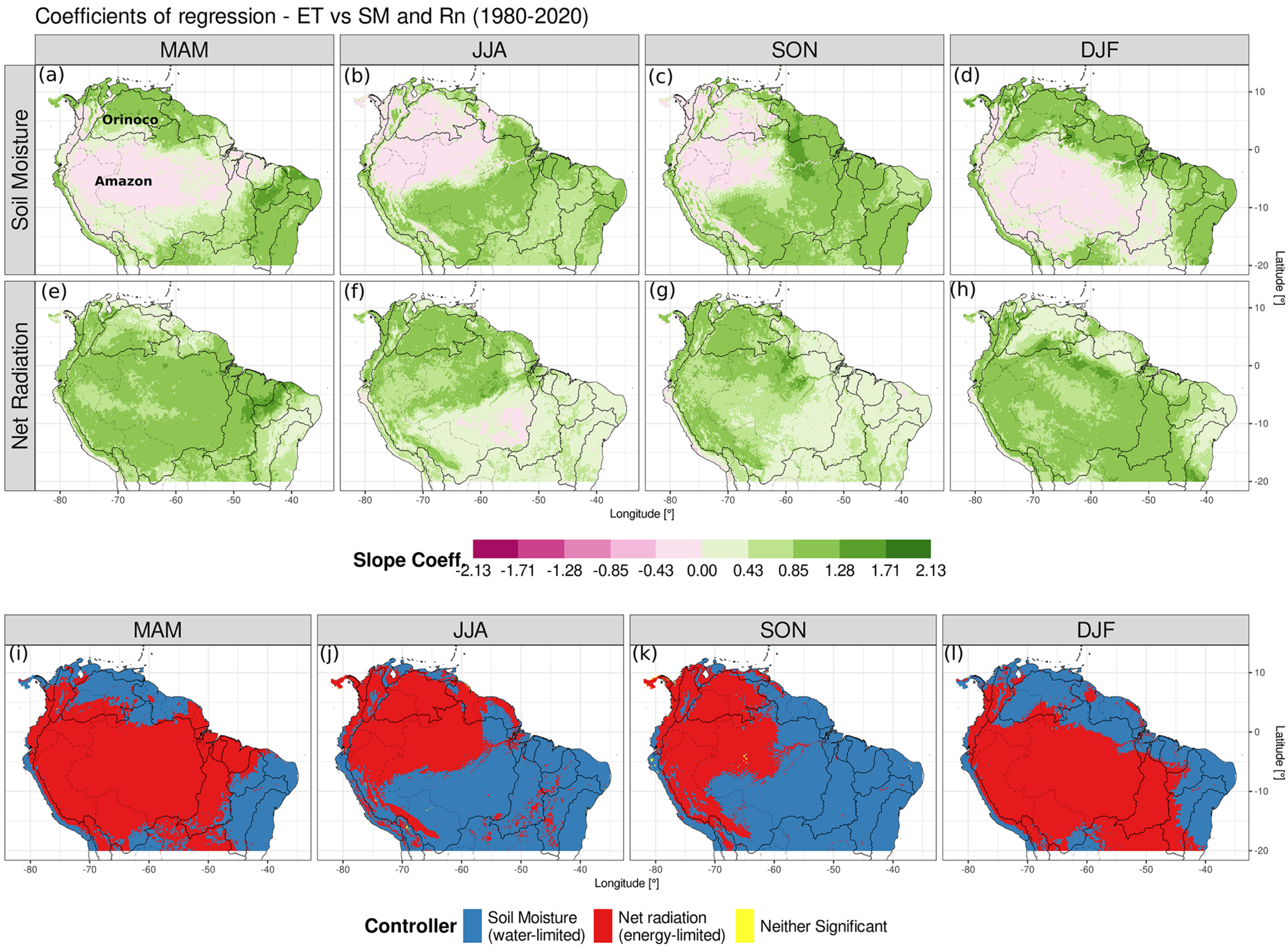

Figure 1. Classification of the ERA5-Land evapotranspiration (ET) controller based on regression coefficients for each season. **(a–d)** Multiple linear regression slope coefficient for soil moisture (SM), **(e–h)** the slope coefficient for the net radiation (Rn), and **(i–l)** the variable with the highest significant linear slope coefficient ($p \leq 0.05$). Panels are divided by season: panels **(a, e, i)** for MAM, panels **(b, f, j)** for JJA, panels **(c, g, k)** for SON, and panels **(d, h, l)** for DJF. Black lines delineate the major river basins; the same boundaries are used in the following figures.

4.2 Chain of physical processes between the Atlantic modes and continental evapotranspiration

This section shows the composites of the variables involved in the chain (see Sect. 3). The steps in the chain repeat as long as a mode is active. However, the impacts have important geographical differences depending on the mode and the season analysed.

4.2.1 March–May (MAM): austral autumn

The Atlantic Meridional Mode (AMM) consists of an SST and SLP seesaw between the tropical North and South Atlantic, creating cross-equatorial wind anomalies (see Fig. S1 for SLP and 850 hPa winds composites). In austral autumn, the positive phase redirects and advects moist air northward, towards the Orinoco, where it provokes positive convergence and precipitation anomalies (Fig. 2a). The locations of the satellite precipitation and reanalysed convergence anomalies are consistent in both datasets. The positive convergence creates more clouds that then reduce net surface radiation (Fig. 2c). Soil moisture (SM) is impacted by the anomalous rainfall; Fig. 2e shows that the SM anomalies in northern Orinoco are sensitive to the AMM in the positive phase. ESA-CCI-SM is available for this region and shows similar dynamics (Fig. S2). The western and southern Amazon have SM anomalies lower than a 2 % absolute value, as it is the rainy season and the soil is near saturation.

The evapotranspiration is impacted afterwards. The Orinoco behaves in a water-limited way (Fig. 1i) since this is the transition from the dry to the wet season; then the increase in rainfall and SM causes above-average ET (Fig. 2g). Over northeast Brazil, the positive phase produces divergence anomalies and less cloud cover (Fig. 2a and c). The lat-