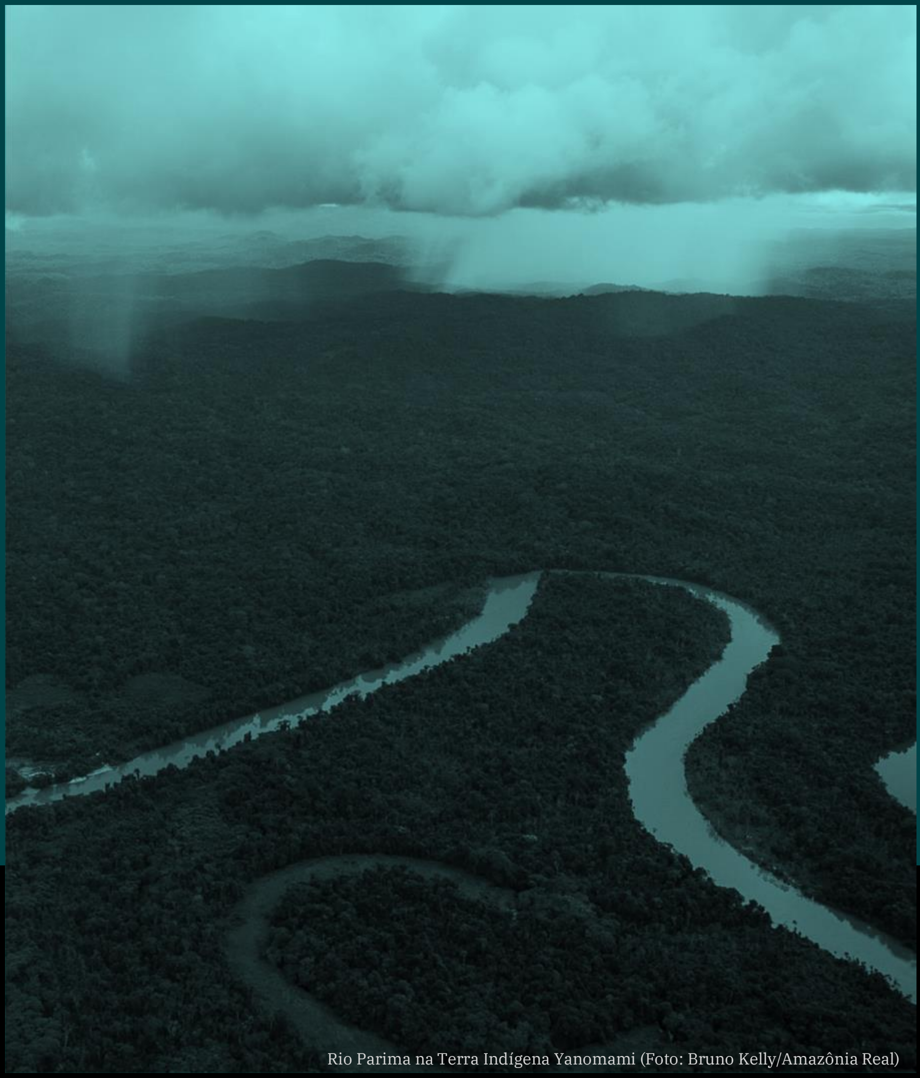
Amazon Assessment Report 2021

Chapter 7

Biogeophysical Cycles: Water Recycling, Climate Regulation



Rio Parima na Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT

Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK

A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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Graphical Abstract

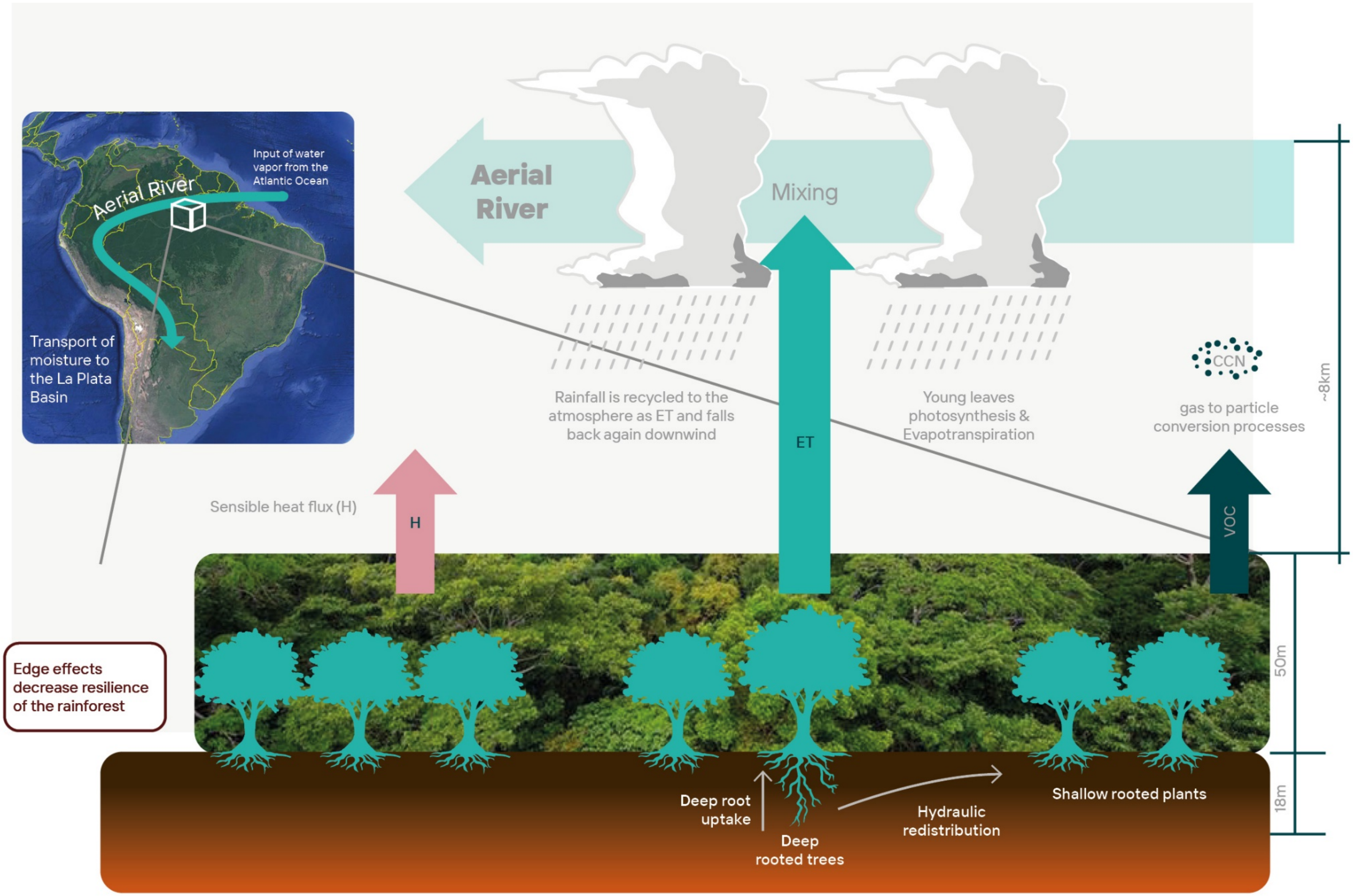

Figure 7.A Graphical Abstract

Biogeophysical Cycles: Water Recycling, Climate Regulation

Marcos H. Costa[*1], Laura Borma[2], Paulo M. Brando[3 4 5], José A. Marengo[6], Scott R. Saleska [7], Luciana V. Gatti[2]*

Key Messages

- The Amazon rainforest can cycle large amounts of water vapor from the soil to the atmosphere via evapotranspiration (ET). The Amazon basin's average recycling ratio varies from 24% to 35%, with a median value of 28%.
- The central and northwestern parts of the Amazon export moisture to the Andes via diverse atmospheric (or aerial) rivers that supply water for tropical glaciers, páramos, and cities. The south-western part of the Amazon Basin is an important direct source of moisture for the La Plata Basin year-round, with moisture transported via the South American low-level jet.
- The amount of forest cover regulates the local temperature and the amount and timing of precipitation, with forest loss (increase) leading to reductions (increases) in rainfall and subsequent impacts on forest cover. Locally, the replacement of deep-rooted rainforest trees with grasses or crops warms the microclimate because of lower ET, despite higher albedo of senesced vegetation. If affected areas are large enough, this can affect rainfall, especially at the end of the dry season, with implications for forest degradation, forest flammability, and crop yields.
- The most important changes in the hydroclimate system occur in the transition between the dry and rainy seasons, with a lengthening of the dry season in regions affected by meso- to large-scale (10-1,000 km^2) deforestation, which has important ecological and hydrological consequences. Future studies should focus on these seasonal transitions.
- Very few (if any) of the new advancements in forest edge degradation have been included in the processes simulated by Earth System Models (ESMs). Projecting the future of Amazonian forests requires a better representation of forest edge effects in ESMs.

Abstract

The warm and humid climates that sustain Amazonian rainforests are partly a consequence of interactions between the forest and the atmosphere. This chapter assesses the biogeophysical processes by which the rainforest provides moisture and energy to maintain its own climate. A combination of several plant traits and processes – low albedo, rough canopies, deep rooting, plant hydraulic lift, and biological regulation of water flux through leaves – allows the capture of water stored at deep soil layers. These mechanisms provide a steady flow of water vapor into the atmosphere, which is recycled internally in the Amazon and is a major water vapor source to other South American regions. Regionally averaged, about 28% of the rainfall in the Amazon has fallen at least once, with this fraction increasing westward, until it exceeds 50% at the foot of the Andes. The rainforest also plays an important climate regulation role in the southern Amazon during the dry-to-wet season transition (Sep-Oct). Forested areas have an early onset and late end of the rainy season (Oct-Apr). They are also associated with a low frequency of dry spells of

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any duration in the transition months between the dry and the rainy seasons (Mar-Apr, Sep-Oct) when compared to highly deforested areas. Finally, the intense loss of latent heat through ET maintains air temperature below 30°C, which is near-optimal for photosynthesis, and consequently, carbon uptake.

Keywords: Aerial rivers, deep soil moisture capture, temperature regulation

7.1 Introduction

The Amazon is well known for two remarkable characteristics: the rainforest and its warm and humid climate. The Amazon rainforest is perhaps the most luxuriant biome globally, with high biomass, tall canopy, and rich biodiversity (Chapter 3). The annual long-term average of rainfall ranges from 2,000 to 2,300 mm, depending on the period used for calculation and whether the Tocantins Basin is included or not (Table 1, Chapter 5). In the rainiest parts of the region, rainfall may reach 6,000-7,000 mm/yr at the Andes' feet (Section 5.3.5, Chapter 5). A "relatively dry season" is found in specific places, such as the southern border of the Amazon, near the transition to the cerrado (savannas of Central Brazil), and in the south-north axis around Santarém (in Pará State, Brazil). "Relatively dry season" describes a season in which the monthly mean precipitation is below monthly ET rates, but still presents high precipitation amounts (~100 mm/mo, as defined by Sombroek 2001). A six-month-long dry season is found on the upstream areas of the southern tributaries of the Amazon River (Tapajós and Xingu rivers), in most of the Tocantins Basin, in the state of Roraima (Brazil), and to the north of Boa Vista (Roraima's capital city), where annual rainfall can be as low as 1,500 mm. Monthly mean temperatures vary between 26°C and 28°C for the lowland Central Amazon, and the annual mean decreases with altitude. In the Andean highlands, the annual mean temperature is 12.6°C in Sucre, Bolivia (elevation 2,800 m), 12.8°C in Cajamarca, Peru (2,740 m), and 6.8°C in La Paz, Bolivia (3,650 m). Seasonality (monthly mean temperature amplitude) increases with latitude, varying from about 2°C near the equator to about 4°C in Brasília (16°S). For locations of the cities, rivers, basin, and biome borders, refer to Figure 7.1.

These two remarkable characteristics – the luxuriant forest and the warm and humid climate – are intrinsically connected by two-way biogeophysical interactions, or cycles. Obviously, the presence of the rainforest in the Amazon is a consequence of the rainy climate that exists there; the tropical rainforest could not grow in a cool or dry environment. However, the functioning of the rainforest also helps produce the warm and humid climate necessary for its permanence. The rainforest interacts with the atmosphere in several ways, which affects the local, continental, and global climate. A major process is the recycling of water (Section 7.2.1). Following the water cycle process, winds near the ocean surface bring moisture from the tropical Atlantic Ocean into the Amazon. Part of this moisture falls as rain, and a portion of the fallen rain may quickly be returned to the atmosphere by the forest through evapotranspiration (ET). Some of this water vapor will come back as rainfall over the rainforest, and some is transported to neighboring regions.

This injection of water vapor does not present significant seasonal or interannual variability, which may be explained by several traits and processes associated with the rainforest, such as deep root capture, hydraulic redistribution, and biological synchronization of new leaf emergence with the dry season (Section 7.2.2).

This chapter assesses the biogeophysical interactions between the Amazon rainforest and the climate. A historical perspective is presented, highlighting breakthroughs that improved our understanding of the mechanisms by which the rainforest interacts with the atmosphere.

Figure 7.1 Orientation map. Biome map of South America, with main rivers and towns. Sources: WWF (https://www.world (wild-life.org/publications/terrestrial-ecoregions-of-the-world), RAISG (2020), WCS- Venticinque (2016).

7.2 The role of forests in water recycling

7.2.1 Water recycling in the Amazon

7.2.1.1 General concepts about water recycling

Water recycling is the process by which ET in a specific location on the continent contributes to precipitation in another place on the continent (Zemp *et al.* 2014). The recycling ratio (ρ) is the ratio of precipitation of continental origin divided by the total precipitation. It depends on several conditions, including spatial scale, the ratio of local ET to other water vapor sources, and the extension of the region downwind.

First, consider the scale. At one extreme, on the global scale, all water molecules evaporate from the Earth's surface, stay in the atmosphere for a few days, and then precipitate back. The recycling ratio is then 100%. At the other scale extreme, an infinitesimal area on the land surface, the probability that a water molecule that evaporates from that area precipitates back inside it is near zero (Eltahir and Bras 1996). A large region like the Amazon tends to have a high recycling ratio, but in between these two scales, regional recycling is more complex.

Figure 7.2 explains the dependence of recycling on the extension of the region downwind. Consider two rectangular areas of the same size, but one has its main dimension across the dominant winds (Figure 7.2a), while the other has its main dimension alongside the prevailing winds (Figure 7.2b). All other conditions (moisture transport from the ocean, precipitation, and evapotranspiration rate) are the same. The longer the dimension of the region along with the dominant winds, the higher the recycling.

Moisture recycling can be calculated from any source region where it evaporates (i.e., the Amazon) to any destination region where it precipitates (e.g., the Amazon Basin itself, including the Andes or the La Plata Basin). This section will first explore the role of recycling within the Amazon Basin and then its role as a source of water to other regions.

7.2.1.2 Historical perspective on the studies of water recycling in the Amazon basin

Classical climatological texts (Sellers 1965; Budyko 1974) consider that local ET is of minor importance as a source of precipitable water over continents. However, this assumption may not be accurate over a continental area where the ET reaches high rates, such as tropical rain forests.

The classical methodology (see, for example, Budyko, 1974) to calculate the recycling of water via ET states that, for a stable climate and in the long term, if there is no recycling; the net advection of water vapor to a region would be balanced by the hydrological runoff. Thus, using atmospheric sounding and hydrological measurements, one can calculate the recycling.

Molion (1975) first suggested that precipitation over the Amazon depends highly on local ET. Using the classical methodology described above, he concluded that the advection of water vapor contributes only 44% of the Amazon Basin's rainfall, while local ET provides the remaining 56%. Continuing this work, Lettau *et al.* (1979) presented data on the variation of the ratio between the total precipitable water and the precipitable water of oceanic origin according to longitude. Since the main wind direction is from east to west, the increase in the proportion of precipitable water from sources other than the ocean suggests that this source is ET. They also calculated that 88% of the rainfall in the westernmost part of the Amazon is water vapor that has fallen at least once previously.

Dall'Olio *et al.* (1979) used concentrations of the stable isotopes ^{18}O and ^{2}H (deuterium) as tracers to study the origin of the precipitable water in the Amazon region. The different masses of isotopes in water cause a distillation that concentrates the heavier isotopes (^{18}O and ^{2}H) closer to the original source of the precipitation and increasingly light isotopes (^{16}O and ^{1}H) with every recycling stage along the way. They concluded that the water vapor

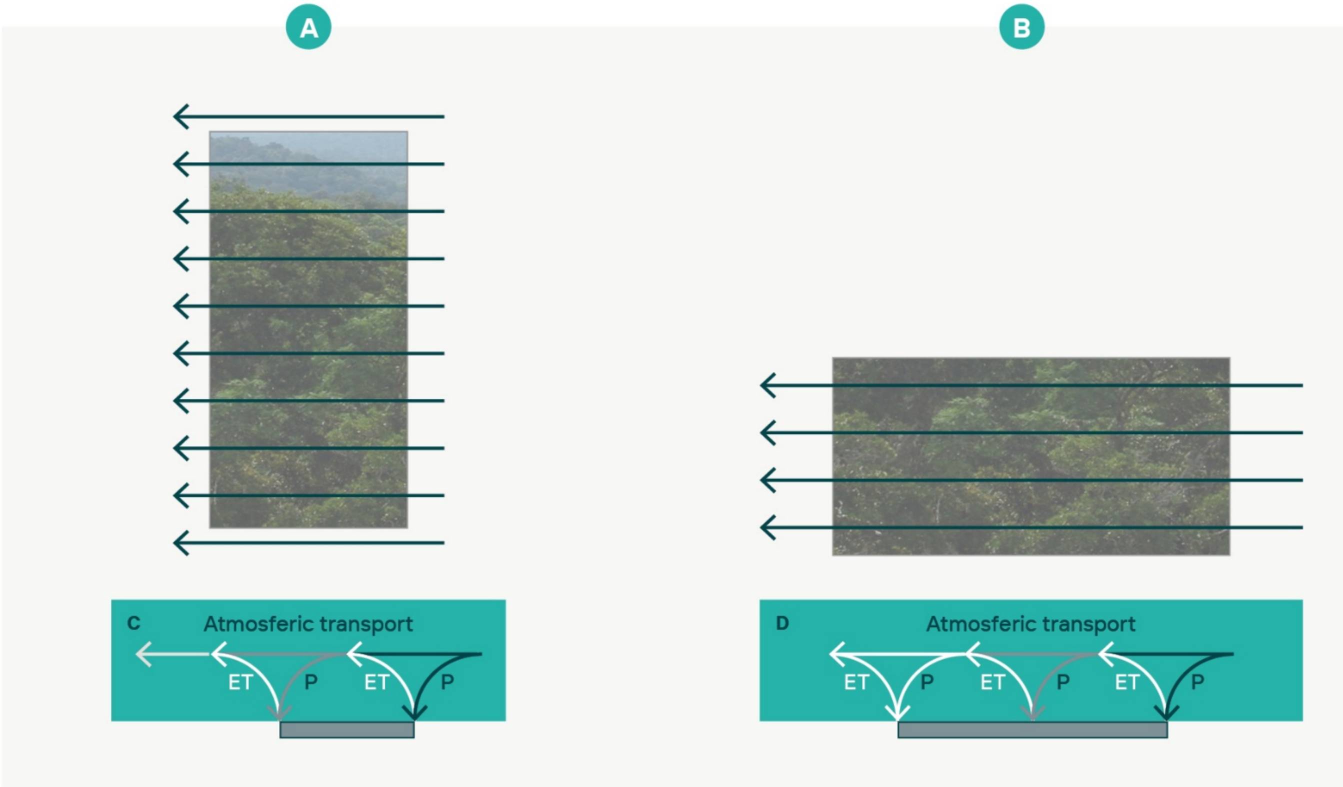


Figure 7.2 Schematic diagram of water recycling of two identical regions (A and B), differing only with respect to the wind direction. P is precipitation, and ET is evapotranspiration. Black arrows represent water vapor flux of oceanic origin, and white arrows indicate water vapor flux originated at the land surface. Shades of gray arrows represent the proportion of oceanic versus land surface water vapor.

flux from the ocean is smaller than the total precipitation over the basin, so it was necessary to consider at least one other water vapor source. Since there was no meteorological evidence of additional external sources of water vapor, they suggested that ET could provide the additional required moisture source. Their data indicated that, on average, both the sources (ocean and forest) are of the same magnitude, which suggests that the vegetation recycled 50% of the precipitation water.

Salati *et al.* (1979), using the same data of Dall'Olio *et al.* (1979), reported that, despite the Amazon basin's appearance as being a relatively uniform hydrometeorological unit, the seasonal and geographic variability of the isotopic data demonstrates the heterogeneity of the region from the hydrometeorological point of view, pointing out variations related to seasonality and location, with the Central and Western Amazon being areas where large amounts of water are recycled. In their classical review, Salati and Vose (1984) said that about 50% of the rainfall is from ET into the atmosphere, of which about 48% falls again as rain.

Nobre *et al.* (1991) calculated water budgets for the Amazon using atmospheric sounding data from the Global Tropospheric Experiment with at least two vertical profiles a day for a prolonged period. They concluded that about 50% of the rain originated from ET and 50% from moisture transport from outside the basin.

However, the soundness of these early estimates was limited by the low availability of the atmospheric sounding measurements, and several questions remained. First, climatological calculations of the recycled water ratio were not available. Second, the interannual variability of precipitation (ranging from 2,000 to 2,800 mm yr^{-1} in a 10-year return period) is much higher than the interannual variability of ET (see Section 5.4, and Chapter 5), and it was unclear how the sources of water vapor to precipitation vary simultaneously to the year-to-year variability of rainfall and ET.

In addition, these initial estimates considered that both the Andes and the Central Brazil plateau were important barriers to water vapor flux. Thus, they assumed that the water vapor flux out of the basin was close to zero. Moreover, Savenije (1996) demonstrated that, under this assumption, $\rho = 1 - C$, where C is the runoff coefficient, which is about 0.5 for the Amazon River. In conclusion, this assumption overestimated the recycling ratio. The ρ estimation did not improve until the next scientific breakthrough: four-dimensional global wind and moisture datasets.

7.2.1.3 Modern estimates

The advent of four-dimensional wind and moisture datasets in the 1990s (three space dimensions plus one time dimension), including atmospheric reanalysis products, allowed the calculation of spatial and temporal patterns of the recycling ratio. These datasets demonstrated that there is indeed a small flow of water vapor across the Andes, and a significant flow of moisture southward, towards central and southern South America (Section 7.2.3). Several studies used these datasets and different methods to calculate recycling, summarized in Table 7.1. The Amazon Basin's average recycling ratio varies from 24% to 35%, with a median value of 28%, or about half of what was previously estimated.

Of the estimates in Table 7.1, Staal *et al.* (2018) use a slightly different definition of water recycling. They count multiple evaporations of the same water molecule multiple times, yielding $\rho > 100\%$ in some months (see Staal *et al.* 2018, Fig. S5). This method also slightly overestimates the recycling ratio when compared to the other studies.

Even these more recent estimates may have limitations. Moisture tracking models vary widely in complexity, depending on the number of physical processes represented (Dominguez *et al.* 2020). Complex models are comprehensive in their physical representation, but computationally much more expensive. Simple models are faster to run, but focus on specific physical processes and simplify assumptions. A common assumption in simple models is that water vapor is well-mixed inside the atmosphere's vertical column. The well-mixing assumption can also be subdivided into several components, i.e., well-mixed during evaporation, transport, and precipitation. For example, the vertical height from where water vapor contributes to precipitation is not necessarily proportional to the level's specific humidity.

In regions where convective precipitation dominates, like the Amazon, water vapor from lower atmospheric levels contributes significantly more to precipitation than upper-level moisture, a process that has been called "fast recycling" (Lettau *et al.* 1979) and leads to an underestimation of terrestrial sources of moisture by simple models when compared to water vapor tracers in climate models (Goessling and Reick 2013; Dominguez *et al.* 2020).

On the other hand, there are models for tracing water vapor sources and pathways in the atmosphere that use Lagrangian particle tracking, like the NOAA HYSPLIT trajectory model (Stein *et al.* 2015) or the Weather Research and Forecasting regional climate model with Water Vapor Tracing (WRF-WVT) (Insua-Costa and Miguez-Macho 2018). These models explicitly simulate or parameterize processes like convection, microphysics, turbulence, and particle tracking, but have the disadvantage of being computationally expensive. Both methods (Eulerian and Lagrangian) can also be sub-divided into offline calculations (performed on previously generated datasets) or online calculations (performed while the model is running) (Dominguez *et al.* 2020). The online Lagrangian models, relying on prognostic water tracers built-into global or regional climate models, may provide

Table 7.1 Studies to calculate recycling.

Study	Method	Data Set	Period	ρ (%)
Brubaker *et al.* (1993)	Atmospheric bulk model	GFDL and NCAR	1963-1973	24
Eltahir and Bras (1994)	Atmospheric bulk model	ECMWF analysis	1985-1990	25
Trenberth (1999)	Atmospheric bulk model	CMAP and NCEP-NCAR reanalysis	1979-1995	35
Costa and Foley (1999)	Atmospheric bulk model	NCEP/NCAR reanalysis	1976-1996	30
Bosilovich and Chern (2006)	AGCM with passive water vapor tracers	initial conditions from the model; no time-evolving boundary conditions	1948-1997	27.2
Dirmeyer *et al.* (2009)	Quasi-isentropic back-trajectory (Lagrangian tracking)	NCEP/DOE reanalysis	1979-2003	28
van der Ent *et al.* (2010)	Eulerian atmospheric moisture tracking method	ERA-Interim reanalysis	1999-2008	28
Zemp *et al.* (2014)	Eulerian atmospheric moisture tracking method	TRMM for (P) and MODIS for ET	2001-2010	28
Zemp *et al.* (2014)	Eulerian atmospheric moisture tracking method	Land surface model for ET, average of CRU, GPCC, GPCP and CPC for P	1990-1995	24
Staal *et al.* (2018)	Eulerian atmospheric moisture tracking method/ cascade recycling	GLDAS	2003-2014	32

more physically consistent values. On the other hand, running them for a long time to calculate the climatological recycling ratio values will most likely lead to severe biases if boundary conditions are not constantly updated. In summary, all methods have advantages and disadvantages. It is unclear today what would be the effect of substituting the well-mixing assumption by the Lagrangian tracking on calculating the recycling ratio.

Nevertheless, these studies also concluded that the recycling ratio varies both spatially, seasonally, and interannually. Several authors, like van der Ent *et al.* (2010), Zemp *et al.* (2014), and Staal *et al.* (2018), provide spatially-explicit calculations of the recycling ratio. They show that ρ is close to zero near the mouth of the Amazon, where moisture from the ocean enters the Amazon, to >50% close to the Andes (Figure 7.3). The mechanical uplift from the mountains and the Andes' concave shape induce low-level convergence several hundred kilometers before the Andes, facilitating high precipitation rates and hindering moisture from crossing the Andes and leaving the basin.

Recycling is also higher during the dry season than during the wet season (contrast Figure 7.3a with Figure 7.3b). During the dry season, the input of moisture from the ocean decreases, and the steady flux of water from the rainforest increases the importance of this local source. As explained in Section 5.4 of Chapter 5 and below in Section 7.2.2, in most of the Amazon, ET is not controlled by the availability of soil moisture but rather by the availability of energy to evaporate water, hence the low seasonal variability. This is because Amazonian trees have access to water stored in deep soil layers and consequently do not suffer much water stress.

The stability of local ET is also associated with the variability of ρ at interannual and decadal time scales. For example, Costa and Foley (1999) found a weakening of the trade winds that transport water vapor from the tropical Atlantic ocean into the Amazon basin during 1976-1996, which caused a decrease in the input of water vapor to the Amazon Basin. In this case, the main source of water vapor to the basin decreased by about 720 mm/yr in 20 years (from 3,430 mm/yr in 1976-77 to 2,710 mm/yr in 1995-96, or 36 mm/yr^2); however, the Amazon Basin maintained precipitation and runoff by increasing the relative contribution of the local source of water vapor (regional ET) from 28% in 1976-77 to 33% in 1995-96.

7.2.2 Mechanisms to capture deep soil moisture by trees

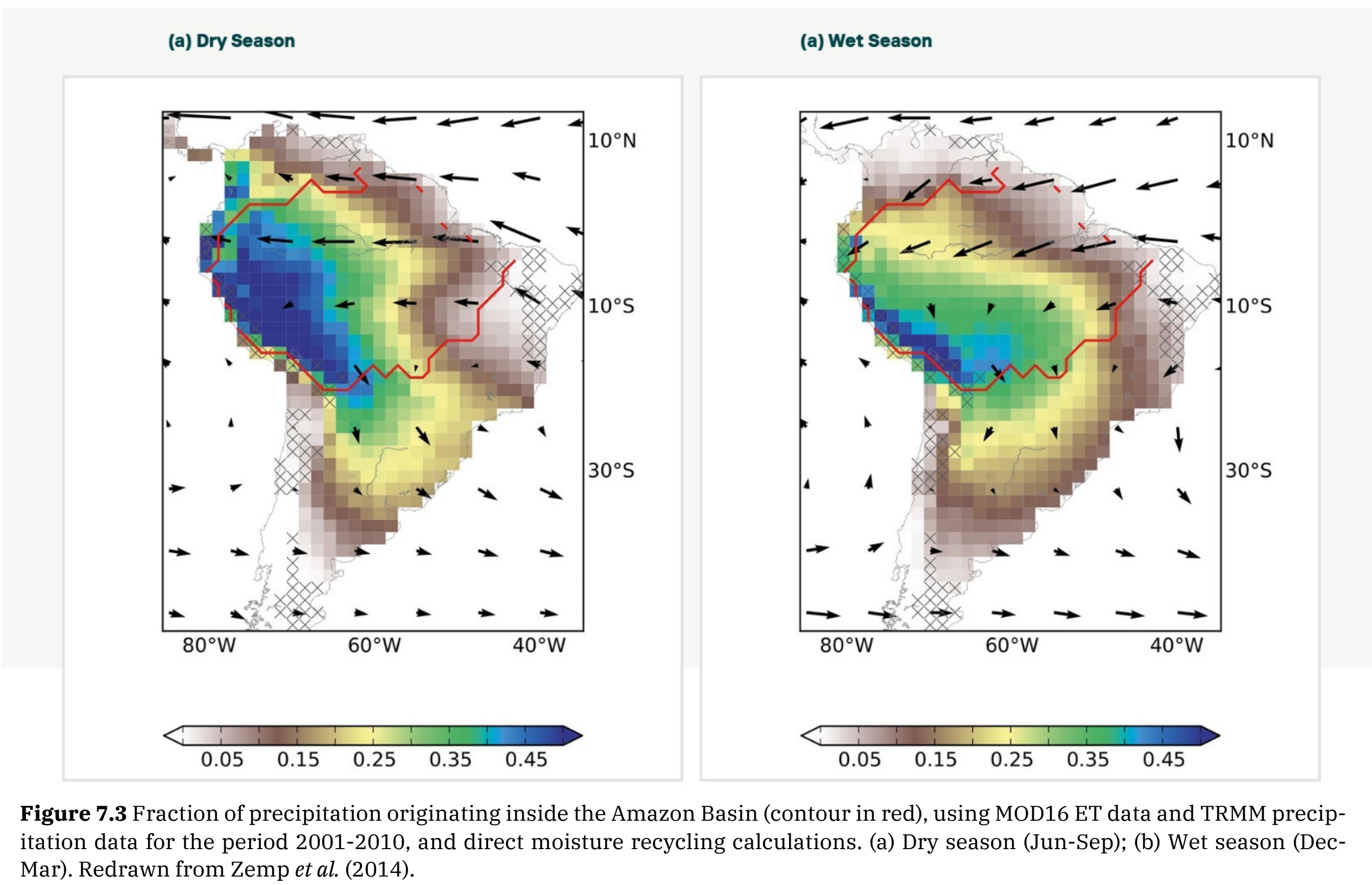


Figure 7.3 Fraction of precipitation originating inside the Amazon Basin (contour in red), using MOD16 ET data and TRMM precipitation data for the period 2001-2010, and direct moisture recycling calculations. (a) Dry season (Jun-Sep); (b) Wet season (Dec-Mar). Redrawn from Zemp *et al.* (2014).

Another breakthrough in understanding the rainforest's role in regional climate was direct measurement of ET using eddy-covariance techniques at several Amazonian upland forest experimental sites. These observations indicate that dry-season ET rates across central Amazonian forests peak during the dry season, consistently exceeding wet season values (Shuttleworth 1988). These observations imply that ET in these forests is regulated by the annual cycle of incoming radiation (which typically increases during the dry season due to a more vertical sun and diminished cloud cover), with dry season ET comparable to, or even consistently exceeding, wet season values (Hasler and Avissar 2007). The more complex seasonal ET dynamics of moisture-limited southern Amazonian upland forests indicates joint regulation by environmental (e.g., net radiation, vapor pressure deficit) and biological factors (forest canopy conductance) in these forests (Da-Rocha *et al.* 2009; Costa *et al.* 2010; Restrepo-Coupe *et al.* 2021).

These findings contradict common understanding (see the discussion between Werth and Avissar 2004, Costa *et al.* 2004), and simulation results from most land surface models, which show a decrease in ET and productivity during the dry season and drought periods because of water limitation (Christoffersen *et al.* 2014; see also Section 5.4 of Chapter 5).

This discussion focuses on upland forests' deep-water uptake mechanisms, as seasonally flooded forests are assumed to be less likely to be water-limited. Several studies have proposed different mechanisms to explain the drought (seasonal or extreme) tolerance of Amazonian rainforests. These mechanisms include deep-root water uptake, plant hydraulic lift, and leaf regeneration in the dry season.

As discussed in Chapter 5, Amazonian soils, due to their predominant clay texture in the plateau area, store, in the wet season, large amounts of rainfall that is released to plants during the dry season (Bruno *et al.* 2006; Chauvel *et al.* 1992; Hodnett *et al.* 1995; Nepstad *et al.* 1994). As the dry season progresses, this water tends to percolate and is stored in deep soil layers, which is mainly composed of the water infiltrated in the previous wet periods (Negron-Juarez *et al.* 2007), and where mainly deeper roots have the ability to take it up (Nepstad *et al.* 1994). Very deep (>6 m) fine roots, although rare, have been found in a few sites in the eastern (Nepstad *et al.* 1994) and central Amazon (Chauvel *et al.* 1992; Negrón-Juárez *et al.* 2020). In the eastern Amazon, where precipitation is more seasonal, Nepstad *et al.* (1994) found roots reaching 18 m. The existence of these roots, associated with low plant-available water in the upper (<1 m) soil layers, give rise to the understanding of the role of deep roots as the primary strategy of plants to deal with seasonal and, potentially, severe droughts (Bruno *et al.* 2006; Hodnett *et al.* 1995; Jipp *et al.* 1998; Nepstad *et al.* 1994).

Despite the documented occurrence of deep roots, it is well recognized that, in the Amazon, shallow roots (<1 m) are much more abundant than deep ones (Chauvel *et al.* 1992; Nepstad *et al.* 1994). The root density decreases from more than a kilogram of roots per cubic meter near the surface to a few tens of grams per cubic meter below two meters, being relatively constant below this level (Nepstad 1989, cited by Bruijnzeel 1996). Although deep roots have low density, research done by Hodnett *et al.* (1995) near Manaus has demonstrated that, in many years, it is impossible to close the dry season water balance of the Amazonian rain forest without using water stored at depths greater than 2 m. Markewitz *et al.* (2010), using data from a rainfall exclusion experiment in Santarém, also concluded that deep root water uptake contributions are crucial. Under control conditions, the 250 to 550 cm soil layer contributed ~20% of water demand, while the deepest layers (550–1,150 cm) contributed ~10%. Under the exclusion, root water uptake was sustained for the first 2 years of the experiment but declined after that.

Other studies have suggested the existence of mechanisms to transport water upward from deep to shallow soil layers, either through the root system, i.e., plant hydraulic lift (Dawson *et al.* 2002; Oliveira *et al.* 2005), or through fine-textured soils by the capillary rise mechanism (Fan and Miguez-Macho 2010; Romero-Saltos *et al.* 2005). However, hydraulic lift also relies on deep root water uptake and, when included in a land surface model, moderately increased the dry season ET rates (Lee *et al.* 2005). Capillary rise, in general, only drives water upward through a few centimeters (Romero-Saltos *et al.* 2005), and is more important in regions where the water table is shallow (Fan and Miguez-Macho 2010), which is not the case for most of the plateau areas where the water table is 30-40 m deep (Fan and Miguez-Macho 2010; Tomasella *et al.* 2008). Other studies have suggested the existence of a third mechanism, root niche partitioning (Brum *et al.* 2019; Ivanov *et al.* 2012), by which plants uptake soil water from different sources, as a function of their height, root depth, and plant hydraulic attributes such as resistance to xylem vessels embolism (Rowland *et al.* 2015).

Mechanisms of root access to soil water are also coupled to biological regulation of water flux through leaves. Because leaf stomata link ET to photosynthetic flux (Gross Primary Productivity, GPP), stomatal regulation that allows increasing dry season GPP (Huete *et al.* 2006; Wu *et al.* 2016; Saleska *et al.* 2016; see also Chapter 6) also facilitates the corresponding dry-season maxima in forest ET discussed above (Shuttleworth 1988; Hasler and Avissar 2007). Recent work shows that high dry-season leaf photosynthetic capacity and high stomatal conductance are both driven by leaf phenology, i.e., the biological synchronization of new leaf emergence and old leaf senescence during the dry season causes large shifts in canopy leaf composition toward younger, more conductive leaves, likely facilitating seasonal increases in ET in the central Amazon (Albert *et al.* 2018; Wu *et al.* 2016). Christoffersen *et al.* (2014) highlight the important complementary roles of root dynamics and leaf phenology in regulating ET.

In conclusion, if the rainforest is replaced with another land cover and use, the Amazon would not be able to keep ET at the same rate, particularly during the dry season. As a result, the rooting depths would be much smaller, hydraulic redistribution would cease, and the evaporating surface (leaf area) would be smaller and possibly present lower greenness than it does today.

7.2.2.1 The role of Amazon tropical forests producing its own climate

As said earlier, tropical rainforests are an obvious consequence of the warm and humid climate in that region. However, in the past decades, evidence is accumulating that the rainforest and the warm and humid climate are strongly connected, forming a two-way interacting system that perpetuates each other (positive feedback). In other words, the humid tropical climate allows the rainforest's existence, which, in turn, helps to produce the rainy climate it needs.

A rainy climate requires two necessary conditions: a humid atmosphere and sufficient ascending vertical motion to form clouds and induce precipitation.

As stated in previous sections, on an annual average basis in the Amazon, around 72% of the water vapor that enters the atmospheric column is of oceanic origin, and 28% is evaporated locally (Table 7.1). In addition to this role as a water vapor source, the evergreen tropical forest has yet another role in the local climate. Theoretical (Eltahir 1996; Zeng and Neelin 1999) and modeling studies (Dirmeyer and Shukla 1994) demonstrate that the rainforest's low albedo favors convection over the basin, while an increase in the surface albedo causes a subsidence anomaly over the region. In addition, forests also emit volatile organic compounds (VOCs, for example terpenes) that become cloud condensation nuclei (CCN) and favor the formation of rain droplets (see also Chapter 6). Because water vapor and convection are key contributors to precipitation, large-scale rainforests likely have some ability to maintain their own climate.

It is puzzling why deep moisture capture mechanisms were selected in some tropical rainforests in a climate so wet. In a competitive environment, species that unnecessarily allocate a big fraction of fixed carbon to grow roots, at the expense of leaves and branches, would be at a disadvantage when competing against species that concentrated the allocation of carbon above ground (Stephenson *et al.* 2011).

Although extreme evolutionary traits like 18 m deep roots may be unnecessary today, they might have represented an advantage in the past. During the Last Glacial Maximum (21,000 years BP) and until the mid-Holocene (14,000 years BP), the trade winds were more zonal, precipitation rates were lower, and parts of the rainforest were replaced by savannas (Haffer 1969; Van-der-Hammen and Absy 1994; Kubatski and Claussen 1998; Maslin and Burns 2000; Mayle *et al.* 2000). If environmental pressures resulted in the selection of trees with very deep roots to compete for water during the Last Glacial Maximum, it is likely that the climate then also had a strong interannual variability. Dry periods may have been long enough to require deep roots (several years), followed by long wet periods that would recharge the soil. Under such a climate, deep roots may have represented a decisive trait for the survival of tropical trees (Kleidon and Lorenz, 2001).

Mechanisms like deep root development, plant hydraulic uplift, and leaf regeneration in the dry season suggest that Amazonian forests can be resilient to extreme droughts. With these mechanisms, the rainforest may have access to around 3,000 mm of water stored in a thick soil layer. These mechanisms may not be present in every tropical forest. First, we still do not know if the ability to grow deep roots is limited to a few species or shared by many. Moreover, Canadell *et al.* (1996) report that the average maximum root depth of deciduous tropical forests is only 3.7 m. Besides, the maximum root depth can be geologically limited. For example, in a part of the Guyanas, roots cannot penetrate deeper than a few meters because of less deeply weathered rocks (Brouwer 1996, p.22).

Despite these uncertainties, Singh *et al.* (2020) were able to map root zone storage capacity and cross-analyze them against transects of tree cover along the rainforest-savanna border in South America. Their results indicate that currently, parts of the Amazon rainforest have access to up to 800 mm of stored water in the root zone, although local measurements suggest higher values (see above). They conclude that rainforest species invest in their rooting strategy and modify aboveground allocation in response to water stress. These responses are focused on allocating carbon in the most efficient way possible to maximize hydrologic benefit.

7.2.2.2 The biotic pump and the role of the forest in the onset of the rainy season

The forest's fundamental role in regional moisture transport and balance has been discussed in the context of the biotic pump theory. This theory suggests that atmospheric condensation of water vapor supplied by plant transpiration from forests is a mechanism that not only contributes to recycling of rain (as described in section 7.2.1 above), but also exerts a major influence over atmospheric dynamics (Makarieva and Gorshkov, 2007; Makarieva *et al.* 2013). Specifically, re-condensation of the forest's evapotranspired water is a mass removal of water from the gas phase that induces a decline in air pressure in the lower atmosphere, with consequent horizontal pressure gradients that accelerate air motion. ET-supplied water vapor thus provides a store of potential energy available to drive additional winds (beyond what would be expected from the general atmospheric circulation) that then contribute to the transport of ocean-evaporated water vapor to continental forests. There is a debate about whether this is a fundamentally different theory or another perspective on classic atmospheric circulation theory, differing in the role of internal versus external sources of water vapor (Meesters *et al.*, 2009; Makarieva and Gorshkov, 2009; Makarieva *et al.* 2014; Makarieva *et al.*, 2017; Jaramillo *et al.*, 2018). In any case, this theory has been increasingly adopted in the literature to explain the exponential increase of rainfall over forested areas of the Amazon (Poveda *et al.* 2014; Sheil, 2018; Molina *et al.* 2019).

Closely related to the biotic pump is the concept that high water fluxes from rainforest transpiration during the dry season stimulate an earlier return of wet season rains than would be expected from atmospheric dynamics alone (Wright *et al.* 2017). Specifically, rainforest transpiration increases shallow convection that moistens and destabilizes the atmosphere during the initial stages of the dry-to-wet season transition, conditioning the regional atmosphere for a rapid increase in rain-bearing deep convection. In turn, this process drives moisture convergence and wet season onset 2–3 months before the arrival of the Amazon Convergence Zone. Recent evidence using both rain gauge and the Tropical Rainfall Measuring Mission (TRMM) data empirically demonstrates the role of rainforests in several critical features of the Southern Amazon rainy season. Leite-Filho *et al.* (2020) have shown that forests' presence is associated with an earlier onset and later end of the rainy season, leading to a longer rainy season. Moreover, Leite-Filho *et al.* (2019) have shown that higher forest cover is associated with a low frequency of dry spells of any duration in September, October, April, and May, the transition months between the dry and rainy seasons. In other words, in well-preserved areas, the rainy season begins earlier and is less likely to be interrupted by a long dry spell in its initial days. On the other hand, in heavily deforested areas, the rainy season starts late and is more likely to be interrupted.

Observational studies of Spracklen *et al.* (2012) confirm the dependence of rainfall amounts on the cumulative exposure of 10-day air back-trajectories to vegetation leaf area index (LAI). They used satellite remote-sensing data of tropical precipitation and LAI, combined with simulated atmospheric transport patterns, and concluded that air that has passed over extensive vegetation in the preceding 10 days produces at least twice as much rain as air that has passed over little vegetation. This empirical correlation is consistent with ET maintaining atmospheric moisture in air that passes over extensive vegetation.

These mechanisms imply active, positive feedback. The amount of forest cover regulates the amount and timing of precipitation received by those forests, with forest loss/increase leading to reductions/increases in rainfall and subsequent further impacts on forest cover (see also discussion on Chapter 21).

7.2.3 The role of the forest as a source of water vapor to other regions

The Amazon region is also an important source of moisture for several regions of South America, such as providing moisture and rainfall to glaciers in the Andes, paramos, major cities, and the La Plata River Basin (Marengo *et al.* 2004, Arraut *et al.* 2012; Zemp *et al.*, 2014; Drumond *et al.*, 2014; Poveda *et al.*, 2014; Gimeno *et al.* 2019). Over the La Plata River Basin, and possibly over the Pantanal (wetlands in Brazil) and Andean regions, the Amazon is the second-highest continental contributor to annual mean precipitation (Martinez and Dominguez, 2014), with local recycling over the La Plata Basin being the main source. This water vapor transport happens in relatively narrow spaces of the atmosphere nicknamed "aerial rivers" (Box 7.1). Moreover, external sources from the southern Pacific and Tropical Atlantic oceans also contribute to precipitation in the basin (Drumond *et al.*, 2008). Drumond *et al.* (2008) highlighted that the influence of the tropical Atlantic Ocean varies seasonally from the northern regions in the austral summer months (Martinez and Dominguez, 2014).

The southwestern part of the Amazon basin is an important direct source of incoming moisture over the La Plata Basin, the Andean Amazon, and the Pantanal regions all year round. Water from the Amazon is exported out of the basin and transported via the South American Low-Level Jet (SALLJ) along the Andes (Marengo *et al.* 2004, Drumond *et al.*, 2008, 2014; Arraut *et al.* 2012; van der Ent *et al.*, 2010, Poveda *et al.*, 2014). This warm-season regional circulation feature represents a nucleus of strong low-level winds (See Chapter 5, Section 5.2) in the middle of moisture transport by the trade winds coming from the tropical Atlantic ocean. This system transports and distributes moisture from the entire Amazon Basin into the La Plata Basin and the Andean Amazon region, producing rainfall, as well as over the Pantanal and the agricultural lands of west-central Brazil. Moisture transport associated with SALLJ and the role of the LLJ east of the Andes in precipitation events that occasionally lead to extreme precipitation and major floods are discussed in studies such as Gimeno *et al.* (2016, 2019) and Marengo *et al.* (2020). This system also transports smoke and aerosols from biomass burning in the Amazon to adjacent regions favoring atmospheric pollution over cities in those regions (Mendez-Espinosa *et al.*, 2019).

7.3 Climate regulation provided by the forests

7.3.1 Temperature regulation

Why are Amazonian forests much cooler than the land uses that often replace them? The answer to this question is crucial to understanding the Amazon's capacity to provide ecosystem services and how this capacity may diminish with deforestation, forest degradation, and global climate change (Foley *et al.* 2007, Coe *et al.* 2016). Recent studies on land surface temperature regulation indicate that Amazonian forests act like giant air-conditioners (Silvério *et al.* 2015, Coe *et al.*, 2017). This characteristic relates primarily to forests' ability to cycle large amounts of water vapor from the soil to the atmosphere via ET (Nobre *et al.*, 2016) (see previous sections). Compared with most crops cultivated in the region, Amazon forests have rougher canopies, denser canopy cover throughout most of the year, deeper roots, and an overall higher capacity to absorb solar energy and return it back to the atmosphere overwhelmingly as latent heat (Coe *et al.* 2016). Combined with the high net surface radiation and precipitation inherent to the region, these characteristics result in a disproportional capacity of forests to cool down their leaves. For instance, the daytime land surface temperature in forested areas of the southeastern Amazon tends to be 5ºC lower than deforested areas during the dry season, a result of ET decreasing, on average, by a third as forests are replaced by pastures and croplands (Silvério *et al.* 2015).

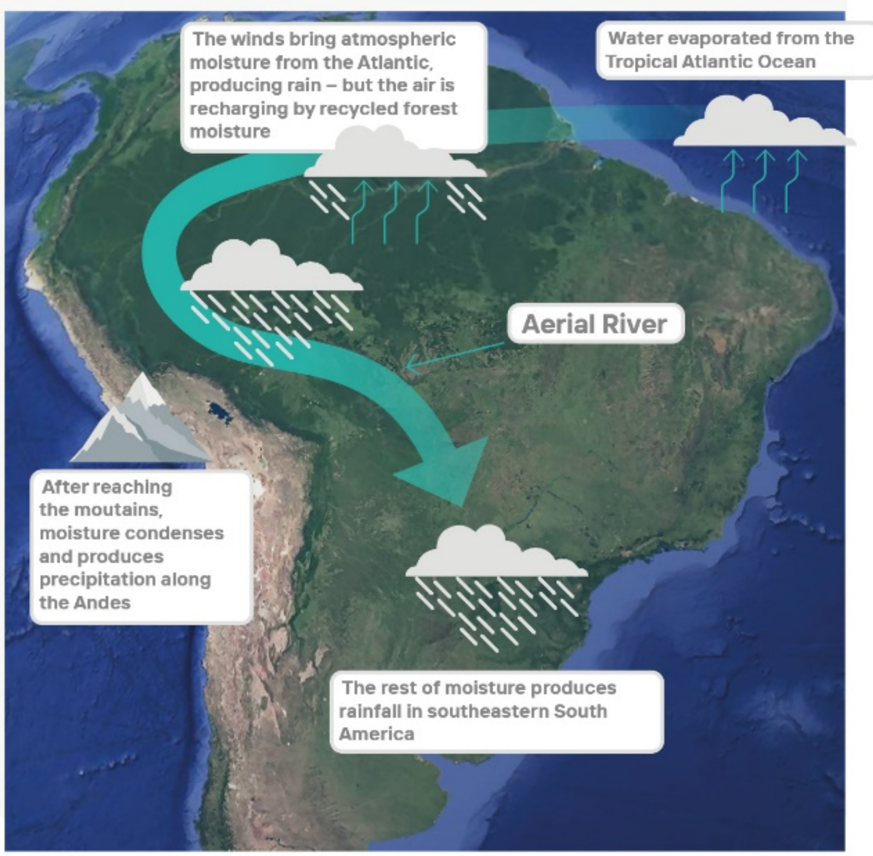
The relatively cool surface of Amazon forests relates to complex interactions between biological, physical, and chemical processes (Still *et al.*, 2019). Most Amazonian tree species prevent leaf temperatures from increasing above critical levels, which can avoid overheating and associated reductions in carbon assimilation, growth, and carbon storage, all of which influence the odds of plant survival (Brando *et al.*, 2019). Some studies suggest that the optimal temperature for leaf photosynthesis is less than 30°C, with leaf photosynthesis dropping abruptly when temperatures rise above 35ºC (Doughty and Goulden 2008), though there is debate about whether the mechanism of photosynthesis limitation is temperature or associated vapor pressure deficit (Smith *et al.* 2020). A recent long-term study found that South America's rainforests carbon stocks and carbon gains decrease significantly ($P < 0.001$) with the mean daily maximum temperature in the warmest month (Sullivan *et al.* 2020). This process helps to explain why the average surface temperature of Amazonian forests is usually below 30ºC (Coe *et al.*, 2016). While ET controls much of this capacity to regulate surface temperatures, other foliar characteristics contributing to leaf cooling include leaf angle, size, shape, and pubescence; canopy position; number of leaves per stem; and canopy structure (Brando *et al.* 2019).

ET and land surface temperatures appear to be relatively constant across the Amazon Basin. Yet, there are important finer-scale spatial and temporal variability in canopy properties, ET, and land surface temperature. The main environmental process controlling this spatial variability is solar radiation (Fisher *et al.*, 2009). Although potential incoming shortwave radiation is high across the entire region, some portions of the Amazon (e.g., near the Andes) receive less radiation due to cloudier conditions than others (the southeastern Amazon). The second factor relates to soil water availa-

Box 7.1 Aerial rivers

In recent years the term atmospheric river has evolved and is now established as describing a narrow band of atmospheric moisture, usually originating from the tropics, making landfall in the mid-latitudes. Low-level jets (LLJs) are defined as regions of anomalously high wind speeds occurring within the first kilometer of the troposphere (see Section 5.2, Chapter 5). In the case of the Amazon Basin, these columns of vapor move with the weather, carrying an amount of water vapor roughly equivalent to the average flow of water at the mouth of the Amazon River (Arraut *et al.* 2012), and are referred as aerial rivers, a nick name for the South American LLJ east of the Andes (SALLJ).

When the atmospheric rivers make landfall, they often release this water vapor in the form of rain. The figure shows a schematic representation of moisture transport in the Amazon region. Moisture evaporated from the Atlantic Ocean is carried by surface winds into the region, with stronger transport along the SALLJ. The winds get even more humidity from the moisture recycling provided by the forest. The moist air first moves westward, but as it approaches the eastern flank of the Andes, it is deflected toward southeastern South America, generating the SALLJ. This moisture transport is like a river in the air that brings moisture and rain to the southern Amazon, Pantanal, and the La Plata Basin, with the SALLJ the core of the river (Arraut *et al.* 2012). That is why this transport is referred to as "aerial rivers" over land, where the moisture flow is in the form of water vapor and clouds.



Source: Rios Voadores project: www.riosvoadores.com and Marengo 2020.

bility. Where there is an intense dry season (or in extremely dry years like the 2015-2016 El Niño event), low soil water availability towards the late dry season can constrain ET and cause related increases in land surface temperature (Gimenez *et al.* 2019). In the southeastern basin, where the dominant land cover is cerrado (mainly savannas), dry season ET may be less than half of that of the wet season (Costa and Pires 2010), with surface temperatures increasing proportionally to decreases in ET during the late dry season. Similarly, when soil moisture drops below critical levels during drought years, plant water stress can trigger reductions in stomatal conductance and ET, resulting in increased land surface temperatures (Toomey *et al.*, 2011). Thus, while the climate over much of the Amazon is adequate for plants to maintain high ET and associated cooler temperatures, broad patterns across the region exist.

Air temperature and land surface temperature, although with the same tendency, often differ, with differences between them resulting from differences in the specific heat values of air, soil, and water, and from complex interactions among atmospheric properties, soil moisture, net radiation, and elevation. In general, air and land surface temperatures converge to similar values during the night but diverge during the hotter parts of the day, when land surface temperatures usually surpass air temperature by several degrees (Still *et al.*, 2019). As large tracts of Amazonian forests are deforested, we expect major increases in surface temperatures (Silvério *et al.*, 2015), given that deforestation results in decreased ET. This warming can be larger than the cooling effects that deforestation causes by increasing albedo.

7.3.2 Edge effects on temperature and moisture

More than 70% of the world's remaining forest is less than 1 km from an edge (border adjacent to a field), and 20% is less than 100 m from an edge (Haddad *et al.*, 2015). In human-dominated tropical landscapes, forest edges and their effects are pervasive (Skole and Tucker 1993, Pfeifer *et al.* 2017). As people clear-cut forests to expand pastures, croplands, and palm oil plantations, associated changes in disturbance regimes and the regional energy balance can degrade much of the residual forest. Thus, we expect additional carbon losses for each hectare deforested, especially along forest edges neighboring agricultural fields. In the 'arc of deforestation' in the southeastern Amazon, nearly 14% of Amazonian forests now grow less than 100 m from a deforested area (Brando *et al.*, 2014).

Forest edges adjacent to cleared fields are subject to prolonged forest degradation. These edges and forest patches are exposed to hotter, dryer, and windier conditions (Didham and Lawton 1999, Schwartz *et al.* 2017). These edge effects degrade forests over time and have important implications for forest structure, especially because they tend to disproportionately increase mortality of canopy dominant trees over the short-term (Laurance *et al.* 2000). The resulting changes in microclimate then facilitate the establishment of light-wooded (low wood density), small-sized, fast-growing pioneer species (Laurance *et al.* 2002), causing regional reductions in forest carbon stocks over the long-term (Chaplin-Kramer *et al.*, 2015, Silva Junior *et al.*, 2020).

Tropical forests are highly resilient to occasional disturbances, but increased frequency or intensity of disturbance events are expected to dramatically change forest structure, composition, and function (Brando *et al.* 2014, Lewis *et al.*, 2015, Nobre *et al.*, 2016). When combined with climate change, these disturbances may outpace adaptation processes (Lewis *et al.* 2015, Trumbore *et al.*, 2015). The combined effects of continued deforestation and a changing climate place large areas of the Amazon at risk of greater degradation in the coming decades (Maxwell *et al.*, 2019), particularly along forest edges neighboring deforested fields and in isolated forest patches (Gascon *et al.* 2000, Matricardi *et al.*, 2020).

Quantifying the drivers of forest degradation in the Amazon (see Chapter 19) is key to developing, validating, and parameterizing Earth system models (ESM) that mechanistically simulate changes in carbon pools and fluxes between the biosphere and atmosphere (Rödig *et al.* 2018). Advances in mapping forest degradation and its drivers have permitted substantial improvements in ESMs' ability to project potential pathways of Amazonian forests. However, very few (if any) of these new advancements have addressed the issue of forest edge degradation. Hence, projecting the future of Amazonian forests requires a better representation of forest edge effects in ESMs.

7.4 Conclusions

Internal biogeophysical processes strongly control the hydrological and climate system of the Amazon Basin. This is possible because several mechanisms to access water stored in deep soil layers were selected for in rainforest tree species and provide the energy necessary to trigger and maintain convection. These combined mechanisms lead to a more humid climate on average and an earlier start and later end of the rainy season. Simultaneously, they maintain surface air warm enough for instability and convection, but within limits that do not hinder the photosynthetic capacity of the trees.

Such mechanisms, along with the microclimate temperature and humidity control at the edges of the forest, are fundamental features of the coupled biosphere-atmosphere system in the Amazon, helping define the Amazon's climate and the climate in other parts of South America. Moreover, these mechanisms ensure this coupled system's ability to endure the dry season along its southern borders and provide a steady source of water vapor to the Amazon's atmosphere when inputs from the Atlantic ocean weaken.

7.5 Recommendations

Forest cover regulates the amount and timing of precipitation received by those forests, with forest loss/increase leading to reductions/increases in rainfall and subsequent further reductions in forest cover. If the rainforest is replaced with another land cover, the Amazon would have a hotter climate and would not maintain ET at the same rate, particularly during the dry season, changing rainfall amounts and decreasing the duration of the rainy season, with implications for forest degradation, forest flammability, and crop yields.

The most important changes in the hydroclimate system are happening in the transition between the dry and the rainy seasons, with a lengthening of the dry season, which has important consequences to ecosystem ecology, surface hydrology, and intensive agriculture in the region. In particular, the lengthening of the dry season makes the climate more seasonal – a tropical savanna climate instead of a tropical rainforest climate. Future biosphere-atmosphere interaction studies should focus on these particular seasons.

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