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On the importance of cascading moisture recycling in South America

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Abstract

Continental moisture recycling is a crucial process of the South American climate system. Evapotranspiration from the Amazon river basin contributes to precipitation regionally and in the La Plata river basin. Here we present an in-depth analysis of South American moisture recycling. We quantify the importance of "cascading moisture recycling", which describes the exchange of moisture between the vegetation and the atmosphere through precipitation and re-evaporation cycles on its way between two locations on the continent. We use the Water Accounting Model 2-layers (WAM-2layers) forced by precipitation from TRMM and evapotranspiration from MODIS for the period 2001 until 2010 to construct moisture recycling networks. These networks describe the direction and amount of moisture transported from its source (evapotranspiration) to its destination (precipitation) in South America. Model-based calculations of continental and regional recycling ratios in the Amazon basin compare well with other existing studies using different datasets and methodologies. Our results show that cascading moisture recycling contributes about 10 % to the total precipitation over South America and 17 % over the La Plata basin. Considering cascading moisture recycling increases the total dependency of the La Plata basin on moisture from the Amazon basin by about 25 % from 23 to 29 % during the wet season. Using tools from complex network analysis, we reveal the importance of the south-western part of the Amazon basin as a key intermediary region for continental moisture transport in South America during the wet season. Our results suggest that land use change in this region might have a stronger impact on downwind rainfed agriculture and ecosystem stability than previously thought.

1 Introduction

Continental moisture recycling, the process by which evapotranspiration from the continent returns as precipitation to the continent (Brubaker et al., 1993; Eltahir and

Bras, 1994; van der Ent et al., 2010) is particularly important for the South American hydrological cycle. In the Amazon river basin, between 25 and 35 % of the moisture is regionally recycled (Eltahir and Bras, 1994; Trenberth, 1999; Bosilovich and Chern, 2006; Burde et al., 2006; Dirmeyer et al., 2009). The moisture from the Amazon basin is also exported out of the basin, transported via the South American Low Level Jet along the Andes and contributes to precipitation over the La Plata river basin particularly during the wet season (Marengo, 2005; Drumond et al., 2008, 2014; Arraut and Satyamurty, 2009; Dirmeyer et al., 2009; van der Ent et al., 2010; Arraut et al., 2012; Martinez et al., 2014).

Land-use change – in particular deforestation in the Amazon basin – impacts the evapotranspiration rate and affects the water cycle (see review in Marengo, 2006). A resulting reduction in regional moisture supply may have important consequences for the ecosystem stability in the Amazon rainforests (Oyama and Nobre, 2003; Cox et al., 2004; Betts et al., 2004; Hirota et al., 2011; Knox et al., 2011; Spracklen et al., 2012). Downwind, e.g., in the La Plata basin, rainfall reduction may affect rainfed agriculture (Rockström et al., 2009; Keys et al., 2012). Even if regional impact of changes in precipitation patterns from deforestation has been intensively studied using simulations from atmospheric general circulation models with deforestation scenarios (Lean and Warrilow, 1989; Shukla et al., 1990; Nobre et al., 1991, 2009; Werth and Avissar, 2002; Sampaio et al., 2007; Da Silva et al., 2008; Hasler et al., 2009; Walker et al., 2009; Medvigy et al., 2011; Bagley et al., 2014) the magnitude of rainfall reduction and the location of the most impacted regions are still uncertain. Therefore, further advancements in our understanding of the continental moisture recycling in the South American continent are needed.

To identify sources and sinks of moisture and to quantify regional and continental moisture recycling in South America, several methods have been used including isotopes (Salati et al., 1979; Gat and Matsui, 1991; Victoria et al., 1991), atmospheric bulk models (Brubaker et al., 1993; Eltahir and Bras, 1994; Trenberth, 1999; Burde et al., 2006), quasi-isentropic back-trajectory method (Dirmeyer et al., 2009; Bagley

et al., 2014) and tagged water experiments with a general circulation model (GCM) (Bosilovich and Chern, 2006) or a posteriory with reanalysis data (Sudradjat et al., 2002; van der Ent et al., 2010; Keys et al., 2012) (see a review of the methods in van der Ent et al., 2013; Burde and Zangvil, 2001). In most of existing studies using tagged water experiments, moisture evaporating from a given region is tracked forward in time from the evapotranspiration until it returns to the land surface as precipitation. However, precipitating water can be re-evapotranspirated in the same location (re-evaporation cycle) and can be transported to a downwind location where it contributes to precipitation. Such exchanges of moisture between the vegetation and the atmosphere through re-evaporation cycles might play a crucial role for the transport of moisture in the Tropics (Spracklen et al., 2012). Adding different types of tracers within a GCM, Numaguti (1999) found that moisture runs on average through more than two re-evaporation cycles between evaporation from the ocean and precipitation in northern Eurasia. In this study we focus for the first time on the following questions:

1. what is the importance of cascading moisture recycling in South America?
2. Which are the important intermediary regions for cascading moisture recycling?
3. Which are the key regions where the pathways of cascading moisture recycling are channeled?

We call “cascading moisture recycling” the process by which evapotranspiration from a specific location on land runs through one or more re-evaporation cycles before it precipitates in another one. On the other hand, “direct moisture recycling” refers to the process by which evapotranspiration is directly transported (without any re-evaporation cycle) from one location on land to another, where it precipitates. We call “intermediary” the location where re-evaporation cycle is occurring. We define a “pathway of moisture recycling” as the set of locations including the starting and the destination locations, as well as the intermediaries.

We perform a tagged water experiment a posteriori with precipitation, evapotranspiration, wind and humidity datasets from reanalysis and satellite products for South

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America using the numerical atmospheric moisture tracking model WAM-2layers (Water Accounting Model-2layers) (van der Ent et al., 2014).

We propose a novel framework to quantify the importance of cascading moisture recycling for the regional climate in South America, and in particular in the Amazon basin and the La Plata basin. In addition, we use tools from complex network theory to improve our understanding of moisture recycling pathways in South America. The potential of the complex network approach has been recently shown in climate science. It has been used to detect large-scale related climate anomalies (teleconnections) (Tsonis et al., 2008; Donges et al., 2009a, b) and to reveal important regions for propagation of extreme events (Malik et al., 2012; Boers et al., 2013). In previous studies, links in the network were usually built according to the strength of the statistically relationships between time series in different locations. In our study, we apply complex network approach for the first time to a network in which the links represent water fluxes.

In Sect. 2.1 we describe the tagged water experiment using the WAM-2layers and we explain how we use it to build moisture recycling networks. We explain the assumptions made in the proposed analysis in Sect. 2.2. We develop new measures in Sects. 2.3 and 2.4 and we present the complex network measures in Sect. 2.5. After comparing the continental and regional recycling ratios with other existing studies in Sect. 3.1, we present and discuss new results on the importance of cascading moisture recycling in Sect. 3.2 and on complex network analysis in Sect. 3.3. Finally, we present an in-depth analysis of the moisture recycling between the Amazon basin and the La Plata basin in Sect. 3.4.

2 Methods

2.1 Building moisture recycling networks

2.1.1 Description of the moisture tracking in WAM-2layers

In this study we make use of the Eulerian atmospheric moisture tracking model WAM-2layers V2.3.01 (van der Ent et al., 2014). The actual tracking in WAM-2layers is performed a posteriori with reanalysis and satellite datasets (see input data in Sect. 2.1.2). Evapotranspiration from a certain region of interest is “tagged” and subsequently tracked in the atmosphere by applying water balance principles to each grid cell, consisting of a well-mixed upper and lower part. The two-layer approach is simplified compared to full-3-D tracking, but was shown to perform comparably well (van der Ent et al., 2013).

WAM-2layers provides the basis for the construction of moisture recycling networks analyzed in the following. To this extent, we performed separate forward tracking runs of evapotranspiration for each continental grid cell in the South American domain (Fig. 4) for the years 2000–2010. The tagged moisture is assumed to be gone when it leaves the domain. We omitted the year 2000 from the results because of model spin-up. The output for the years 2001–2010 are aggregated first to monthly, then to seasonally average imports and exports between all land grid cells. These seasonal averages are used to build two seasonal moisture recycling networks which are assumed to be static for the whole season. This implies that in the proposed analysis, for each season moisture is tracked forward and backward in space but not in time.

2.1.2 Input of WAM-2layers

The input for WAM-2layers are 3 hourly precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) based on the algorithm 3B-42 (version 7) (Huffman et al., 2007), 8 days evapotranspiration estimates from Moderate Resolution Imaging

Spectroradiometer (MODIS) based on the MOD16 ET algorithm (Mu et al., 2011) as well as 6 hourly specific humidity and wind speed in three dimensions from the ERA-Interim reanalysis product (Dee et al., 2011). We downscaled the MODIS evapotranspiration to a 3 hourly resolution based on ERA-Interim, as WAM-2layers needs finer temporal resolution in the input data. All data is upscaled to a regular grid of 1.5° longitude/latitude and covers the South American continent until 50° S, which is the southernmost latitude covered by TRMM product. In addition, all data is downscaled to 0.5 h as requested by the numerical scheme of WAM-2layers.

Humidity estimation has been improved in the ERA-Interim product in comparison with others reanalysis products (Dee and Uppala, 2008). Precipitation dataset from TRMM are considered reliable over South America and in particular in the Amazonian region where others products perform poorly due to the lack of ground based measurements (Franchito et al., 2009; Rozante et al., 2010). TRMM precipitation dataset are shown to represent high frequency variability sufficiently well (Kim and Alexander, 2013). However, it is systematically biased during the dry season in the northeastern coast of Brazil, where precipitation is underestimated (Franchito et al., 2009) and at the junction of Argentina, Paraguay and Brazil, where it is overestimated (Rozante and Cavalcanti, 2008). Evapotranspiration is estimated using a recently improved algorithm (Mu et al., 2011) based on the Penman–Monteith equation (Monteith et al., 1965) and forced by satellite data from MODIS and meteorological reanalysis data. The quality of the evapotranspiration dataset depends on the quality of the input data and the parametrization of the algorithm. The evapotranspiration dataset has been validated with 10 eddy flux towers located in the Amazonian region under various land cover types (Loarie et al., 2011; Ruhoff, 2011).

The long term seasonal average of evapotranspiration and precipitation as well as moisture flux divergence (evapotranspiration – precipitation) are shown in Fig. 4. The high rainfall in the South Atlantic Convergence Zone (including the Amazon basin, central and south-eastern Brazil) during the wet season (December to March) compared to the dry season (June to September) characterizes the South American Monsoon

System (SAMS) (Liebman et al., 1999; Grimm et al., 2004; Arraut and Satyamurty, 2009). The evapotranspiration is high in the Amazon basin and varies little in time and space. It exceeds the total precipitation in the southern part of the Amazon basin during the dry season, indicating that this region is a net source of moisture for the atmosphere (Fig. 4c). This is in agreement with previous studies demonstrating a maintaining of the greenness of the Amazon forests (Morton et al., 2014) and the absence of water stress during the dry season due to the deep root system which enables the pumping of the water from the deeper water table (Nepstad et al., 1994; Miguez-Macho and Fan, 2012).

We find that, averaged over the full time period, evapotranspiration exceeds precipitation in northeastern Brazil, in the Atacama Desert and along the Andes. Possible explanations for the imbalance in these arid to semi-arid regions are irrigation or biases in the input data as mentioned above. As this might lead to a bias in moisture recycling ratios due to an overestimation of the contribution of evapotranspiration to local precipitation, we will exclude these grid cells from our analysis.

2.1.3 Output of WAM-2layers as a complex network

The output of WAM-2layers is a matrix $\mathbf{M} = \{m_{ij}\}_{i,j \in N}$ with N the number of grid cells in the continent ($N = 681$). The non-diagonal element m_{ij} is the amount of evapotranspiration in grid cell i which precipitates in grid cell j and the diagonal element m_{ii} is the amount of evapotranspiration which precipitates in the same grid cell (locally recycled moisture). The output of WAM-2layers can transformed into a directed and weighted complex network with self-interactions, where nodes of the network represent grid cells and links between nodes represent the direction and amount of moisture transported between them (Fig. 1).

2.2 Basic assumptions

In order to track moisture forward or backward from a given region Ω which can be of any shape and scale (grid cell, basin, continent), we assume that the moisture composition within the surface reservoir and the atmosphere for each grid cell remains the same. This implies that, in each grid cell, the tagged fraction of precipitation is linearly proportional to the tagged fraction of evapotranspiration and the tagged fraction of transported moisture:

$$\frac{P_\Omega}{P} = \frac{E_\Omega}{E} = \frac{m_\Omega}{m}, \quad (1)$$

where E is the total evapotranspiration, P is the total precipitation, m is the transported moisture towards or from another grid cell, P_Ω is the tagged fraction of precipitation, E_Ω is the tagged fraction of evapotranspiration and m_Ω is the tagged fraction of transported moisture towards or from another grid cell. We call "tagged fraction" the share of the moisture originating from Ω in the case of a backward tracking and the share of moisture precipitating over Ω in the case of a forward tracking.

This assumption is valid under two conditions: (1), evapotranspiration follows directly after the precipitation event or (2), the fraction of tagged moisture in the surface reservoir and the atmosphere can be assumed to be temporally constant (i.e., in steady state) (Goessling and Reick, 2013). The first condition is usually fulfilled during interception and fast transpiration which are important components of the total evapotranspiration, particularly in warm climates and for shallow rooted plants (Savenije, 2004). However, in seasonal forests with deep rooted trees, the moisture which is evaporated during the dry season can be hold back for one or several months (Savenije, 2004). The second condition is fulfilled if the soil water at the beginning has the same composition (in term of tagged fraction) as the atmospheric moisture at the end of the season.

2.3 Moisture recycling ratio

In this section, we define measures to track moisture from a given region forward or backward in space. In the case of a forward tracking, the measures indicate the destination (precipitative sink) of evapotranspiration from the region. In the case of a backward tracking, they indicate the origin (evaporative source) of precipitation over the region. We first consider direct moisture recycling only (Sect. 2.3.1). We then track moisture further forward or backward in space through cascading moisture recycling (Sect. 2.3.2). Considered together, the direct and cascading moisture recycling ratios provide a full picture of the sources and sinks of moisture from a region of interest.

2.3.1 Direct moisture recycling ratios

We define the direct precipitation recycling ratio as the fraction of precipitation in each grid cell i that comes directly from evapotranspiration from Ω:

$$\rho_{\Omega,i} = \frac{P_{i\leftarrow\Omega}}{P_i}, \quad (2)$$

where $P_{i\leftarrow\Omega}$ is the amount of precipitation in i that is originating from evapotranspiration from Ω through direct moisture recycling and P_i is the total precipitation in i (see also Appendix A1). $\boldsymbol{\rho}_{\boldsymbol{\Omega}}$ quantifies the dependency on direct moisture recycling from Ω for local rainfall. High values indicate locations which receive moisture (direct precipitative sink) from Ω. We note that $\boldsymbol{\rho}_{\boldsymbol{\Omega}}$ averaged over all grid cells in Ω gives the regional recycling ratio, i.e, the fraction of precipitation that is regionally recycled (Eltahir and Bras, 1994; Burde et al., 2006; van der Ent and Savenije, 2011).

We also define the direct evapotranspiration recycling ratio as the fraction of evapotranspiration in each grid cell i that contributes directly to precipitation over Ω:

$$\varepsilon_{\Omega,i} = \frac{E_{i\rightarrow\Omega}}{E_i}, \quad (3)$$

where $E_{i\to\Omega}$ is the amount of evapotranspiration in i that contributes to precipitation over Ω through direct moisture recycling and E_i the total evapotranspiration in i (see also Appendix A1). $\boldsymbol{\varepsilon}_{\boldsymbol{\Omega}}$ quantifies the local contribution to precipitation over Ω through direct moisture recycling. High values indicate locations which distribute moisture (direct evaporative source) over Ω.

If Ω is the entire South American continent, $\boldsymbol{\varepsilon}_{\boldsymbol{\Omega}}$ becomes the continental evapotranspiration recycling ratio ($\boldsymbol{\varepsilon}_{\mathbf{c}}$) and $\boldsymbol{\rho}_{\boldsymbol{\Omega}}$ the continental precipitation recycling ratios ($\boldsymbol{\rho}_{\mathbf{c}}$) as defined in van der Ent et al. (2010). Considered together, $\boldsymbol{\varepsilon}_{\mathbf{c}}$ and $\boldsymbol{\rho}_{\mathbf{c}}$ indicate respectively sources and sinks of continental moisture. In this study we neglect possible contributions of moisture in South America from and to other continents, since these contributions to the overall moisture budget are small (van der Ent et al., 2010, Table 2).

To study the direct moisture recycling between the Amazon basin and the La Plata basin (defined by the red boundaries in Fig. 7), we use $\boldsymbol{\rho}_{\boldsymbol{\Omega}}$ with Ω being all grid cells covering the Amazon basin ($\boldsymbol{\rho}_{\mathrm{Am}}$) and $\boldsymbol{\varepsilon}_{\boldsymbol{\Omega}}$ with Ω being all grid cells covering the La Plata basin ($\boldsymbol{\varepsilon}_{\mathrm{Pl}}$). While $\boldsymbol{\rho}_{\mathrm{Am}}$ is useful to track moisture from the Amazon basin as a whole, $\boldsymbol{\varepsilon}_{\mathrm{Pl}}$ provides information regarding the spatial heterogeneity of the contribution inside the Amazon basin.

The direct recycling ratios underestimate the strength of the relationship, in term of moisture recycling, between two specific locations. In fact, moisture can be exchanged not only through direct moisture recycling, but also through cascading moisture recycling.

2.3.2 Cascading moisture recycling ratios

We define the cascading precipitation recycling ratio as the fraction of precipitation in each grid cell i that is originating from evapotranspiration from Ω through cascading moisture recycling:

$$\rho^{\mathrm{casc}}_{\Omega,i} = \frac{P^{\mathrm{casc}}_{i\leftarrow\Omega}}{P_i}, \tag{4}$$

where $P^{\mathrm{casc}}_{i\leftarrow\Omega}$ is the amount of precipitation in i that is originating from evapotranspiration from Ω through cascading moisture recycling. $\boldsymbol{\rho}^{\mathrm{casc}}_{\boldsymbol{\Omega}}$ quantifies the dependency on cascading moisture recycling from Ω for local rainfall. High values indicate the final destination of moisture from Ω after one ore more re-evaporation cycles (indirect precipitative sink).

We also define the cascading evapotranspiration recycling ratio as the fraction of evapotranspiration in each grid cell i which contributes to precipitation over Ω through cascading moisture recycling as:

$$\varepsilon^{\mathrm{casc}}_{\Omega,i} = \frac{E^{\mathrm{casc}}_{i\to\Omega}}{E_i}, \tag{5}$$

where $E^{\mathrm{casc}}_{i\to\Omega}$ is the amount of evapotranspiration in i that contributes to precipitation over Ω through cascading moisture recycling. $\boldsymbol{\varepsilon}^{\mathrm{casc}}_{\boldsymbol{\Omega}}$ quantifies the local contribution to precipitation over Ω through cascading moisture recycling. High values indicate locations where moisture initially originated (indirect evaporative source) before it is distributed over Ω.

The moisture inflow (resp. outflow) that crosses the border of Ω may be counted several times as it is involved in several pathways of cascading moisture recycling. To avoid this, we only track moisture that crosses the border of Ω. This implies that we consider re-evaporation cycles outside Ω only (Fig. 2, see also Appendix A2).

To study the cascading moisture recycling between the Amazon basin and the La Plata basin, we use $\boldsymbol{\rho}^{\mathrm{casc}}_{\boldsymbol{\Omega}}$ with Ω being all grid cells covering the Amazon basin ($\boldsymbol{\rho}^{\mathrm{casc}}_{\mathrm{Am}}$) and $\boldsymbol{\varepsilon}^{\mathrm{casc}}_{\boldsymbol{\Omega}}$ with Ω being all grid cells covering the La Plata basin ($\boldsymbol{\varepsilon}^{\mathrm{casc}}_{\mathrm{Pl}}$). While $\boldsymbol{\rho}^{\mathrm{casc}}_{\mathrm{Am}}$ considers cascading recycling of moisture originating from the Amazon basin (see Fig. 2a), $\boldsymbol{\varepsilon}^{\mathrm{casc}}_{\mathrm{Pl}}$ provides information regarding the importance of cascading recycling of moisture that has final destination the La Plata basin (see Fig. 2b).

Considered together, the direct and cascading recycling ratios provide a full picture of the origin and destination of moisture from a given region. High values of $\boldsymbol{\rho}_{\mathrm{Am}}$ and $\boldsymbol{\rho}^{\mathrm{casc}}_{\mathrm{Am}}$ indicate together the precipitative sink region of moisture from the Amazon basin and high values of ρ_{Am} and $\rho_{\mathrm{Am}}^{\mathrm{casc}}$ highlight evaporative source regions of precipitation over the La Plata basin.

2.4 Quantifying cascading moisture recycling

In this section, we are interested in the importance of cascading moisture recycling for the total moisture inflow (precipitation) and outflow (evapotranspiration). To quantify this, we forbid re-evaporation of moisture originating from the continent and we estimate the resulting reduction in total moisture inflow ($\boldsymbol{\Delta P_c}$) and outflow ($\boldsymbol{\Delta E_c}$) (see Appendix B). $\boldsymbol{\Delta P_c / P}$ is the fraction of precipitation that comes from cascading moisture recycling on the continent, i.e., that has been evaporated at least twice on the continent. It quantifies the dependency on cascading moisture recycling for local rainfall. $\boldsymbol{\Delta E_c / E}$ is the fraction of total evapotranspiration that is involved in cascading moisture recycling on the continent, i.e., that comes from the continent and that further precipitates over the continent. It quantifies the contribution of a specific location to cascading moisture recycling. Regions which have a larger $\boldsymbol{\Delta E_c / E}$ than the 80 percentile (corresponding to 0.27 during the wet season and 0.17 during the dry season) are called "intermediary regions".

In addition, we are interested in the importance of cascading moisture recycling in the intermediary regions for the total moisture in- and outflow. We use the same approach as above. We forbid re-evaporation in the intermediary region of moisture originating from the continent and we estimate the resulting reduction in total moisture inflow ($\boldsymbol{\Delta P_m}$) (see Appendix B). $\boldsymbol{\Delta P_m / P}$ is the fraction of total moisture inflow that comes from cascading moisture recycling in the intermediary region. It can be seen as the fraction of precipitation that comes from the continent and that has been re-evaporated in the intermediary region. It quantifies the dependency on cascading moisture recycling in the intermediary region for local rainfall.

2.5 Complex network analysis

We investigate important moisture recycling pathways using two measures from complex network analysis: clustering coefficient associated with Middleman motifs and betweenness centrality.

2.5.1 Clustering coefficient associated with Middleman motifs

In complex network theory, motifs are defined as significant and recurring patterns of interconnections that occur in the network (Milo et al., 2002). Here, we are interested in a particular pattern of directed triangles: the Middleman motif (Fagiolo, 2007). In our study, a grid cell forms a Middleman motif if is an intermediary on an alternative pathway to the direct transport of moisture between two other grid cells (Fig. 3).

The clustering coefficient is a measure from complex network analysis which measures the tendency to form a particular motif (Fagiolo, 2007). Here, it reveals intermediary locations in cascading moisture recycling pathways, as the alternative to the direct recycling of moisture between sources and sinks. We compute the weighted version of the clustering coefficient associated with Middleman motifs ($\tilde{\boldsymbol{C}}$) (Fagiolo, 2007; Zemp et al., 2014) for each grid cell as described in the Appendix C1. A grid cell has a high $\tilde{\boldsymbol{C}}$ if it forms a lot of Middleman motifs and if these motifs contribute largely to relative moisture transport. $\tilde{\boldsymbol{C}}$ is equal to zero if the grid cell forms no Middleman motif at all.

It is worth to note that the Middleman motif considers three interconnected grid cells which corresponds to cascading moisture recycling pathways involving only one re-evaporation cycle. These pathways contribute usually most to moisture transport between two locations. In fact, the amount of moisture transported in a pathway typically decreases with the number of re-evaporation cycles involved in the pathway. Other motifs formed by three or more grid cells linked by moisture recycling exist (Zemp et al., 2014), but are not analyzed here.

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2.5.2 Betweenness centrality

The betweenness centrality (***B***) aims to highlight nodes in the network with central position "to the degree that they stand between others and can therefore facilitate, impede or bias the transmission of messages" in the network (Freeman, 1977, p. 36). Here, we use it to reveal intermediary grid cells where cascading moisture recycling pathways are channeled.

To compute it, we first identify for each pair of grid cells the moisture recycling pathways with the greatest throughput, called "optimal pathways". These pathways can include any number of re-evaporation cycles. As the optimal pathway is usually the direct one (without any re-evaporation cycle), we first had to modify the network such that the optimal pathways involve cascading moisture recycling. To do so, we removed from the network all long-range moisture transport, i.e, occurring over distances larger than 15 geographical degrees. The choice of this threshold does not influence the results qualitatively. Once optimal pathways are identified, we find intermediary grid cells that they have in common (see Appendix C2). A grid cell has a high ***B*** if many optimal pathways pass through it, i.e., moisture often cascades in the grid cell, and has a ***B*** equal to 0 if none of these pathways pass through it, i.e., moisture never cascades in the grid cell.

2.5.3 Similarities and differences between the betweenness centrality and the Middleman motif

We expect similar spatial patterns in the results of the ***B*** (Sect. 2.5.2) and the $\tilde{\boldsymbol{C}}$ (Sect. 2.5.1). In fact, both measures reveal important intermediary grid cells in cascading moisture recycling pathways. However, these two measures are based on different concepts and methods.

1. While the ***B*** is based on the optimal pathways, the $\tilde{\boldsymbol{C}}$ relies on particular motifs formed by three connected grid cells.

2. An implication of (1) is that the $\tilde{\boldsymbol{C}}$ refers to cascading moisture recycling pathways as alternative to the direct transport of moisture between two locations, while the ***B*** shows locations where cascading moisture recycling pathways are channeled.

3. In the $\tilde{\boldsymbol{C}}$, only cascading moisture recycling pathways with one re-evaporation cycle are considered. In the ***B***, all number of cycles are possible in the pathways.

4. Moisture recycling pathways involving long-range transport are not considered in the calculation of the ***B***.

For these reasons, the ***B*** and the $\tilde{\boldsymbol{C}}$ are complementary measures.

3 Results and discussion

3.1 Comparison of continental and regional moisture recycling ratios with other existing studies

The main continental source of precipitation in South America is the Amazon basin, with large heterogeneity in time and space (Fig. 4e and j and Table 2). The southern part of the Amazon basin contributes 80 % to continental precipitation during the wet season but only 40 % during the dry season. As the evapotranspiration in the Amazon basin is high and varies little in space and time (Fig. 4b and g), this observation indicates that during the dry season, a high amount of moisture from the southern part of the Amazon basin is advected out of the continent. Using a Lagrangian particle dispersion model, Drumond et al. (2014) also found a maximum contribution of moisture from the Amazon basin to the ocean during this period.

The main sink regions of moisture originating from the continent are the western part of the Amazon basin during the dry season, the south-western part of the basin during the wet season and the La Plata basin especially during the wet season (Fig. 4d and i and Table 2). In fact, in the La Plata basin, 42 % of the precipitation during the wet season and 35 % during the dry season evaporated from the continent. This difference between seasons is explained by a weaker transport of oceanic moisture associated with the subtropical Atlantic high and by an intensification of the South American Low-Level Jet (SALLJ) which transports moisture in the meridional direction during this season (Marengo et al., 2004). The importance of continental moisture recycling in the La Plata basin during the wet season has been emphasized in Drumond et al. (2008); Martinez et al. (2014). Despite this importance, we find that the ocean remains the main source of moisture in the La Plata basin in agreement with previous studies (Drumond et al., 2008; Arraut and Satyamurty, 2009; Drumond et al., 2014). However, some other studies estimated a higher contribution of moisture from the continent to precipitation over the La Plata basin (van der Ent et al., 2010; Keys et al., 2012; Martinez et al., 2014).

There are uncertainties in the moisture recycling ratios depending on the quality of the datasets used, the assumptions made in the methods and the boundaries used to define the domain (for example in Brubaker et al., 1993, the Amazon region is represented by a rectangle). Considering these uncertainties, the regional precipitation recycling ratio in the Amazon basin (Table 2) compares well with previous studies using other datasets and methodologies (See Table 1). The spatial patterns of continental moisture recycling ratios (Fig. 4d, i, e and j) are slightly different from those found by (van der Ent et al., 2010, Figs. 3 and 4) due to the differences in the versions of the model (here we use WAM-2layers) and the datasets used. The continental precipitation recycling ratio in the Amazon basin reaching 30 % during the Southern Hemisphere summer is compatible with the estimation of 36.4 % found by Bosilovich and Chern (2006). The maps of direct recycling ratios (Fig. 7c, and g, a and e) are in good agreement with maps of regional recycling ratio presented in previous studies (Eltahir and Bras, 1994, Figs. 4 and 6 and Burde et al., 2006, Figs. 2 and 8 and Dirmeyer et al., 2009 see http://www.iges.org/wcr/, Moisture Sources by Basin).

We note that our analysis period from 2001–2010 includes two major droughts in the Amazon basin (Marengo et al., 2008; Lewis et al., 2011). Because the

land–atmosphere coupling on the hydrological cycles increases during drought years (Bagley et al., 2014), this might influence the output of the atmospheric moisture tracking model used in this study. Analyzing these periods separately is ongoing research.

3.2 Importance of cascading moisture recycling

Continental moisture recycling is of crucial importance for South American precipitation patterns (Fig. 4). We now quantify this importance and identify intermediary and sink regions of cascading moisture recycling.

3.2.1 The dependency on cascading moisture recycling

The share of cascading moisture on total moisture inflow is on average 10 % in the South American continent. Regions which are dependent on cascading moisture recycling for local rainfall (Fig. 5a and c) are also dominant sinks of moisture from the continent (Fig. 4d and i).

We note that cascading moisture contributes more to the precipitation over the Amazon basin during the dry season (11 % on average, up to 25 % in the western part) compared to the wet season (8 % on average) (Table 2). The inverse situation is observed in the La Plata basin, where on average 14 % of the precipitation during the dry season and 17 % during the wet season comes from cascading moisture recycling (Table 2). In Sect. 3.4, we reveal the evaporative source of cascading moisture which precipitates over the La Plata basin and we understand this seasonal variability.

The share of cascading moisture on total moisture inflow reaches up to 50 % in the eastern side of the central Andes (Fig. 5a and c), one of the most vulnerable biodiversity hotspots on Earth (Myers et al., 2000). However, this latter observation should be considered with caution due to the imbalance of the water cycle in this area which might lead to an over-estimation of the regional recycling process and thus an over-estimation of the importance of cascading moisture recycling.

3.2.2 The contribution of intermediary regions to cascading moisture recycling

The contribution of evapotranspiration from the Amazon basin to cascading moisture recycling in the continent reaches up to 25 % during the dry season in the central part of the Amazon basin and 35 % during the wet season in its southwestern part (Fig. 5b and d). These regions are important intermediaries in cascading moisture recycling pathways.

In order to quantify the importance of these intermediary regions for regional rainfall over the La Plata basin, we quantify the share of the moisture inflow in the La Plata basin that has cascaded in these regions. This share is 8 % during the wet season and 4 % during the dry season. These estimations represent almost half of the share of total moisture inflow that has cascaded in the entire continent during the wet season and one third during the dry season (Table 2). These results mean that the south-western part of the Amazon basin is an important intermediary for cascading moisture transported towards the La Plata basin during the wet season.

3.3 Complex network analysis

We have shown the importance of cascading moisture recycling for South American moisture transport (see Fig. 5). Using the clustering coefficient associated with the Middleman motif ($\tilde{\boldsymbol{C}}$), we are able to identify intermediary locations involved in cascading moisture recycling as alternative pathways to the direct transport of moisture. These regions are the central part of the Amazon basin during the dry season and the south-western part of the Amazon basin during the wet season (Fig. 6a and c). This is in good agreement with other measures quantifying the contribution of intermediary regions to cascading moisture recycling (Fig. 5b and d).

The betweenness centrality ($\boldsymbol{B}$) reveals intermediary regions where cascading moisture recycling pathways are channeled. Regions with high $\boldsymbol{B}$ coincide with regions which high $\tilde{\boldsymbol{C}}$ during the wet season (Fig. 6c), but not during the dry season (Fig. 6). This non-overlap is probably explained by the cutting of long-range moisture recycling

pathways in the calculating of the B, as we have shown that the incoming moisture over the La Plata basin during the dry season is mainly transported through direct (and thus long-range) moisture recycling pathways (Fig. 5a).

During the wet season, cascading moisture recycling pathways are channeled in the south-western part of the Amazon basin and a narrow band east of the subtropical Andes (Fig. 6d). This observation may be explained by the combined effect of the acceleration of the South American Low Level Jet (Vera et al., 2006) and the high precipitation and evapotranspiration during the wet season (Fig. 4) allowing for an intensive local exchange of moisture between the vegetation and the atmosphere.

3.4 Direct and cascading moisture recycling from the Amazon basin to the La Plata basin

We have shown the importance of the Amazon basin as the dominant source of continental moisture and the La Plata basin as a central sink region (see Fig. 4). In the following, we further investigate the transport mechanism between the two basins.

In the La Plata basin, 23 % of the precipitation during the wet season and 25 % during the dry season originated from the Amazon basin through direct moisture recycling (Fig. 7c and g and Table 2). This is compatible with the yearly average estimates of 23 % found in Dirmeyer et al. (2009, see http://www.iges.org/wcr/) and 23.9 % found in Martinez et al. (2014). Considering cascading moisture recycling once moisture has left the Amazon basin (Fig. 2a) increases the dependency from 23 to 29 % during the wet season (Fig. 7h and Table 2). As mentioned above, this might be explained by the high evapotranspiration and precipitation allowing for an exchange of moisture on the way, downwind of the Amazon basin, and by the intensification of the SALLJ during this time of the year (Marengo et al., 2004). This result suggests that the impact of deforestation in the Amazonian forest on the moisture supply in the La Plata basin might be larger than expected if only direct transport of moisture between the two basins are considered.

The southern part of the Amazon basin is a direct source of precipitation over the La Plata basin, with a direct contribution reaching 15 % of its evapotranspiration during the dry season and 35 % during the wet season (Figs. 7a and 7e). This finding is in agreement with Martinez et al. (2014) who found that the southern part of the basin is an quasi-permanent direct source of moisture for the La Plata basin. However, if cascading moisture recycling are considered (Fig. 2b), the entire Amazon basin becomes the evaporative source of moisture over the La Plata basin during the wet season (Fig. 7f). The indirect contribution represents on average 7 % of the total evapotranspiration in the Amazon basin during the wet season (Table 2). This result means that during the wet season, the southern part of the Amazon basin is not only a source of moisture but also an intermediary region where moisture originating from the entire basin cascades on its way to the La Plata basin. This finding is in agreement with other measures showing intermediary locations involved in cascading moisture recycling (see Sect. 3.2).

3.5 Possible impact of land cover change in the intermediary regions

The southern part of the Amazon basin is a key region for moisture transport towards the La Plata basin. It is a source of moisture for precipitation over the La Plata basin all year round and it is in addition an intermediary region for cascading moisture recycling originating from the entire Amazon basin during the wet season (Sect. 3.4).

Land cover change in the southern part of the Amazon basin might weaken continental moisture recycling and might lead to an important decrease in the total precipitation locally and downwind. Among the affected regions, important impacts would be observed in particular in the south-western part of the Amazon basin which has already a high probability to experience a critical transition from forest to savanna (Hirota et al., 2011) and in the La Plata basin which is dependent on incoming rainfall for the agriculture (Rockström et al., 2009; Keys et al., 2012). In the eastern side of the central Andes, the impact of an upwind weakening of cascading moisture recycling might be reduced since precipitation in this region is insured by orographic lifting (Figueroa and Nobre, 1990).

4 Conclusions

In this work we investigated the exchange of moisture between the vegetation and the atmosphere on the way between sources and sinks of continental moisture in South America. We have introduced the concept of “cascading moisture recycling” to refer to moisture recycling between two locations on the continent which involve one or more re-evaporation cycles along the way. We have proposed measures to quantify the importance of cascading moisture recycling and to reveal direct and indirect sources and sinks of moisture for a given region. We have used for the first time a complex network approach to identify intermediary regions in the cascading moisture recycling pathways.

Using the atmospheric moisture tracking model WAM-2layers (WAM-2 layers) forced by precipitation from TRMM and evapotranspiration from MODIS in South America, we have shown that even if the amount of water transported through cascading moisture recycling pathways is typically smaller than the one transported directly in the atmosphere, the contribution by the ensemble of cascading pathways can not be neglected. In fact, 10 % of the total precipitation over South America and 17 % of the precipitation over the La Plata basin comes from cascading moisture recycling.

The La Plata basin is highly dependent on moisture from the Amazon basin during both seasons, as 23 % of the total precipitation over the La Plata basin during the wet season and 25 % during the dry season comes directly from the Amazon basin. To these direct dependencies, 6 % of the precipitation during the wet season can be added if cascading moisture recycling outside the Amazon basin are considered. During the dry season, the main source of continental moisture over the La Plata basin is the southern part of the Amazon basin. During the wet season, the southern part of the Amazon basin is not only a source region but is also an intermediary region which distributes moisture from the entire Amazon basin into the La Plata basin. Land use change in these regions, which include the arc of deforestation, may weaken moisture

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recycling processes and may have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind as previously thought.

In addition, we showed that the eastern flank of the subtropical Andes – located in the pathway of the South American Low Level Jet – plays an important role in the continental moisture recycling as it channels many cascading pathways. This study offers new methods to improve our understanding of vegetation and atmosphere feedback on the water cycle needed in a context of land use and climate change.

Appendix A: Moisture recycling ratios

In these measures the irregular sizes of the portion of the Earth's surface covered by the grid cells are taken into account as described in Zemp et al. (2014).

A1 Direct moisture recycling ratio

The fraction of precipitation in grid cell j that comes directly from Ω is calculated as:

$$\rho_{\Omega,j} = \frac{\sum_{i \in \Omega} m_{ij}}{P_j}, \tag{A1}$$

where m_{ij} is the amount of moisture which evaporates in i and precipitates in j and P_j is the precipitation in j. The fraction of evapotranspiration in grid cell i which precipitates directly in Ω is calculated as:

$$\varepsilon_{\Omega,i} = \frac{\sum_{j \in \Omega} m_{ij}}{E_i}, \tag{A2}$$

where E_i is the evapotranspiration in i.

A2 Cascading moisture recycling ratio

To calculate the cascading moisture recycling ratios as defined in Sect. 2.3.2, we calculate the individual contributions of cascading moisture recycling pathways consisting of k re-evaporation cycles ($k \in \{1,\ldots,n\}$) which add up to the total cascading moisture recycling contribution. We chose a maximum number of cycles $n = 100$, while the contribution of pathways with number of cycles larger than 3 are close to zero. If we track moisture forward in space, we have to take into account that moisture is lost as runoff on the way during the cascading recycling. This is not the case for moisture backward tracking in space because we quantify the remaining amount of moisture that actually arrives at destination.

A2.1 Cascading precipitation recycling ratio

The fraction of precipitation in grid cell j that comes from Ω through cascading moisture recycling involving one re-evaporation cycle is:

$$\rho^{(1)}_{\Omega,j} = \frac{\sum_{i \notin \Omega} m_{ji} \cdot \rho_{\Omega,i}}{P_j}, \tag{A3}$$

where ρ_{Ω_j} is the fraction of precipitation in j that comes directly from Ω (Sect. A1). Following the same principle as in Eq. (A3), the fraction of precipitation in j that comes from Ω through cascading moisture recycling involving n re-evaporation cycles is:

$$\rho^{(n)}_{\Omega,j} = \frac{\sum_{i \notin \Omega} m_{ij} \cdot \rho^{(n-1)}_{\Omega,i}}{P_j}, \tag{A4}$$

where $\rho^{(n-1)}_{\Omega,i}$ is the fraction of precipitation in i that comes from Ω through cascading moisture recycling involving $n-1$ re-evaporation cycles. The total fraction of precipitation in j that comes from Ω through cascading moisture recycling is the sum of all individual contributions of cascading recycling:

$$\rho^{\text{casc}}_{\Omega,j} = \rho^{(1)}_{\Omega,j} + \ldots + \rho^{(n)}_{\Omega,j}. \tag{A5}$$

A2.2 Cascading evapotranspiration recycling ratio

The fraction of evapotranspiration in grid cell i that contributes to precipitation over Ω through cascading moisture recycling involving one re-evaporation cycle is:

$$\varepsilon^{(1)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij} \cdot \varepsilon_{\Omega,j} \cdot \alpha_j}{E_i}, \tag{A6}$$

where $\varepsilon_{\Omega,j}$ is the fraction of evapotranspiration in j which precipitates directly over Ω (Sect. A1) and $\alpha_j = E_j/P_j$. Similarly, the fraction of evapotranspiration in i that precipitates over Ω through cascading moisture recycling involving n re-evaporation cycles is:

$$\varepsilon^{(n)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij} \cdot \varepsilon^{(n-1)}_{\Omega,j} \cdot \alpha_j}{E_i}, \tag{A7}$$

where $\varepsilon^{(n-1)}_{\Omega,j}$ is the fraction of evapotranspiration in j that precipitates over Ω through cascading moisture recycling involving $n-1$ re-evaporation cycles. The total fraction of evapotranspiration in i that precipitates over Ω through cascading moisture recycling is the sum of the individual contribution of cascading recycling:

$$\varepsilon^{\text{casc}}_{\Omega,i} = \varepsilon^{(1)}_{\Omega,i} + \ldots + \varepsilon^{(n)}_{\Omega,i} \tag{A8}$$

Appendix B: Quantifying cascading moisture recycling

To quantify the contribution of cascading moisture recycling to total moisture in- and outflow, we remove the re-evaporation of moisture from continental origin. By doing so,

we inhibit all cascading recycling of moisture from continental origin in the network (see Fig. B1). To achieve this, we derive for each grid cell the evaporation of moisture from oceanic origin (i.e., that has been last evaporated over the ocean) as in Eq. (1):

$$E_{i\leftarrow\text{ocean}} = \frac{E_i}{P_i} \cdot P_{i\leftarrow\text{ocean}}, \tag{B1}$$

where $P_{i\leftarrow\text{ocean}}$ is the precipitation from oceanic origin in i ($P_{j\leftarrow\text{ocean}} = P_j - P_{j\leftarrow\text{continent}}$ and $P_{j\leftarrow\text{continent}} = \sum_{i\in\text{continent}} m_{ij}$.). Using the same assumption, we get the moisture transport between each pair of grid cells i and j that results from evaporation of moisture from oceanic origin only:

$$m_{ij\leftarrow\text{ocean}} = \frac{m_{ij}}{E_i} \cdot E_{i\leftarrow\text{ocean}}, \tag{B2}$$

At this stage, $m_{ij\leftarrow\text{ocean}}$ can be interpreted as the evapotranspiration in i which precipitates in j and which has been evaporated from the ocean before that ($m_{ij\leftarrow\text{ocean}} < m_{ij}$).

In a second step, we derive the corresponding moisture in- and outflow from or towards a given region Ω for each grid cell:

$$P_{j\leftarrow\Omega,o} = \sum_{i\in\Omega} m_{ij\leftarrow\text{ocean}} \tag{B3a}$$

$$E_{i\rightarrow\Omega,o} = \sum_{j\in\Omega} m_{ij\leftarrow\text{ocean}}. \tag{B3b}$$

$P_{j\leftarrow\Omega,o}$ can be interpreted as the precipitation in j originating from the re-evaporation of oceanic moisture in Ω. Similarly, $E_{i\rightarrow\Omega,o}$ can be seen as the evapotranspiration of oceanic moisture in i which precipitates over Ω.

Thus, are able to derive the corresponding reduction in total moisture inflow towards Ω or outflow from Ω:

$$\Delta P_{j\leftarrow\Omega} = P_{j\leftarrow\Omega} - P_{j\leftarrow\Omega,o} \tag{B4a}$$

$$\Delta E_{i\rightarrow\Omega} = E_{i\rightarrow\Omega} - E_{i\rightarrow\Omega,o}, \tag{B4b}$$

where $P_{j\leftarrow\Omega} = \sum_{i\in\Omega} m_{ij}$ is the total precipitation in j originating from Ω and $E_{j\rightarrow\Omega} = \sum_{j\in\Omega} m_{ij}$ is the total evapotranspiration in i which contributes to precipitation over Ω. Thus, $\Delta P_{j\leftarrow\Omega}$ is the precipitation in j originating from the re-evaporation of continental moisture in Ω and $\Delta E_{i\rightarrow\Omega}$ is the re-evaporation of continental moisture in i which precipitates over Ω.

If Ω is the entire South American continent (resp. the intermediary region), $\Delta P_{j\leftarrow\Omega}$ becomes $\mathbf{\Delta P_c}$ (resp. $\mathbf{\Delta P_m}$) and $\Delta E_{i\rightarrow\Omega}$ becomes $\mathbf{\Delta E_c}$ (resp. $\mathbf{\Delta E_m}$) as defined in Sect. 2.4.

Appendix C: Complex network analysis

C1 Clustering coefficient associated with Middleman motifs

Mathematically, the clustering coefficient C of the grid cell i is:

$$C_i = \frac{t_i}{T_i}, \tag{C1}$$

where t_i is the number of Middleman motifs that i forms and T_i is the total number of that motif that i could have formed according to its number of incoming and outgoing arrows. To give more weight to a motif involved in the transport of a larger amount of moisture, we assign a weight to each motif. In agreement with Fagiolo (2007), the weight of a motif is defined as the geometric mean of the weights of the three involved arrows. The weighted counterpart of Eq. (C1) is:

$$\tilde{C}_i = \frac{\tilde{t}_i}{T_i}, \tag{C2}$$

with $\tilde{t}_i$ the weighted counterpart of t_i (i.e., the sum of the weights of the Middleman motifs that is formed by i).

The calculation of the clustering coefficient is derived from the methodology of a previous study (Fagiolo, 2007, Table 1) and has been corrected in order to account for the

irregular sizes of the portion of the Earth's surface covered by the grid cells as explained in (Zemp et al., 2014). The numerator of Eq. (C2) can be derived as $\tilde{t}_i = (\mathbf{PP}^{\mathrm{T}}\mathbf{P})_{ii}$ with $\mathbf{P} = \{p_{ij}^{1/3}\}_{i,j\in N}$ and p_{ij} is the weight of the arrow originating from i and pointing towards j. Here, in order to avoid a strong correlation between the clustering coefficient and the mean evapotranspiration and precipitation, we chose this weight to be $p_{ij} = m_{ij}^2/(E_i P_j)$. The denominator of Eq. (C2) is $T_i = k_i^{\mathrm{in}} k_i^{\mathrm{out}}$ where k_i^{in} is the number of arrows pointing towards i and k_i^{out} the number of arrows originating from i:

$$k_i^{\mathrm{in}} = \sum_{j\neq i} a_{ji}, \tag{C3a}$$

$$k_i^{\mathrm{out}} = \sum_{j\neq i} a_{ij}, \tag{C3b}$$

where $a_{ij} = 1$ if there is an arrow originating from i and pointing towards j and $a_{ij} = 0$ otherwise. In order to compare the results for the two seasons, we normalize $\tilde{C}$ with the maximum observed value for each network.

C2 Optimal pathways and betweenness

C2.1 Optimal pathway

In complex network theory, many centrality measures (e.g. closeness and betweenness) are based on the concept of a shortest path. The shortest path is usually defined as the pathway between nodes which has the minimum cost. In this work, it is defined as the pathway which contributes most to the moisture transport between two grid cells. As this pathway is not necessarily the shortest one in term of geographical distance, we will call it "optimal pathway" to avoid confusion.

Let $(t_1, t_2, \ldots, t_n)$ be the intermediary grid cells in a cascading moisture recycling pathway from grid cell i to grid cell j. The contribution of this pathway is defined as the fraction of precipitation in j that comes from evapotranspiration in i through cascading moisture recycling:

$$W_{i,t_1,\ldots,t_n,j} = \frac{m_{it_1}}{P_{t_1}} \cdot \prod_{l=1}^{n-1} \frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}} \cdot \frac{m_{t_n j}}{P_j} \tag{C4}$$

An example of pathway contributions is provided in Fig. B1. The contribution of each existing pathway is calculated between any pair of grid cells in the network. The optimal pathway is the path with the maximum contribution.

To find the optimal pathway, we use the method `shortest_paths` in the package iGraph for Python based on an algorithm proposed by Newman (2001). In this method, the cost of a pathway is calculated as the sum of the weight of its arrows. In order to adapt the method to our purpose, we chose the weight of the arrows as $w_{t_l t_{l+1}} = -\log(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}})$. The cost of a pathway from grid cell i to grid cell j as calculated in iGraph becomes:

$$\begin{aligned}
W'_{i,t_1,\ldots,t_n,j} &= w_{1t_1} + \sum_{l=1}^{n-1} w_{t_l t_{l+1}} + w_{t_n j} \\
&= -\log(\frac{m_{it_1}}{P_{t_1}}) - \sum_{l=1}^{n-1} \log(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}}) - \log(\frac{m_{t_n j}}{P_j}) \\
&= \log(\frac{1}{\frac{m_{1t_1}}{P_{t_1}} \cdot \prod_{l=1}^{n-1}(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}}) \cdot \frac{m_{t_n j}}{P_j}}) \\
&= \log(\frac{1}{W_{i,t_1,\ldots,t_n,j}})
\end{aligned}$$

Because the optimal pathway is defined as the pathway with the minimum cost W', it corresponds to the pathway with the maximum contribution W as defined above.

C2.2 Betweenness centrality

Mathematically, betweenness of the grid cell i is the fraction of the number of optimal pathways between any pair of grid cells which pass through i:

$$B_i = \sum_{j,k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{C5}$$

with σ_{jk} is the number of optimal pathways between grid cells j and k, and $\sigma_{jk}(i)$ is the number of these pathways that pass through the grid cell i. B reaches values between 0 and $\binom{N-1}{2} = (N^2 - 3N + 2)/2$ with N the number of grid cells. To calculate it, we used the directed and weighted version of the method `betweenness` in the package iGraph for Python. The choice of the weights used in this method is explained in Sect. C2.1.

Author contribution

J. F. Donges, H. M. J. Barbosa, C.-F. Schleussner and D. C. Zemp developed the analysis. R. J. Van der Ent, performed the simulation of WAM-2layers. G. Sampaio provided the mask of the La Plata basin. D. C. Zemp performed the analysis and prepared the manuscript with contributions from all co-authors. C.-F. Schleussner conceived the project together with J. Heinke and supervised it together with A. Rammig.

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References

Arraut, J. M. and Satyamurty, P.: Precipitation and water vapor transport in the Southern Hemisphere with emphasis on the South American region, J. Appl. Meteorol. Clim., 48, 1902–1912, 2009. 17481, 17486, 17495

Arraut, J. M., Nobre, C., Barbosa, H. M., Obregon, G., and Marengo, J.: Aerial rivers and lakes: looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America, J. Climate, 25, 543–556, 2012. 17481

Bagley, J. E., Desai, A. R., Harding, K. J., Snyder, P. K., and Foley, J. A.: Drought and deforestation: has land cover change influenced recent precipitation extremes in the Amazon?, J. Climate, 27, 345–361, 2014. 17481, 17496

Betts, R., Cox, P., Collins, M., Harris, P., Huntingford, C., and Jones, C.: The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming, Theor. Appl. Climatol., 78, 157–175, 2004. 17481

Boers, N., Bookhagen, B., Marwan, N., Kurths, J., and Marengo, J.: Complex networks identify spatial patterns of extreme rainfall events of the South American Monsoon System, Geophys. Res. Lett., 40, 4386–4392, 2013. 17483

Bosilovich, M. G. and Chern, J.-D.: Simulation of water sources and precipitation recycling for the MacKenzie, Mississippi, and Amazon River basins, J. Hydrometeorol., 7, 312–329, 2006. 17481, 17482, 17495, 17516

Brubaker, K. L., Entekhabi, D., and Eagleson, P. S.: Estimation of continental precipitation recycling, J. Climate, 6, 1077–1089, 1993. 17480, 17481, 17495, 17516

Burde, G. I. and Zangvil, A.: The estimation of regional precipitation recycling. Part I: Review of recycling models, J. Climate, 14, 2497–2508, 2001. 17482

Burde, G. I., Gandush, C., and Bayarjargal, Y.: Bulk recycling models with incomplete vertical mixing. Part II: Precipitation recycling in the Amazon basin, J. Climate, 19, 1473–1489, 2006. 17481, 17488, 17516

Costa, M. H., Biajoli, M. C., Sanches, L., Malhado, A. C. M., Hutyra, L. R., da Rocha, H. R., Aguiar, R. G., and de Araújo, A. C.: Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: are the wet and seasonally dry rain forests any different?, J. Geophys. Res.-Biogeo., 115, G0402, doi:10.1029/2009JG001179, 2010.

Cox, P. M., Betts, R. A., Collins, M., Harris, P. P., Huntingford, C., and Jones, C. D.: Amazonian forest dieback under climate-carbon cycle projections for the 21st century, Theor. Appl. Climatol., 78, 137–156, 2004. 17481

Da Silva, R. R., Werth, D., and Avissar, R.: Regional impacts of future land-cover changes on the Amazon basin wet-season climate, J. Climate, 21, 1153–1170, 2008. 17481

Dee, D. and Uppala, S.: Variational bias correction in ERA-Interim, no. 575 in Technical Memorandum, ECMWF, Shinfield Park, Reading, England, 2008. 17485

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, 2011. 17485

Dirmeyer, P. A., Brubaker, K. L., and DelSole, T.: Import and export of atmospheric water vapor between nations, J. Hydrol., 365, 11–22, 2009. 17481, 17495, 17498, 17516

Donges, J. F., Zou, Y., Marwan, N., and Kurths, J.: Complex networks in climate dynamics – Comparing linear and nonlinear network construction methods, Eur. Phys. J.-Spec. Top., 174, 157–179, 2009a. 17483

Donges, J. F., Zou, Y., Marwan, N., and Kurths, J.: The backbone of the climate network, Europhys. Lett., 87, 48007, doi:10.1209/0295-5075/87/48007, 2009b. 17483

Drumond, A., Nieto, R., Gimeno, L., and Ambrizzi, T.: A Lagrangian identification of major sources of moisture over Central Brazil and La Plata basin, J. Geophys. Res., 113, D14128, doi:10.1029/2007JD009547, 2008. 17481, 17495

Drumond, A., Marengo, J., Ambrizzi, T., Nieto, R., Moreira, L., and Gimeno, L.: The role of Amazon basin moisture on the atmospheric branch of the hydrological cycle: a Lagrangian analysis, Hydrol. Earth Syst. Sci. Discuss., 11, 1023–1046, doi:10.5194/hessd-11-1023-2014, 2014. 17481, 17494, 17495

Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling in the Amazon basin, Q. J. Roy. Meteor. Soc., 120, 861–880, 1994. 17480, 17481, 17488, 17516

Fagiolo, G.: Clustering in complex directed networks, Phys. Rev. E, 76, 026107, doi:10.1103/PhysRevE.76.026107, 2007. 17492, 17505

Figueroa, S. N. and Nobre, C. A.: Precipitation distribution over central and western tropical South America, Climanalise, 5, 36–45, 1990. 17499
Franchito, S. H., Rao, V. B., Vasques, A. C., Santo, C. M. E., and Conforte, J. C.: Validation of TRMM precipitation radar monthly rainfall estimates over Brazil, J. Geophys. Res.-Atmos., 114, D02105, doi:10.1029/2007JD009580, 2009. 17485
Freeman, L. C.: A set of measures of centrality based on betweenness, Sociometry, 40, 35–41, 1977. 17493
Gat, J. and Matsui, E.: Atmospheric water balance in the Amazon basin: an isotopic evapotranspiration model, J. Geophys. Res.-Atmos., 96, 13179–13188, 1991. 17481
Goessling, H. F. and Reick, C. H.: Continental moisture recycling as a Poisson process, Hydrol. Earth Syst. Sci., 17, 4133–4142, doi:10.5194/hess-17-4133-2013, 2013. 17487
Grimm, A. M., Vera, C. S., and Mechoso, C. R.: The South American Monsoon System, in: The Third International Workshop on Monsoons, World Meteorological Organizations, Hangzhou, 111–129, 2–6 November 2004. 17486
Hasler, N., Werth, D., and Avissar, R.: Effects of tropical deforestation on global hydroclimate: a multimodel ensemble analysis, J. Climate, 22, 1124–1141, 2009. 17481
Hirota, M., Holmgren, M., Van Nes, E. H., and Scheffer, M.: Global resilience of tropical forest and savanna to critical transitions, Science, 334, 232–235, 2011. 17481, 17499
Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y., Stocker, E. F., and Wolff, D. B.: The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales, J. Hydrometeorol., 8, 38–55, 2007. 17484
Keys, P. W., van der Ent, R. J., Gordon, L. J., Hoff, H., Nikoli, R., and Savenije, H. H. G.: Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions, Biogeosciences, 9, 733–746, doi:10.5194/bg-9-733-2012, 2012. 17481, 17482, 17495, 17499
Kim, J.-E. and Alexander, M. J.: Tropical precipitation variability and convectively coupled equatorial waves on submonthly time scales in reanalyses and TRMM, J. Climate, 26, 3013–3030, 2013. 17485
Knox, R., Bisht, G., Wang, J., and Bras, R.: Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia, J. Climate, 24, 2368–2377, 2011. 17481
Lean, J. and Warrilow, D. A.: Simulation of the regional climatic impact of Amazon deforestation, Nature, 342, 411–413, 1989. 17481

Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M., and Nepstad, D.: The 2010 amazon drought, Science, 331, 554–554, 2011. 17495
Liebman, B., Kiladis, G. N., Marengo, J. A., Ambrizzi, T., and Glick, J. D. : Submonthly convective variability over South America and the South Atlantic convergence zone, J. Climate, 12, 1877–1891, 1999. 17486
Loarie, S. R., Lobell, D. B., Asner, G. P., Mu, Q., and Field, C. B.: Direct impacts on local climate of sugar-cane expansion in Brazil, Nature Climate Change, 1, 105–109, 2011. 17485
Malik, N., Bookhagen, B., Marwan, N., and Kurths, J.: Analysis of spatial and temporal extreme monsoonal rainfall over South Asia using complex networks, Clim. Dynam., 39, 971–987, 2012. 17483
Marengo, J. A.: Characteristics and spatio-temporal variability of the Amazon River Basin Water Budget, Clim. Dynam., 24, 11–22, 2005. 17481
Marengo, J. A.: On the hydrological cycle of the Amazon basin: a historical review and current state-of-the-art, Revista Brasileira de Meteorologia, 21, 1–19, 2006. 17481
Marengo, J. A., Soares, W. R., Saulo, C., and Nicolini, M.: Climatology of the low-level jet east of the Andes as derived from the NCEP-NCAR reanalyses: Characteristics and temporal variability, J. Climate, 17, 2261–2280, 2004. 17495, 17498
Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., Sampaio de Oliveira, G., De Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F.: The drought of Amazonia in 2005, J. Climate, 21, 495–516, 2008. 17495
Martinez, J. A., and Dominguez, F.: Sources of Atmospheric Moisture for the La Plata River Basin, J. Climate, doi:10.1175/JCLI-D-14-00022.1, in press, 2014. 17481, 17495, 17498, 17499
Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., Sampaio de Oliveira, G., De Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F.: The drought of Amazonia in 2005, J. Climate, 21, 495–516, 2008. 17495
Medvigy, D., Walko, R. L., and Avissar, R.: Effects of deforestation on spatiotemporal distributions of precipitation in South America, J. Climate, 24, 2147–2163, 2011. 17481
Miguez-Macho, G. and Fan, Y.: The role of groundwater in the Amazon water cycle. 2. Influence on seasonal soil moisture and evapotranspiration, J. Geophys. Res., 117, D15114, doi:10.1029/2012JD017540, 2012.
Milo, R., Shen-Orr, S., Itzkovitz, S., Kashtan, N., Chklovskii, D., and Alon, U.: Network motifs: simple building blocks of complex networks, Science, 298, 824–827, 2002. 17492

Monteith, J.: Evaporation and environment, Sym. Soc. Exp. Biol., 19, 205–234, 1965. 17485
Morton, D. C., Nagol, J., Carabajal, C. C., Rosette, J., Palace, M., Cook, B. D., Vermote, E. F., Harding, D. J., and North, P. R. J.: Amazon forests maintain consistent canopy structure and greenness during the dry season, Nature, 506, 221–224, 2014.
Mu, Q., Zhao, M., and Running, S. W.: Improvements to a MODIS global terrestrial evapotranspiration algorithm, Remote Sens. Environ., 115, 1781–1800, 2011. 17485
Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A. B., and Kent, J.: Biodiversity hotspots for conservation priorities, Nature, 403, 853–858, 2000. 17496
Nepstad, D. C., de Carvalho, C. R., Davidson, E. A., Jipp, P. H., Lefebvre, P. A., Negreiros, G. H., da Silva, E. D., Stone, T. A., Trumbore, S. E., and Vieira, S.: The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures, Nature, 372, 666–669, 1994.
Newman, M. E. J.: Scientific collaboration networks. II. Shortest paths, weighted networks, and centrality, Phys. Rev. E, 64, 016132, doi:10.1103/PhysRevE.64.016132, 2001. 17507
Nobre, C. A., Sellers, P. J., and Shukla, J.: Amazonian deforestation and regional climate change, J. Climate, 4, 957–988, 1991. 17481
Nobre, P., Malagutti, M., Urbano, D. F., de Almeida, R. A., and Giarolla, E.: Amazon deforestation and climate change in a coupled model simulation, J. Climate, 22, 5686–5697, 2009. 17481
Numaguti, A.: Origin and recycling processes of precipitating water over the Eurasian continent: experiments using an atmospheric general circulation model, J. Geophys. Res.-Atmos., 104, 1957–1972, 1999. 17482
Oyama, M. D. and Nobre, C. A.: A new climate-vegetation equilibrium state for tropical South America, Geophys. Res. Lett., 30, 2199, doi:10.1029/2003GL018600, 2003. 17481
Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: the potential of green water for increasing resilience to global change, Water Resour. Res., 45, W00A12, doi:10.1029/2007WR006767, 2009. 17481, 17499
Rozante, J. R. and Cavalcanti, I. F. A.: Regional Eta model experiments: SALLJEX and MCS development, J. Geophys. Res.-Atmos., 113, D17106, doi:10.1029/2007JD009566, 2008. 17485

Rozante, J. R., Moreira, D. S., de Goncalves, L. G. G., and Vila, D. A.: Combining TRMM and surface observations of precipitation: technique and validation over South America, Weather Forecast., 25, 885–894, 2010. 17485
Ruhoff, A.: Predicting evapotranspiration in tropical biomes using MODIS remote sensing data, Ph.D. thesis, Federal University of Rio Grande do Sul, Porto Alegre, 2011. 17485
Salati, E., Dall'Olio, A., Matsui, E., and Gat, J. R.: Recycling of water in the Amazon basin: an isotopic study, Water Resour. Res., 15, 1250–1258, doi:10.1029/WR015i005p01250, 1979. 17481
Sampaio, G., Nobre, C., Costa, M. H., Satyamurty, P., Soares-Filho, B. S., and Cardoso, M.: Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion, Geophys. Res. Lett., 34, L17709, doi:10.1029/2007GL030612, 2007. 17481
Savenije, H. H. G.: The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrol. Process., 18, 1507–1511, 2004. 17487
Shukla, J., Nobre, C., and Sellers, P.: Amazon deforestation and climate change, Science, 247, 1322–1325, 1990. 17481
Spracklen, D. V., Arnold, S. R., and Taylor, C. M.: Observations of increased tropical rainfall preceded by air passage over forests, Nature, 489, 282–285, 2012. 17481, 17482
Sudradjat, A., Brubaker, K., and Dirmeyer, P.: Precipitation source/sink connections between the Amazon and La Plata River basins, in: AGU Fall Meeting Abstracts, vol. 1, p. 0830, San Francisco, California, 6–10 December 2002. 17482
Trenberth, K. E.: Atmospheric moisture recycling: role of advection and local evaporation, J. Climate, 12, 1368–1381, 1999. 17481, 17516
Tsonis, A. A., Swanson, K. L., and Wang, G.: On the role of atmospheric teleconnections in climate, J. Climate, 21, 2990–3001, 2008. 17483
van der Ent, R. J. and Savenije, H. H. G.: Length and time scales of atmospheric moisture recycling, Atmos. Chem. Phys., 11, 1853–1863, doi:10.5194/acp-11-1853-2011, 2011. 17488
van der Ent, R. J., Savenije, H. H. G., Schaefli, B., and Steele-Dunne, S. C.: Origin and fate of atmospheric moisture over continents, Water Resour. Res., 46, W09525, doi:10.1029/2010WR009127, 2010. 17481, 17482, 17489, 17495, 17516
van der Ent, R. J., Tuinenburg, O. A., Knoche, H.-R., Kunstmann, H., and Savenije, H. H. G.: Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?, Hydrol. Earth Syst. Sci. Discuss., 10, 6723–6764, doi:10.5194/hessd-10-6723-2013, 2013. 17482, 17484

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van der Ent, R. J., Wang-Erlandsson L., Keys P. W., and Savenije H. H. G.: Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling, Earth Syst. Dynam. Discuss., 5, 281–326, 2014.

Vera, C., Baez, J., Douglas, M., Emmanuel, C. B., Marengo, J., Meitin, J., Nicolini, M., Nogues-Paegle, J., Paegle, J., Penalba, O., Salio, P., Saulo, C., Silva Dias, M. A., Silva Dias, P., and Zipser, E.: The South American low-level jet experiment, B. Am. Meteorol. Soc., 87, 63–77, 2006. 17498

Victoria, R. L., Martinelli, L. A., Mortatti, J., and Richey, J.: Mechanisms of water recycling in the Amazon basin: isotopic insights, Ambio, 20, 384–387, 1991. 17481

Walker, R., Moore, N. J., Arima, E., Perz, S., Simmons, C., Caldas, M., Vergara, D., and Bohrer, C.: Protecting the Amazon with protected areas, P. Natl. Acad. Sci. USA, 106, 10582–10586, 2009. 17481

van der Ent, R. J., Gordon, L. J., and Savenije, H. H. G.: Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Simple Terrestrial Evaporation to Atmosphere Model, Earth Syst. Dynam. Discuss., 5, 203–279, doi:10.5194/esdd-5-203-2014, 2014. 17484

Werth, D. and Avissar, R.: The local and global effects of Amazon deforestation, J. Geophys. Res.-Atmos., 107, 1322–1325, 2002. 17481

Zemp, D. C., Wiedermann, M., Kurths, J., Rammig, A., and Donges, J. F.: Node-weighted measures for complex networks with directed and weighted edges for studying continental moisture recycling, Europhys. Lett., revised, 2014. 17492, 17501, 17506

Table 1. Overview of regional precipitation recycling ratio in the Amazon basin as found in many studies. Abbreviations: the European Centre for Medium-Range Weather Forecasts (ECMW); Geophysical Fluid Dynamics Laboratory Precipitation (GFDL); Climate Prediction Center Merged Analysis of Precipitation (CMAP); Initinal conditions (IC); October-November-December (OND); Data Assimilation Office (DAO); Integral Moisture Balance (IMB) model; NCEP – Department of Energy (DOE); World Monthly Surface Station Climatology distributed by the National Center for Atmospheric Research (NCAR).

Study	Method	Dataset	Period	Precipitation recycling ratio
(Brubaker et al., 1993)	Atmospheric Bulk model	GFDL and NCAR	1963–1973	24
(Eltahir and Bras, 1994)	Atmospheric Bulk model	ECMWF reanalysis	1985–1990	25
		GFDL	1963–1973	35
(Trenberth, 1999)	Atmospheric Bulk model	CMAP and NCEP-NCAR reanalysis	1979–95	34
(Bosilovich and Chern, 2006)	AGCM with water vapor tracers	IC from the model	1948–1997	27.2 during OND
(Burde et al., 2006)	Atmospheric Bulk model (general)	DAO	1981–1993	31
	Atmospheric Bulk model (Budyko model)			26
	Atmospheric Bulk model (IMB)			41
(Dirmeyer et al., 2009)	Quasi-isentropic back-trajectory method	DOE reanalysis	1979–2003	10.8 for area 10^6 km^2
(van der Ent et al., 2010)	Atmospheric moisture tracking model	ERA-Interim reanalysis	1999–2008	28
Zemp et al. (this study)	Atmospheric moisture tracking model	TRMM and MODIS	2001–2010	28

Table 2. Results (in %) averaged for the La Plata basin, the Amazon basin and for the South American continent during the wet season (DJFM), the dry season (JJAS) and all year round.

Notation	Description	La Plata basin			Amazon basin			South America		
		wet	dry	year	wet	dry	year	wet	dry	year
ρ_c	Fraction of precipitation originating from evapotranspiration from the continent	42	35	41	30	35	32	30	29	31
ρ_{Am}	Fraction of precipitation originating from evapotranspiration from the Amazon basin through direct moisture recycling	23	25	24	26	30	28	18	21	20
ρ_{Am}^{casc}	Fraction of precipitation originating from evapotranspiration from the Amazon basin through cascading moisture recycling	6	2	4	–	–	–	11	6	8
ε_c	Fraction of evapotranspiration that contributes to precipitation over the continent	43	16	35	77	45	65	56	31	47
ε_{Pl}	Fraction of evapotranspiration that contributes to precipitation over the La Plata basin through direct moisture recycling	32	12	26	16	7	11	15	7	12
ε_{Pl}^{casc}	Fraction of evapotranspiration that contributes to precipitation over the La Plata basin through cascading moisture recycling	–	–	–	7	3	5	4	1	3
$\Delta P_c/P$	Fraction of precipitation that comes from cascading moisture recycling on the continent	17	14	17	8	11	10	10	9	10
$\Delta P_m/P$	Fraction of precipitation that comes from cascading moisture recycling in the intermediary region	8	4	6	4	6	5	4	4	4
$\Delta E_c/E$	Fraction of evapotranspiration that is involved in cascading moisture recycling	11	9	9	11	24	12	13	15	10

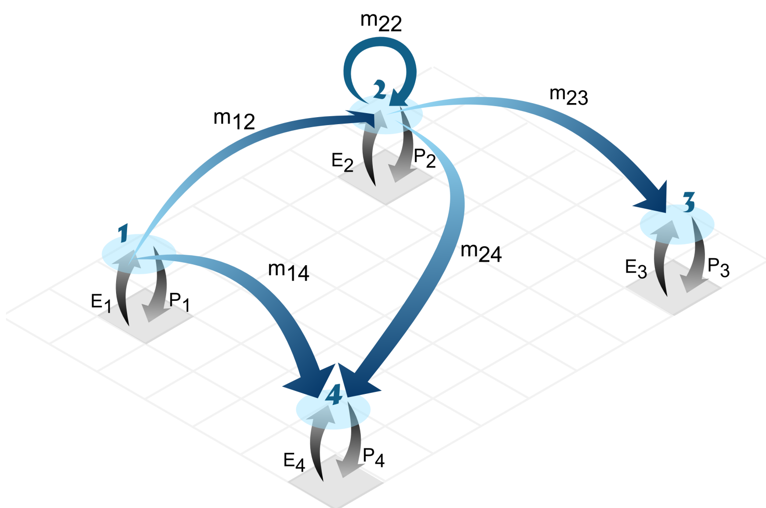

Figure 1. Scheme of the moisture recycling network. Nodes 1,2,3,4 represent different grid cells and arrows indicate the direction and amount of moisture originating from evapotranspiration in the source cell and contributing to precipitation in the target cell. For example, the total evapotranspiration in 2 (E_2) splits up in three branches: m_{23} precipitates in 3, m_{24} precipitates in 4 and m_{22} is locally recycled. m_{22} contributes together with m_{12} to the total precipitation in 2 (P_2).

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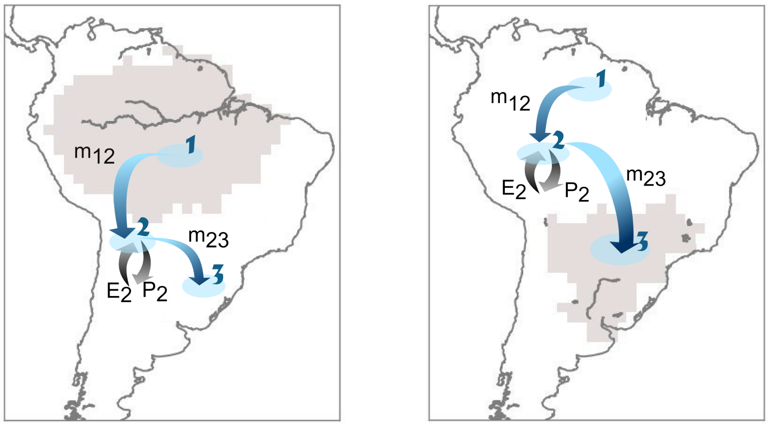

(a) (b)

Figure 2. Scheme of cascading moisture recycling **(a)** for moisture originating from the Amazon basin and **(b)** for moisture that has final destination the La Plata basin. In both figures, the amount of precipitation in grid cell 3 that is originating from evapotranspiration in grid cell 1 is $m_{23} \cdot m_{12}/P_2$.

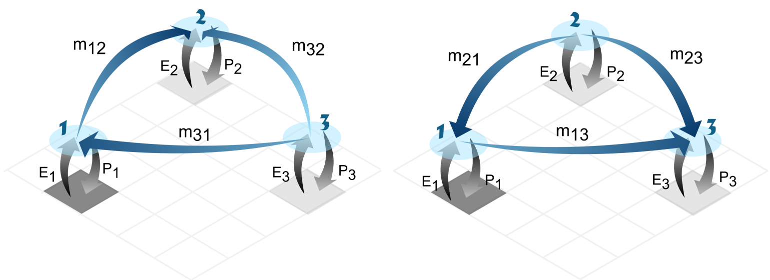

Figure 3. Scheme of two possible patterns in the Middleman motif from the perspective of grid cell 1. The grid cell 1 (dark gray) receives and distributes moisture from and to grid cells 2 and 3 (light gray) which also exchange moisture such that there is no cyclic relation. The exchange of moisture between 2 and 3 uses two alternative pathways: the direct one (m_{23} in **(a)** or m_{32} in **(b)**) and the cascading pathway ($m_{21}m_{13}$ in **(a)** or $m_{31}m_{12}$ in **(b)**). The grid cell 1 is an intermediary on an alternative pathway to the direct transport of moisture between 2 and 3.

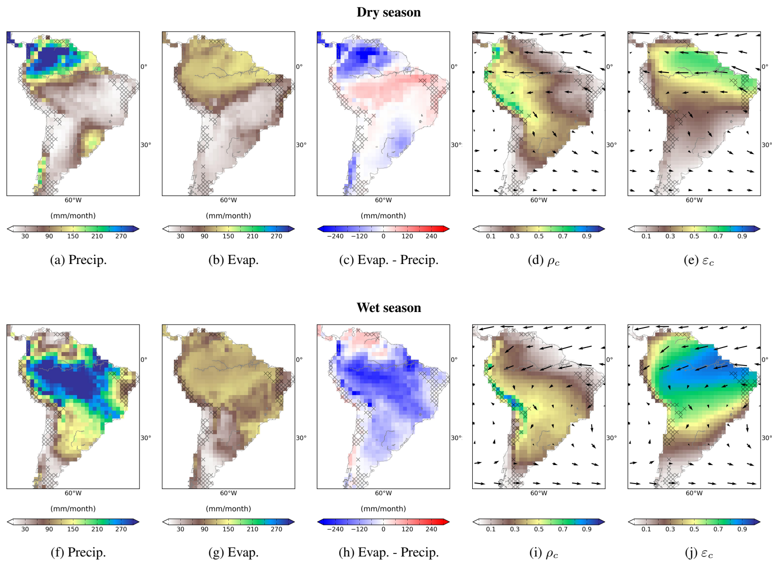

Figure 4. Long term seasonal mean of precipitation **(a, f)**, evapotranspiration **(b, g)**, precipitation – evapotranspiration **(c, h)** for the period 2001–2010 as calculated from TRMM and MODIS. Continental precipitation recycling ratio ρ_c **(d, i)** and continental evapotranspiration recycling ratio ε_c **(e, j)** showing respectively sinks and sources of continental moisture. Here and in the following figures, the vectors indicate the horizontal moisture flux field (in m^3 of moisture $\times m^{-2} \times month^{-1}$) and the hatches represent grid cells where annual mean evapotranspiration exceeds mean annual precipitation. Results are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

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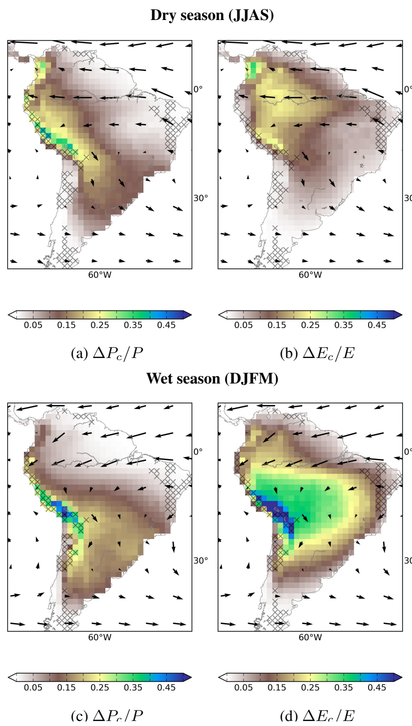

Figure 5. Fraction of total precipitation originating from cascading moisture recycling ($\Delta P_c/P$) **(a, c)** and fraction of total evapotranspiration that is involved in cascading moisture recycling ($\Delta E_c/E$) **(b, d)**. While high values of $\Delta P_c/P$ indicate regions which are dependent on cascading moisture recycling for local rainfall, high values of $\Delta E_c/E$ indicate intermediary regions which contribute to cascading moisture recycling.

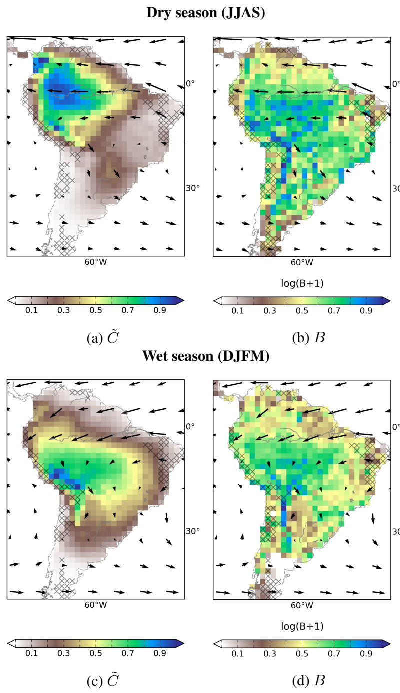

Figure 6. Complex network analysis. Clustering coefficient $\tilde{C}$ associated with the motif Middleman **(a, c)** and betweenness centrality B **(b, d)**. While high values of $\tilde{C}$ indicate intermediary locations where cascading moisture recycling allows for alternative pathways to the direct transport of moisture, high values of B indicate regions where pathways of cascading moisture recycling are channeled. Results are given for the dry season (upper row) and the wet season (lower row).

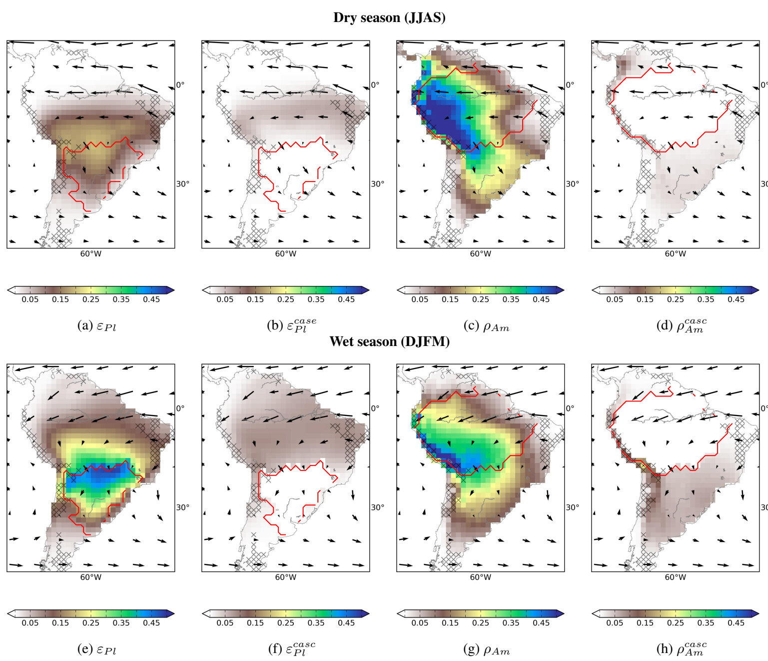

Figure 7. Fraction of evapotranspiration which precipitates over the La Plata basin (defined by the red boundaries) through direct ($\varepsilon_{\mathrm{Pl}}$, **a** and **e**) and cascading moisture recycling ($\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$, **b** and **f**) and fraction of precipitation which comes from the Amazon (defined by the red boundaries) basin through direct (ρ_{Am}, **c** and **g**) and cascading moisture recycling ($\rho_{\mathrm{Am}}^{\mathrm{casc}}$, **d** and **h**). Considered together, $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$ show source regions of precipitation over the La Plata basin and ρ_{Am} and $\rho_{\mathrm{Am}}^{\mathrm{casc}}$ show sink regions of evapotranspiration from the La Plata basin. Results are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

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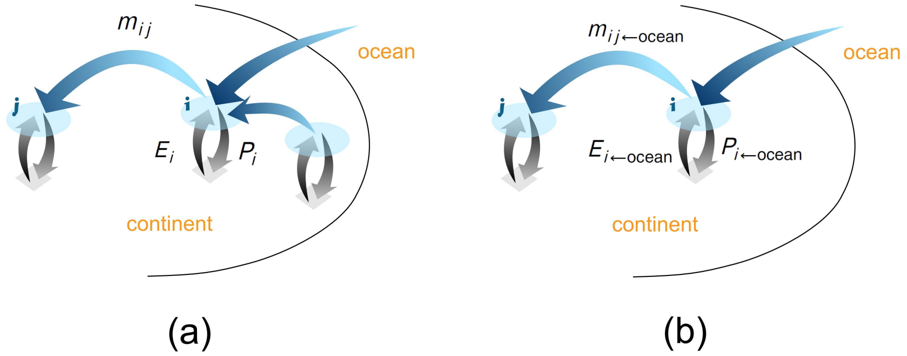

Figure B1. Scheme explaining the removal of cascading moisture recycling. **(a)** Originally, the precipitation in the grid cell i (P_i) is composed by oceanic and continental moisture. The total incoming moisture is evaporated in i (E_i) and some part of it contributes to precipitation in the grid cell j (m_{ij}). **(b)** If we forbid the re-evaporation of continental precipitation, only the precipitation in i that has oceanic origin ($P_{i\leftarrow \text{ocean}}$) is evaporated in i ($E_{i\leftarrow \text{ocean}}$) and can contribute to precipitation in j ($m_{ij\leftarrow \text{ocean}}$). By doing so, we remove cascading recycling of continental moisture from the network.

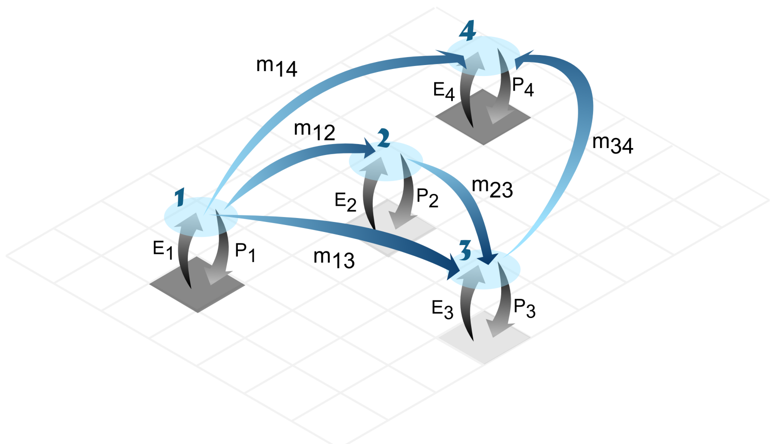

Figure C1. Different cascading moisture recycling pathways from grid cell 1 to grid cell 4. The contribution of the direct pathway is $W_{1,4} = m_{14}/P4$, the contribution of the path involving one re-evaporation cycle in grid cell 3 is $W_{1,3,4} = m_{13}/P3 \cdot m_{14}/P4$ and the contribution of the path involving re-evaporation cycles in grid cells 2 and 3 is $W_{1,2,3,4} = m_{12}/P2 \cdot m_{13}/P3 \cdot m_{14}/P4$.