Atmospheric Basins: Identification of Quasi-Independent Spatial Patterns in the Global Atmospheric Hydrological Cycle Via a Complex Network Approach

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Abstract A river basin is commonly assumed to be a closed unit of the terrestrial hydrological cycle. Further research is required to identify analogous regional-scale and quasi-independent spatial patterns with the potential to be treated as basic hydrological units of the atmospheric hydrological cycle. To this purpose, we constructed global atmospheric moisture networks (GAMNs) for the boreal summers and winters from 2007 to 2016 based on the atmospheric source-sink relationships between grid cells of a global 3° × 3° grid generated by the Eulerian atmospheric moisture tracking model WAM-2layers (water accounting model-two layers). By adopting a complex network-based approach, we identified regional-scale patterns in the GAMNs that reflect the regional moisture transport characteristics and have high moisture recycling ratios (>50%) and defined these patterns as atmospheric basins. Moisture exchanges between atmospheric basins are non-negligible, and several atmospheric basins act as strong moisture providers/receivers. Moreover, typical atmospheric basins were selected to check the stability and variation of atmospheric basins during 2007–2016. We observed core regions that persist throughout the years in these atmospheric basins. Inter-annual differences in the positions and areas of these atmospheric basins were also observed, and we attributed these to inter-annual differences in the atmospheric moisture links. Identifying atmospheric basins can help to better understand the global hydrological cycle dynamics and drivers as it reduces the complexity of the grid-based source-sink relationships of atmospheric moisture.

1. Introduction

Rivers flow on the Earth’s surface and build water links between different terrestrial locations. These links are not only a key part of the global hydrological cycle, but they also exert a significant influence on the establishment of generalized links in environment, ecosystem, and human society (Anderson et al., 2019; McMillin, 2011). Atmospheric moisture transport processes act as “rivers” in the atmosphere (Arraut et al., 2011), transporting moisture from its terrestrial source location where it enters the atmosphere through evaporation, to the terrestrial sink location where it precipitates and leaves the atmosphere. Therefore, atmospheric moisture transport processes build links between evaporation and precipitation locations and serve as linkages between terrestrial river basins (Sori et al., 2018; Wang-Erlandsson et al., 2018; Weng et al., 2018), closing the hydrological cycle from a land-atmosphere perspective. A deep understanding of atmospheric moisture transport processes and the built links will improve our understanding of the global hydrological cycle from the viewpoint of land-atmosphere coupling.

Atmospheric moisture links have been well studied as atmospheric moisture source-sink (evaporation-precipitation) relationships between different locations. Moisture evaporated at source locations is called to be recycled when the source and sink locations are located within the same predefined region, and moisture recycling processes of different regions around the world have been quantified based on analytical models (e.g., Brubaker et al., 1993; Burde & Zangvil, 2001; Dominguez et al., 2006; Eltahir & Bras, 1994; Trenberth, 1999). With the fast development of computational power, many numerical models, including online models (water vapor tracers embedded in global or regional climate/weather models;
e.g., Bosilovich & Schubert, 2002; Dominguez et al., 2016; Numaguti, 1999; Nusbaumer et al., 2017; Pan et al., 2017; Sodemann et al., 2009) and offline models (numerical models derived from moisture mass conservation and based on meteorological data acquired beforehand; e.g., Dirmeyer & Brubaker, 1999; van der Ent et al., 2010; Sodemann et al., 2008; Stohl & James, 2004), have been developed to locate remote moisture sources and quantify their contributions to the predefined sink regions. Notably, the definition of the local and remote moisture sources is scale- and shape-dependent since all sources become local sources from the global viewpoint (moisture recycling ratio, defined as ratio of recycled moisture amount to total regional precipitation/evaporation, equals 100%) and nearly all sources become remote sources for one single point (moisture recycling ratio goes asymptotically to zero).

Recently, using offline models, several studies have estimated the spatial and temporal scales of atmospheric moisture recycling (Läderach & Sodemann, 2016; Tuinenburg & van der Ent, 2019; van der Ent & Savenije, 2011; van der Ent & Tuinenburg, 2017). Their findings indicated that atmospheric moisture links around the world have various but limited spatial and temporal scales. Considering this point and the existence of relatively stable regional structures in the global atmospheric circulation systems (e.g., monsoons, the intertropical convergence zones [ITCZ], and westerlies), potential regional-scale structures representing certain patterns of moisture links may exist in the atmospheric hydrological cycle. Some efforts have been made in this direction. Gimeno et al. (2012) depicted the spatial boundaries of the atmospheric moisture source regions of nine predefined sink regions by tracking the backward Lagrangian trajectories starting from these regions and drawing contour lines that surround the areas covered by 95% of the particles that reach the corresponding sink regions. Keys et al. (2012) proposed the concept of a precipitationshed and determined the quantitative spatial boundaries of the moisture source regions of seven predefined sink regions by tracing the moisture sources of precipitation over the seven regions and drawing the spatial boundaries of the moisture sources that provide 70% of the moisture to the corresponding sink regions. Van der Ent and Savenije (2013) proposed a similar concept, that is, the evaporationshed, and they found the quantitative boundaries of the moisture sink regions of 15 major oceanic source regions by forward tracking the destinations of the moisture evaporated from these predefined source regions. Link et al. (2020) further provided a global dataset on moisture links of terrestrial source regions defined on a fine-meshed grid (1.5° × 1.5°) and facilitated a global view of evaporationsheds for terrestrial regions on the grid cell, country, and river basin scales. Keune and Miralles (2019) investigated the moisture links on the river basin scale by treating 50 European river basins as sink regions and they found that external moisture sources contributed up to 74% to the precipitation in some of these river basins, indicating that some of these river basins are dependent structures of the atmospheric hydrological cycle. These studies improved our understanding of the possible spatial boundaries of moisture links. Using the concept of precipitationshed/evaporationshed, one can delineate areas with high moisture recycling ratios for the predefined sink/source regions (e.g., 70% in the study of Keys et al., 2012, and 50% in the study of van der Ent & Savenije, 2013). However, even precipitationsheds and evaporationsheds are not independent structures of the atmospheric hydrological cycle since multiple locations on Earth can contain the same moisture source location of precipitation. In other words, evaporation from a specific source location can contribute to multiple precipitation events that cover multiple precipitationsheds. In this sense, the concepts of precipitationshed and evaporationshed still incompletely match with the concept of a river basin where water barely flows outside (except water at the pour point). Moreover, a precipitationshed/evaporationshed is based on direct, one-way, many-to-one/one-to-many moisture links, while more complex links and transport patterns of moisture exist among worldwide locations through direct two-way moisture links (two locations acting as each other’s moisture source and sink; e.g., Keys et al., 2017) and cascading moisture links (consecutive direct and one-way moisture links; e.g., Keys et al., 2017; Zemp et al., 2014). A concise and efficient extraction of the representative linkage and transport patterns behind the massive number of complex grid-based moisture links from a global perspective still remains to be conducted.

This study aims to delineate regional-scale areas in the global atmospheric hydrological cycle that are relatively closed with respect to moisture recycling, analogous to the terrestrial river basins. Toward this purpose, we investigate atmospheric moisture links from the viewpoint of a complex network (CN). A direct, one-way moisture link consists of a start (evaporation) location, an end (precipitation) location and the amount of moisture that the start location contributes to the end location. This type of link is a typical element, that is, a directed and weighted edge (formed by a start node, an end node and a weight value from the
start node to the end node), in a CN. By creating direct, one-way moisture links between worldwide locations, we can obtain a global atmospheric moisture network (GAMN), in which complex moisture links can be well depicted. In particular, a cascading moisture link in a GAMN, that is, a finite sequence of edges joining a sequence of locations (also called a path in the terminology of CN or graph theory), can be used to spatially mimic the transport behavior of moisture. Zemp et al. (2014) referred to the cascading moisture links within South America as cascading moisture recycling (CMR) and quantified the contribution of CMR to the precipitation over South America by constructing a regional atmospheric moisture network. We hold the view that due to the limited spatial scales of atmospheric moisture links and the existence of certain regional structures in the global atmospheric circulation systems, the cascading moisture links in a GAMN also have finite spatial scales and locations connected by certain cascading moisture links may form a regional-scale pattern. Inside this pattern, if a moisture tracer is released and moves along the cascading links, it will tend to stay within that pattern, similar as the case of a river basin where water flowing along the river channels of that river basin seldom flows outside. In the CN research, many algorithms have been developed to identify this type of pattern, that is, flow-based communities (in the terminology of CN or graph theory) where a random walker born inside a community and traveling along the edges of a CN is more likely trapped within that community than to go outside (for a comprehensive review of the fundamental concept and algorithms of the flow-based communities, please refer to Malliaros & Vazirgiannis, 2013).

Taking advantage of cascading moisture links and borrowing the idea of the flow-based communities in a CN, in this study, we apply an offline Eulerian atmospheric moisture tracking model, the two-layer version of the water accounting model (WAM-2layers) developed by van der Ent et al. (2014), to establish seasonal (boreal summer and winter) moisture links over 10 years (2007–2016), build 22 seasonal GAMNs (20 seasonal GAMNs for boreal summers and winters from 2007 to 2016 and two 10-year average seasonal GAMNs), and identify the flow-based communities in these GAMNs by a widely used flow-based community detection algorithm (Infomap) (Bohlin et al., 2014; Rosvall et al., 2009; Rosvall & Bergstrom, 2008). Then we quantify the moisture recycling and moisture inflows and outflows of the identified communities and plot them on global maps to create a spatial description of the relationships between the identified communities from a global perspective. Moreover, we define the communities with high moisture recycling ratios as atmospheric basins and investigate the stability and variation of typical atmospheric basins in 2007–2016. Finally, we present detailed discussions of the methodology, uncertainties in data and model, the implications for hydrological research, and several potential future research directions.

2. Methods

2.1. Input Data and Model Setup of the WAM-2layers

The establishment of direct, one-way moisture links (moisture links refer to direct, one-way moisture links hereafter unless specified) around the world lays the foundation of the GAMN construction. Specifically, we established moisture links for 10-year (2007–2016) boreal summers (June, July, and August, referred to as JJA below) and winters (December, January, and February, referred to as DJF below). Considering the balance between computational efficiency and numerical accuracy, we chose the WAM-2layers developed by van der Ent et al. (2014) to conduct moisture source attribution of daily precipitation and establish moisture links. The core idea of the WAM-2layers is backward (forward) solving the Eulerian mass balance equation of a moisture tracer tagged with mass equaling the precipitation (evaporation) amount of a given target region. Then precipitation (evaporation) over the target region can be attributed to different locations according to the “well-mixed” assumption that the proportion of evaporation (precipitation) of one location that contributes to precipitation (evaporation) in the target region equals the ratio of the tagged moisture mass of that location to the precipitable water amount in that location. Atmospheric variables including three-dimensional winds and specific humidity, vertically integrated moisture states and fluxes, surface moisture fluxes (precipitation and evaporation), and surface pressure were retrieved from reanalysis datasets to drive the model. Considering the fact that different reanalysis datasets show substantial differences in the depiction of water cycle (Bosilovich et al., 2017; Trenberth et al., 2011; Yu et al., 2017), we used two reanalysis datasets, the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al., 2011; shorted as ERA in the following text) and the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2; Gelaro et al., 2017), to drive the model. For
both datasets, all the required variables from 2006 to 2016 were downloaded and linearly interpolated on a 1.5° × 1.5° global grid. A complete list of downloaded variables can be found in the Data Availability Statement section.

In order to balance accuracy and computation cost, we ran the model on a 1.5° × 1.5° global grid but actually dealt with moisture links on a 3° × 3° global grid (longitude range: −180° to 180°; latitude range: −70° to 70°; with 5,640 grid cells in total). Specifically, in a single calculation process, we ran the WAM-2layers on the 1.5° × 1.5° grid and backward in time to track the moisture sources of the daily precipitation in four neighboring 1.5° × 1.5° grid cells and terminated the calculation if the sum of attributed precipitation provided by current moisture sources contributed to 90% of the daily precipitation in the four grid cells. Then we obtained a 2-D spatial distribution (1.5° × 1.5°) of moisture sources of precipitation for the 3° × 3° grid cell centered at the center of the four 1.5° × 1.5° grid cells. We upscaled the spatial distribution to the 3° × 3° grid to quantify the moisture contribution of each 3° × 3° grid cell to the target 3° × 3° grid cell. Then a daily moisture link arriving at the target grid cell was established, consisting of a source 3° × 3° grid cell, the target grid cell, and the moisture provided by the source grid cell for precipitation in the target grid cell. By conducting this calculation process repeatedly throughout all 1.5° × 1.5° grid cells, we obtained daily moisture links for 5,640 3° × 3° grid cells for JJA and DJF from 2007 to 2016.

2.2. Construction of the GAMNs and Moisture Transport in the GAMNs

Daily- or weekly-scale moisture links may be controlled by different meso- and small-scale atmospheric processes (e.g., Bohlinger et al., 2017; Huang et al., 2018; Zhang et al., 2019). To obtain relatively stable and representative moisture links, the daily moisture links of a 3° × 3° grid cell were aggregated seasonally, and the seasonal moisture links for that 3° × 3° grid cell were obtained. The obtained seasonal links are the cumulative result of all of the moisture transport scenarios related to the precipitation in that grid cell during a season. Therefore, as was also noted by Zemp et al. (2014), a seasonal moisture link is assumed to be static on the seasonal scale, to be free of temporal information, and to only contain spatial information for the source and target grid cells. Then we constructed a seasonal, time-independent GAMN with nodes represented by the 3° × 3° grid and edges represented by the seasonal links. In this study, we constructed 20 seasonal GAMNs (JJA and DJF for each year during 2007–2016) and two 10-year average seasonal GAMNs (for completeness, 22 GAMNs for the transitional seasons, i.e., MAM [March, April, and May] and SON [September, October, and November], were also constructed, but we mainly focused on JJA and DJF). For a GAMN, an adjacency matrix \( W = \{wij\} (i, j = 1, 2, ..., 5,640) \) is constructed where \( w_{ij} \) represents the weight of the edge from node \( i \) to node \( j \), that is, the amount of moisture evaporated at node \( i \), transported to node \( j \) and converted into precipitation at node \( j \). A \( W \) can be treated as the transposed source-sink matrix used by Link et al. (2020). A \( W \) can be a dense matrix with many minor edges and can affect the computational efficiency of the following steps. Therefore, we eliminated the minor edges arriving at one node in the following manner. We traversed all of the non-zero weights \( w_{ij} (i = 1, 2, ..., 5,640) \) arriving at node \( j \) in a descending order and summed the visited \( w_{ij} \) until the ratio of the current sum of weights to the total sum of weights reached 0.9. Then the unvisited weights were eliminated.

The adjacency matrix \( W \) represents all of the possible direct, one-way moisture links between the 5,640 grid cells. A cascading moisture link between node \( i \) and \( j \) can be established if there is a sequence of consecutive edges (direct, one-way moisture links) joining \( i \) and \( j \) (e.g., an edge sequence of \( i \rightarrow n_1, n_1 \rightarrow n_2, \) and \( n_2 \rightarrow j \) that joins \( i \) and \( j \) through nodes \( n_1 \) and \( n_2 \)), forming an indirect, multi-step link between \( i \) and \( j \). Apparently, although there is only one direct, one-way moisture link from \( i \) to \( j \), multiple cascading moisture links can be found between them, indicating that if a moisture tracer is released at a certain node, it may have multiple transport paths to reach a certain destination node. We established a random walk paradigm based on the cascading moisture links of a GAMN to spatially approximate the possible transport paths of a moisture tracer and the propagation of moisture it carries. Suppose a moisture tracer (i.e., a random walker) is released at node \( i \), tagged with moisture amount \( E_i \) (the total evaporation amount over node \( i \); \( E_i = \sum_{j=1}^{N} w_{ij} \), where \( N \) is the total number of nodes), and moves along the GAMN through edges. The tracer is assumed to be first-order Markovian, and thus, its next step only depends on the edges starting from the node it currently occupies. More precisely, the tracer currently at node \( i \) follows one of the outgoing edges of node \( i \) and moves to the end node of that edge with a probability proportional to the edge’s weight. It means that the probability \( p(j|i) \) of choosing \( w_{ij} \) and moving to node \( j \) is
Since the tracer has other options of the next destination node, we assume that only a portion of $E_i$ can be brought to $j$ and the portion is assumed to be also proportional to the edge’s weight, which means that the tracer will bring $E_i \cdot \frac{w_{ij}}{\sum_{j=1}^{N} w_{ij}}$ to $j$. The following transport processes of the tracer follow the same rule.

Finally, a consecutive multistep transport path of the tracer is obtained and moisture carried by the tracer is transported to the nodes on the way. The probability of a tracer tagged with $E_{n_0}$ at node $n_0$ moving to node $n_i$ through a $i$-step random walk path (i.e., a $i$-step cascading moisture link) $n_0 \rightarrow n_1 \rightarrow ... \rightarrow n_i$ is

$$p(n_1, ..., n_{i-1}, n_i|n_0) = \prod_{k=1}^{i} p(n_k|n_{k-1}) = \prod_{k=1}^{i} \frac{w_{n_k\rightarrow n_{k-1}}}{\sum_{l=1}^{N} w_{n_l\rightarrow n_{l-1}}}$$

and the amount of moisture that the tracer carries to $n_i$ is

$$m_{n_0 \rightarrow n_1 \rightarrow ... \rightarrow n_i} = E_{n_0} \prod_{k=1}^{i} \frac{w_{n_k\rightarrow n_{k-1}}}{\sum_{l=1}^{N} w_{n_l\rightarrow n_{l-1}}}$$

where $E_{n_0}$ is the amount of evaporation at node $n_0$. By tracing all of the possible paths starting at $n_0$, we can capture the propagation processes of the moisture evaporated at $n_0$. The above description focuses on random walks of moisture tracers along the forward direction of moisture links and tagged with evaporated moisture. Random walks of tracers along the backward direction can be also realized by reversing the moisture link directions and tagging the tracer with the total precipitation amount of one node (e.g., $P_i$ is the total precipitation amount over node $i$; $P_i = \sum_{j=1}^{N} w_{ij}$). This random walk paradigm was used by Zemp et al. (2014) to quantify the contribution of CMR to precipitation over South America. We present schematic examples of three-step forward and backward random walks in Figure 1 to provide an intuitive demonstration of the random walk paradigm. Four real examples of propagations of moisture through multi-step forward and backward random walks on the two 10-year average seasonal GAMNs are presented in Figure S1 in the supporting information. The results indicate that the amount of moisture that each grid cell can obtain rapidly decreases with increasing step of the random walk, indicating that the cascading moisture links may become quite weak (i.e., moisture carried by the tracer nearly runs out) when a tracer has moved too many steps.
2.3. Atmospheric Basins: Identification and Characteristic Metrics

Since random walks can be used to spatially approximate moisture transport processes, a natural idea is to find a random-walk-based community detection algorithm to detect flow-based communities in a GAMN. From the perspective of random walks, a flow-based community in a directed network is a group of nodes with a certain connectivity pattern that forces a random walker that has entered the community to predominantly stay inside instead of stepping out of the community. In other words, a flow-based community favors the intra-community movements and suppresses the inter-community movements. In terms of a GAMN, a forward moisture tracer tagged with the evaporation of a certain node in a certain flow-based community will predominantly move and release moisture within the community, implying that most of the tagged moisture will be recycled within the community. A random-walk-based community detection algorithm called Infomap, which was developed under the framework of the map equation (Rosvall & Bergstrom, 2008), was used to identify flow-based communities in the GAMN. Infomap discovers the duality between finding the best flow-based community partition of a directed and weighted network and the coding problem of minimizing the codeword length used to describe a random walk on that network. A synthetic GAMN with 40 nodes is shown in Figure 2 to give a brief introduction of the core idea of Infomap. Each node is named with a code word so that we can describe a random walk via a sequence of code words. If a uniform and global code scheme in which all of the nodes are coded with equal-length code words is chosen, then a six-step random walk can be described as a sequence of the code words of the seven nodes. Suppose we have a certain community partition. We can give a two-level code scheme based on the information of the community partition to shorten the codeword description of a random walk. Specifically, each community is named using a unique code word. Each community has its own codebook to name its nodes, which means that the same code word can be assigned to several nodes that belong to different communities. The code words of the nodes within the same community can be shorter than those in the global code scheme since there are fewer nodes to be coded in every community.

Figure 2. Schematic diagram of the core idea of Infomap. The synthetic GAMN consists of 40 nodes (rectangular boxes enclosed by gray lines). The weights of the edges (black arrows) are represented by arrow widths. A six-step forward random walk through seven nodes (gray-shaded rectangles numbered from 1 to 7) is represented by blue arrows. A certain community partition \( C \) (five communities, shaded with five different colors) is shown in the bottom left corner. The top right panel shows two kinds of code schemes of this random walk: a uniform and global code scheme (blue-shaded rectangles) and a two-level code scheme (multicolor rectangles; the same color scheme is used as that in community partition). A number in a rectangle denotes which node the random walker currently visits. A letter “C” in a rectangle indicates that the corresponding rectangle is the code word of a community, while a letter “E” indicates that the corresponding rectangle is the exit code of a community. When the walker exits one community, the exit code of that community is used, followed by the code word of the community that the walker steps in. As shown in the bottom right panel, Infomap aims to find the best \( C \) that minimizes the map equation \( L(C) \), that is, the lower limit of the average per-step codeword length with community partition \( C \).
community. Using a two-level code scheme, the description of the six-step random walk can be divided into two parts: one describing the movements within the communities and the other describing the movements between communities (i.e., entering and exiting communities). Infomap does not aim to find the best code scheme to encode random walks on a network, and it instead develops the map equation \( L(C) \) (Rosvall & Bergstrom, 2008) to give the theoretical lower limit of the average per-step codelength of a random walk under a given community partition \( C \):

\[
L(C) = q_{\infty} H(\mathcal{E}) + \sum_{i=1}^{C} p_{i}^{C} H(\mathcal{P}^{i})
\]

where \( L(C) \) is the lower limit of the average per-step codelength of a random walk, \( q_{\infty} \) is the probability that a random walker switches communities on any given step, \( H(\mathcal{E}) \) is the lower limit length of code words used to name communities, \( p_{i}^{C} \) is the probability that a random walker stays in community \( i \), and \( H(\mathcal{P}^{i}) \) is the lower limit length of code words used to name nodes of community \( i \). Network structure information (i.e., edge direction and weight) is considered in the determination of \( q_{\infty} \), \( H(\mathcal{E}) \), \( p_{i}^{C} \), and \( H(\mathcal{P}^{i}) \) based on a similar idea with that described by Equation 1 (a brief introduction of how the network structure information is used in these four parameters is given in Text S2 in the supporting information). Then the \( C \) that minimizes \( L(C) \) is founded via a greedy-search based algorithm and is treated as the optimal community partition. More detailed descriptions of the map equation and Infomap can be found in the studies of Bohlin et al. (2014), Rosvall et al. (2009), and Rosvall and Bergstrom (2008).

After the identification of the flow-based communities in the GAMN, several metrics can be calculated to investigate moisture recycling of each community and moisture exchanges between communities on the node scale and community scale. Our main concern for the node scale metrics lies in moisture recycling. Suppose we are dealing with node \( i \), with \( C_{i} \) denoting which community it belongs to. Then, \( R_{i}^{P} \), the precipitation recycling ratio of node \( i \) (the proportion of the precipitation in node \( i \) that originates from the evaporation within \( C_{i} \)) is expressed as follows:

\[
R_{i}^{P} = \frac{\sum_{j} w_{ij} \delta(C_{j}, C_{i})}{P_{i}}
\]

where \( C_{j} \) is the community that node \( j \) belongs to, \( \delta \) is the Kronecker delta function—\( \delta(i, j) = 1 \) if \( i = j \); \( \delta(i, j) = 0 \) if \( i \neq j \)—with which we can pick out all nodes that belong to the same community as node \( i \) does, \( \sum_{j} w_{ij} \delta(C_{j}, C_{i}) \) represents the total amount of moisture evaporated within \( C_{i} \) and converted into precipitation at node \( i \), and \( P_{i} = \sum_{j} w_{ij} \) represents the total amount of moisture converted into precipitation at node \( i \). And \( R_{i}^{E} \), the evaporation recycling ratio of node \( i \) (the proportion of evaporation at node \( i \) that turns into precipitation within \( C_{i} \)) is written as

\[
R_{i}^{E} = \frac{\sum_{j} w_{ij} \delta(C_{j}, C_{i})}{E_{i}}
\]

where \( \sum_{j} w_{ij} \delta(C_{j}, C_{i}) \) represents the total amount of moisture evaporated at node \( i \) and converted into precipitation within \( C_{i} \) and \( E_{i} = \sum_{j} w_{ij} \) represents the total amount of moisture evaporated at node \( i \). For the community scale metrics, we quantify the total inter-community moisture exchanges and their proportions with respect to the total precipitation/evaporation of the communities. Specifically, \( M_{IJ} \), the total amount of moisture evaporated at community \( I \) and converted into precipitation in community \( J \), is written as

\[
M_{IJ} = \sum_{m, n} w_{mn} \delta(C_{m}, I) \delta(C_{n}, J)
\]

where \( C_{m} \) and \( C_{n} \) denote the communities that node \( m \) and \( n \) belong to and we can use the product of two Kronecker delta functions to pick out all edges starting from nodes in \( I \) and arriving at nodes in \( J \). \( M_{IJ} \) can be treated as a moisture outflow for \( I \) and as a moisture inflow for \( J \). Then, the ratios of \( M_{IJ} \) to the total evaporation over \( I \) and of \( M_{IJ} \) to the total precipitation over \( J \) are quantified as
3. Results

3.1. Community Detection Results of the 10-Year Average Seasonal GAMNs

We identified the flow-based communities in the 10-year average JJA and DJF GAMNs to give an overall description for these 10 years. The identified communities are shown in Figure 3 (for completeness, we also identified the communities for MAM and SON and the results are shown in Figure S2 in the supporting information), and we name nine communities in JJA and six communities in DJF (names and acronyms of these communities are presented in Table 1). Vertically integrated horizontal moisture flux fields averaged over 2007–2016 JJA and DJF are also shown to qualitatively demonstrate the moisture transport conditions, together with horizontal winds at 850 hPa to qualitatively show the low-level circulation conditions. In general, a high level of agreement was observed between the results of ERA and MERRA2, which was also quantitatively suggested by the adjusted mutual information (AMI; Vinh et al., 2010), a metric used to assess the similarity between two community partitions of a network (e.g., Hanteer & Rossi, 2019; Jeub et al., 2018), with the knowledge that an AMI of 1 indicates perfect match and an AMI of 0 indicates total mismatch (AMI between ERA and MERRA2: 0.80 in JJA and 0.84 in DJF). Intuitively, the major identified communities basically match the regional characteristics of moisture transport fluxes. For the JJA cases, according to the moisture transport flux and 850 hPa wind fields (Figures 3a–3d), we observed significant oceanic anticyclone structures in the four oceanic communities (over 70% of areas of these communities are covered by the oceans): NAO, SAO, ESP, and NP. The shape of CETP basically matches the obvious moisture convergence structures over the central-eastern tropical Pacific. Moisture transport conditions over the Asian summer monsoon regions are mainly represented by three communities: NIO, WNP, and IND-TP. We treated NIO as an oceanic community (over 85% covered by the oceans) and treated IND-TP as a terrestrial community (over 75% covered by the lands) covering the Indian subcontinent and southwestern China (including the Tibet Plateau), Eastern China, the South China Sea, the Philippine Islands, and part of Japan are under control of WNP. For the DJF cases, the anticyclone structures in NAO, SAO, and ESP are still obvious, and NAO and NP are characterized by strong northeastward moisture transport fluxes. CETP can reach the easternmost tropical Pacific and is characterized by strong southwestward moisture transport fluxes. The major differences between the results of ERA and MERRA2 lie in the community partitioning over the coast of Central America, tropical South America, and the tropical Atlantic. These regions are divided into several communities in JJA and DJF according to the ERA results (Figures 3a, 3c, 3e, and 3g). For the JJA case of MERRA2 (Figures 3b and 3d), an east-west oriented community covers the easternmost tropical Pacific, Central America, and tropical South America, while part of the tropical Atlantic merges together with Africa as
one community. For the DJF case of MERRA2 (Figures 3f and 3h), the community covering the tropical Atlantic can reach western tropical South America.

The spatial distributions of the node-scale moisture recycling ratios (calculated using direct moisture links) are shown in Figure 4. We observed relatively high precipitation and evaporation recycling ratios (≥50%) at most of the nodes. Low precipitation and evaporation recycling ratios were observed near the boundaries of many communities, indicating the relatively low connectivity of the boundary nodes with their communities. According to the moisture flux fields, the low precipitation recycling ratios are mainly located at the upwind boundaries of the communities, while the low evaporation recycling ratios are mainly located at the downwind boundaries, indicating strong directionality of direct moisture links within communities. Notably, the relatively low precipitation recycling ratios are found over the entire regions of several communities, such as the communities covering northern Africa and North America in DJF (Figures 4e and 4f).

Figure 5 shows the spatial maps of the inter-community moisture exchanges and moisture recycling ratios on the community scale (calculated using direct moisture links). In general, the communities largely occupied by the oceans have stronger moisture recycling (the total amounts of recycled moisture are basically larger than $3.0 \times 10^{12}$ m$^3$ per season) than those of the communities largely occupied by the continents. We
observed extremely strong moisture recycling (recycled moisture \( \geq 7.0 \times 10^{12} \text{ m}^3 \text{ per season} \)) in the communities located at the Indian Ocean and the tropical Pacific according to the ERA results (Figures 5a and 5c). The results of MERRA2 indicate that the community covering Central America and its adjacent oceanic regions in JJA (Figure 5b) and the community covering the North Pacific in DJF (Figure 5d) have extremely strong moisture recycling (recycled moisture \( \geq 7.0 \times 10^{12} \text{ m}^3 \text{ per season} \)). Moisture recycling dominates the precipitation and evaporation in most of the communities (domination of the precipitation and evaporation here means that the amount of the recycled moisture of a community is larger than any moisture inflow or outflow of that community). Exceptions are found in the precipitation recycling ratios of a small community located at Central America in the JJA case of ERA (Figure 5a), communities covering North America, western tropical South America, and northern Africa in the DJF case of ERA (Figure 5c), and communities covering Eurasia, the northern North Atlantic, North America, western extratropical South America, and northern Africa in the DJF case of MERRA2 (Figure 5d). The precipitation processes within these communities are largely supported by the external moisture. Notably, exceptions are also found in the evaporation recycling ratios of the communities covering northeastern Asia and North America in the DJF case of MERRA2 (Figure 5d), where the evaporated moisture is largely transported outside. Besides the moisture recycling features, non-negligible moisture exchanges (\( \geq 0.1 \times 10^{12} \text{ m}^3 \text{ per season} \)) exist between most of the communities, and they balance the surplus or deficit of moisture of a community induced by the unequal generation (evaporation) and consumption (precipitation) of moisture. We observed strong moisture exchanges (\( \geq 1.0 \times 10^{12} \text{ m}^3 \text{ per season} \)) in the communities located at the Asian summer monsoon regions and the tropical Pacific (IND-TP, NIO, WNP, and CETP) in the JJA cases (Figures 5a and 5b). WNP acts as a significant “collector hub” of precipitation, collecting 5.4 (4.7) \( \times 10^{12} \text{ m}^3 \) (value in parentheses represents the MERRA2 result, similarly hereinafter) (54% [52%] of the seasonal precipitation in WNP) moisture from NIO, CETP, and the community covering the southern tropical Pacific.

According to our definition of an atmospheric basin in section 2.3 and the results shown in Figure 5, the named nine and six communities in JJA and six communities in DJF according to the geographical regions they mainly cover.

| Number | Full name | Acronym |
|--------|-----------|---------|
| 1      | The community mainly covering the North Atlantic Ocean | NAO     |
| 2      | The community mainly covering the South Atlantic Ocean | SAO     |
| 3      | The community mainly covering the eastern South Pacific | ESP     |
| 4      | The community mainly covering the central-eastern tropical Pacific | CETP    |
| 5      | The community mainly covering the Eurasia continent | EA      |
| 6      | The community mainly covering the North Pacific | NP      |
| 7      | The community mainly covering the Indian subcontinent and the Tibet Plateau | IND-TP |
| 8      | The community mainly covering the northern Indian Ocean | NIO     |
| 9      | The community mainly covering the western North Pacific | WNP     |

| Number | Full name | Acronym |
|--------|-----------|---------|
| 1      | The community mainly covering the North Atlantic Ocean | NAO     |
| 2      | The community mainly covering the South Atlantic Ocean | SAO     |
| 3      | The community mainly covering the eastern South Pacific | ESP     |
| 4      | The community mainly covering the central-eastern tropical Pacific | CETP    |
| 5      | The community mainly covering the Eurasia continent | EA      |
| 6      | The community mainly covering the North Pacific | NP      |

Note: We reused the names of JJA communities in the DJF cases in view of their similar geographical locations, and we did not imply any relations between the communities with the same name in different seasons. We named nine communities in JJA and six communities in DJF according to the geographical regions they mainly cover.
Among these oceanic atmospheric basins, NIO generates 13.9 (11.6) × 10^{12} m^3 moisture and consumes 9.4 (7.7) × 10^{12} m^3 in JJA. The significant surplus of the moisture makes NIO become the biggest moisture provider that provides 5.6 (4.8) × 10^{12} m^3 to its neighboring atmospheric basins and communities. In contrast, in JJA, WNP consumes 10.1 (9.0) × 10^{12} m^3 moisture but only generates 5.3 (5.1) × 10^{12} m^3. WNP receives 6.5 (5.7) × 10^{12} m^3 from its neighboring atmospheric basins and communities to support its precipitation, acting as the biggest moisture receiver among atmospheric basins and communities. Considerable amounts of moisture generation (evaporation) and consumption (precipitation) were also observed in CETP in both seasons. CETP are also significant moisture providers that provide 4.0 (2.9) × 10^{12} m^3 and 4.5 (3.4) × 10^{12} m^3 moisture in JJA and DJF for its neighboring atmospheric basins and communities. Relatively strong moisture generation and consumption were observed in NAO, SAO, ESP, and NP in both seasons. For the terrestrial atmospheric basins, that is, IND-TP in JJA and EA in both seasons, although the moisture generation and consumption are relatively weak (generation: 3.9 [2.9] × 10^{12} m^3 in IND-TP, 3.8 [2.9] × 10^{12} m^3 in EA in JJA, 1.2 [1.1] × 10^{12} m^3 in EA in DJF; consumption: 5.8 [4.3] × 10^{12} m^3 in IND-TP, 4.0 [3.4] × 10^{12} m^3 in EA in JJA, 2.0 [2.0] × 10^{12} m^3 in EA in DJF), IND-TP can receive 2.1 (1.6) × 10^{12} m^3 (accounting for 37% of the total precipitation in IND-TP).

Figure 4. Spatial distributions of the node-scale precipitation and evaporation recycling ratios (color shaded; unit: %) of the 10-year average JJA (a–d) and DJF (e–h) GAMNs using ERA (left) and MERRA2 (right) data. Overlaid are the vertically integrated horizontal moisture flux fields (black arrows; unit: kg m^{-1} s^{-1}) averaged over the corresponding period.
moisture from NIO. The strong moisture transport from NIO to IND‐TP indicates that although moisture recycling plays the most important role in precipitation over South Asia and southwestern China, the South Asian summer monsoon also profoundly impacts the precipitation processes over these regions.

Besides the community-scale moisture exchanges calculated using direct moisture links, we also quantified the community-scale precipitation and evaporation recycling ratios of the named atmospheric basins based on cascading moisture links of two- to 20-step, as shown in Figure 6. The results of ERA and MERRA2 match well. The precipitation and evaporation recycling ratios of these atmospheric basins decrease within the first several steps. Notably, due to the significant anticyclone structures, the precipitation recycling ratios of NAO, SAO, and ESP in both seasons keep relatively high even at step 20. However, the precipitation recycling ratios of NP in JJA, which also has a significant anticyclone structure, keep decreasing with increasing step of cascading moisture links; in contrast, the evaporation recycling ratios of NP in JJA stop decreasing and stay around 20% after step 10. The evaporation recycling ratios of EA in JJA stop decreasing at step 8 and start to increase, indicating that the moisture transported outside at previous steps comes back to EA. For other atmospheric basins, the precipitation and evaporation recycling ratios keep decreasing and reach relatively low values after many steps of random walks, indicating that the long-distance cascading moisture recycling activities play a limited role in the precipitation and evaporation processes of these atmospheric basins.

3.2. Stability of Atmospheric Basins

The communities and atmospheric basins presented in section 3.1 are the representative patterns of the 10-year average moisture links during JJA and DJF. It is a natural thought to check if these patterns also exist in JJA and DJF for each year during 2007–2016. Therefore, we identified the communities in the 20 seasonal
GAMNs (JJA and DJF for each year during 2007–2016). Figure 7 shows the AMI between the results of the community detection using ERA and MERRA2 for JJA and DJF of each year. The spatial distributions of the identified communities in 2007–2016 for all seasons are presented in Figures S3–S6 in the supporting information. All of the AMI values exceeded 0.75, indicating a satisfactory consistency between the results of ERA and MERRA2. In the following, we present in detail the stability and variation of some of the named atmospheric basins in these 10 years. To demonstrate the stability of an atmospheric basin, we calculated the frequency of each node (grid cell) identified as a member of that atmospheric basin during the 10-year period. In addition, the area of that atmospheric basin in each year was calculated.

Figure 6. Community-scale moisture recycling ratios (unit: %) of precipitation (columns 1 and 3) and evaporation (columns 2 and 4) of the nine and six named atmospheric basins under different steps of cascading moisture links for the 10-year average JJA (columns 1 and 2, and the last row of columns 3 and 4) and DJF (rows 1–6 of columns 3 and 4) GAMNs using ERA (blue shaded bars) and MERRA2 (orange shaded bars) data. A precipitation recycling ratio of 80% at step 1 indicates that 80% of the precipitation of an atmospheric basin is supported by the moisture that is evaporated at the nodes (grid cells) within the same atmospheric basin and transported to the precipitation nodes of that atmospheric basin via one-step (direct) moisture links, and a precipitation recycling ratio of 20% at step 10 indicates that 20% of the precipitation of an atmospheric basin can be attributed to the moisture that is evaporated at the nodes within the same atmospheric basin and transported to the precipitation nodes of that atmospheric basin via 10-step cascading moisture links.
core regions that persist throughout the 10-year period (grid cells with frequencies of 1). For both seasons, the core region of NAO reaches North America. NAO identified using ERA in JJA is stable, while NAO identified using MERRA2 in JJA extends to 70°N in 2008 and 2010. NAO in DJF is reported to extend to 70°N in 2011 by both ERA and MERRA2. For SAO, the core region in JJA can reach South America, while in DJF it stays in the South Atlantic due to the shrinkage of SAO in 2007 and 2011. Both ERA and MERRA2 indicate that SAO in DJF merges with the atmospheric basin located in the tropical Atlantic in 2016. For ESP, the core regions in both seasons stay in the eastern South Pacific.

Figure 9 shows the results for the atmospheric basins located at the tropical Pacific. In DJF, the tropical Pacific is mainly covered by CETP, with a core region located at the eastern tropical Pacific (east of 160°W), and the temporal variation in the positions of CETP described by ERA and MERRA2 match well. In JJA, the tropical Pacific is mainly covered by two communities: CETP and the community covering the easternmost tropical Pacific. The core region of CETP is located at the central tropical Pacific. Except for 2011 and 2014–2016, ERA and MERRA2 agree in the temporal variation of CETP. In 2011, CETP identified using MERRA2 extends southward and reaches Australia. In 2014–2016, CETP identified using ERA merges with the community covering the easternmost tropical Pacific, while that from MERRA2 does not support this merging in 2014 and 2016. In 2015, the western edge of CETP retreats to the date line, and CETP merges with the community covering the easternmost tropical Pacific. This results in the extension of CETP to the easternmost tropical Pacific (suggested by ERA) or to tropical South America (suggested by MERRA2). As in the 10-year average JJA cases, ERA indicates that the easternmost tropical Pacific is covered by a relatively small community in 2007–2013, while MERRA2 indicates that a large community covers the easternmost tropical Pacific, Central America, tropical South America, and part of the South Atlantic in all years except for 2008, 2011, and 2015.

Figure 10 shows the results of the atmospheric basins located at the Asian summer monsoon regions, that is, IND-TP, NIO, and WNP, together with those of NP (the atmospheric basin located in the northeast of WNP).
As suggested by its name, the core regions of IND-TP cover the Indian subcontinent and the Tibet Plateau. Both ERA and MERRA2 indicate that IND-TP expands in 2010, 2011, and 2014 (area exceeding $20 \times 10^{12}$ m$^2$). In these years, IND-TP extends to the Indian Ocean, touches the eastern coast of Africa, and crosses the equator. Consequently, NIO is pushed to a further eastern position in these years. WNP basically covers the western edge of the North Pacific and the eastern coast of China. The position and area of WNP are closely related to those of NP: WNP expands and extends to the date line when the position of NP is further east than usual in 2014. Although the core region of NP is confined to the North Pacific, NP can reach North America in 2013 and 2014 and reach the eastern coast of China by merging with WNP in 2011, confirmed by both ERA and MERRA2. Figure 11 shows the results of NP in DJF. According to the ERA results, NP cannot reach into North America in 2010, and thus, the core region is confined to the coast of North America. However, MERRA2 indicates that the core region can reach the western North America. The southern and northern extents of NP are stably located near 25°N and 70°N, respectively. The western and eastern extents vary in different years and NP can reach East Asia (e.g., in 2008) and eastern North America (e.g., in 2007).

3.3. Causes of the Variations of Atmospheric Basins

According to section 3.2, differences in positions and areas of the atmospheric basins were identified using the same dataset (ERA or MERRA2) in different years and also using different datasets (ERA and MERRA2) in the same year. In general, the inter-annual and data-related differences are attributed to the differences in regional moisture links induced either by inter-annual variation or by data inconsistency. Here we select the direct moisture links starting from several subregions of some of the atmospheric basins in the 20 seasonal

Figure 9. The same as Figure 8, but for the atmospheric basins located at the tropical Pacific. Season information is annotated in the upper right corners of the subfigures in rows 1–2.

Figure 10. The same as Figure 8, but for IND-TP, NIO and WNP, that is, the atmospheric basins located at the Asian summer monsoon regions, together with NP, the atmospheric basin located in the northeast of WNP. The Tibet Plateau is delineated by the blue line in the spatial distribution of the frequency of IND-TP. Season information is annotated in the lower right corners of the subfigures in rows 1–2.
GAMNs and check the inter-annual and data-related differences in these links to intuitively demonstrate how the differences in the moisture links induce the differences in the identified atmospheric basins.

Figure 12 shows the inter-annual differences in the positions of IND-TP and WNP/NP in JJA and also shows the corresponding differences in the regional moisture links. As noted in section 3.2, both ERA and MERRA2 suggest that IND-TP expands to the Indian Ocean and crosses the equator in 2010, 2011, and 2014 (expanding years), and it mainly covers the Indian subcontinent and the Tibet Plateau in 2008, 2009, 2012, and 2013 (normal years). We selected direct moisture links starting from the oceanic regions covered by IND-TP only in 2010, 2011, and 2014 and checked their differences in the two types of years. The evaporated moisture from the oceanic regions tends to move to the Arabian Sea, the Bay of Bengal and the Indian subcontinent (the major positive areas in the subfigures in column 2 of Figure 14) in the expanding years, while it tends to move to the eastern adjacent oceanic areas (the major negative areas in the same subfigures) in the normal years. Infomap was able to recognize the strong links between the oceanic regions and the Indian subcontinent and its adjacent seas in the expanding years, and thus, it merged them into one atmospheric basin (IND-TP). Similarly, in 2011, the evaporated moisture from the regions covered by WNP during 2007–2009 and 2012–2016 tends to move further into the North Pacific, and thus, Infomap merged them into one atmospheric basin (NP).

Figure 13 shows the inter-annual differences in the positions of CETP in JJA and SAO in DJF and also shows the corresponding differences in the regional moisture links. In 2015, the evaporated moisture over the core...
Figure 13. The same as Figure 12, but for CETP in JJA and SAO in DJF. CETP cases: The blue shaded regions in the subfigures in column 1 represent the regions covered by CETP in at least one year of 2007–2014 and 2016, and the orange shaded regions represent the regions covered by CETP in 2015; the black rectangular boxes in the subfigures in column 2 indicate the core regions of CETP (regions covered by CETP in all 10 years), the gray rectangular boxes indicate the grid cells of the blue shaded regions in column 1, and the green boxes delineate areas between 160°E to 150°W and 0° to 15°N; the years for comparison in the subfigures of column 2 are 2007–2014 and 2016, and 2015. SAO cases: The blue shaded regions in the subfigures of column 3 represent the regions covered by SAO in at least 1 year of 2008–2010 and 2012–2016 (normal years), and the orange shaded regions represent the regions covered by SAO in 2007 or 2011 (shrinkage years); the black rectangular boxes in the subfigures in column 4 indicate part of Brazil that is not covered by SAO in shrinkage years and the gray rectangular boxes indicate the grid cells of the blue shaded regions in column 3; the years for comparison in subfigures of column 4 are the normal and the shrinkage years.

region of CETP tends to remain local, as suggested by the strong local links (negative areas in the subfigures in column 2 of Figure 13). In contrast, in other years (2007–2014 and 2016), the evaporated moisture tends to move westward and can reach the western edge of the North Pacific. Under the control of the strong El Niño in 2015 (Blunden & Arndt, 2016), the magnitude of the area-averaged (160°E to 150°W, 0° to 15°N) westward moisture fluxes decreases to 165 kg m⁻¹ s⁻¹ (ERA) or 196 kg m⁻¹ s⁻¹ (MERRA2), in contrast to the yearly averaged value, that is, 321 kg m⁻¹ s⁻¹ (ERA) or 332 kg m⁻¹ s⁻¹, in other years. The weakened westward moisture transport processes near the date line induced by the weakened Walker circulation during El Niño hinder the moisture links between areas on the opposite sides of the date line, and thus, CETP is confined to the east of the date line in the strong El Niño year (2015). For SAO, the evaporated moisture over part of Brazil tends to remain local (negative areas in the subfigures in column 4 of Figure 13) in 2007 and 2011, while the evaporated moisture tends to flow southeastward to the South Atlantic in other years (part of the positive areas in the subfigures in column 4 of Figure 13). Inflomap identified the weak moisture links between Brazil and the South Atlantic in 2007 and 2011 and excluded Brazil from SAO.

In terms of the data-related differences in the identified atmospheric basins and communities, Figure 14 shows the cases of IND-TP and the community covering the easternmost tropical Pacific in JJA. In 2007 and 2015, IND-TP identified using MERRA2 crosses the equator, while that identified using the ERA suggests that the oceanic regions only identified as IND-TP by MERRA2 have weaker moisture links with the Indian subcontinent and its adjacent seas (positive areas in the subfigures in column 2 of Figure 14) and stronger local moisture links, leading to the exclusion of these regions from IND-TP. As noted in section 3.2, the easternmost tropical Pacific is identified as a single community by ERA. However, MERRA2 suggests relatively strong moisture links between the easternmost tropical Pacific and tropical South America, and thus, Inflomap merged them as one large community.

4. Discussions

4.1. Network-Related Issues

Nodes are the most basic elements of a network, and they determine the edge establishment and network structure. As a global spatial network, a GAMN uses grid cells from a global grid as nodes, and thus, the spatial resolution of the grid directly determines the number of nodes. In order to balance the representativeness
of the global moisture links and the computational efficiency, we designed a 3° × 3° global grid and treated the 3° × 3° grid cells as GAMN nodes. A different spatial resolution directly changes the number of nodes and thus alter the network size. More importantly, a finer spatial resolution may even alter the network structure since some small-scale moisture links may not be considered in a coarse-grained GAMN. Therefore, we also constructed four seasonal GAMNs (JJA and DJF in 2015 and 2016) on a finer global grid (1.5° × 1.5°, a spatial resolution widely used in regional studies of moisture source-sink relationships, e.g., Guo et al., 2019; Keys et al., 2014; Zemp et al., 2014; with 22,320 grid cells in total) using ERA and conducted community detection. The spatial distributions of the identified communities are shown in Figure S7 in the supporting information. Then we upscaled the 1.5° × 1.5° communities to the 3° × 3° grid to compare the results with the original 3° × 3° communities. The AMI values between the upscaled and original 3° × 3° community partitions are 0.88 (2015 JJA), 0.86 (2016 JJA), 0.84 (2015 DJF), and 0.85 (2016 DJF), all of which are higher than those between the 3° × 3° ERA and MERRA2 results, indicating a satisfactory consistency between the fine- and coarse-grained GAMN. Therefore, the adoption of a coarse-grained grid (3° × 3°) is acceptable to conduct community detection in GAMNs. Another node-related issue is the potential impact of the variation in the node sizes along latitudinal direction induced by the adoption of the regular longitude-latitude gridded reanalysis data. The variation in the node sizes results in significant differences in the actual spatial distances between neighboring nodes in the low and high latitudes. Such a heterogeneous distribution of nodes has been reported to have a non-negligible impact on the structures of correlation-based climate networks (e.g., Heitzig et al., 2012; Radebach et al., 2013) since the correlation relationships between the nodes in climate networks are directly affected by the actual spatial distances. The GAMNs used in this study are flux-based networks focusing on moisture exchanges between nodes, in which the node sizes were considered during the application of the moisture tracking model. However, a denser distribution (from the perspective of the actual spatial distance) of nodes at high latitudes may lead to too many small moisture exchanges at high latitudes, and the performance of the Eulerian based moisture tracking model may be affected by the potential discordance between high wind speeds and the sizes of the grid cells at high latitudes. A detailed investigation of the potential impact of the node sizes on community detection in the GAMNs is beyond the scope of this study, but it deserves additional analysis in the future.

The edge of a seasonal GAMN quantifies the total amount of moisture that one node can directly provide for precipitation in another node in a given season. Actually, the edge from node a to node b is the cumulative results of all of the actual trajectories that transport moisture from a to b in a given season. From the perspective of a seasonal scale, an edge does not contain any specific temporal information about the actual moisture transport trajectories between the nodes, so it can be treated as being static during a season. Therefore, the communities and atmospheric basins identified in this study are also static on the seasonal scale. Moreover, a first-order Markovian random walk represented by a sequence of consecutive edges and the amount of moisture transported via that walk (Equations 2–3) do not match with any actual moisture transport
trajectory between nodes. Instead, the random walk paradigm provides us with a probabilistic and spatial description of the possible routes and destinations of a moisture tracer released at a certain node, based on which we can efficiently extract the prominent transport patterns hidden behind the massive number of actual moisture transport trajectories in the global atmospheric hydrological cycle. Besides the applications to the atmospheric moisture processes, the random walk paradigm has also been adopted to depict the transport of many substances in a CN framework, such as air mass transport related to the atmospheric blocking of Eastern Europe and Western Russia (Ser-Giacomi, Vasile, Recuerda et al., 2015) and toxic substance transport within the urban canopy (Fellini et al., 2019), indicating the effectiveness of the random walk paradigm. In particular, Ser-Giacomi, Vasile, Hernández-García, and López (2015) provided a spatial and temporal description of ocean water transport in the Mediterranean Sea using the random walk paradigm based on a set of directed and weighted adjacency matrices that specify the links between the oceanic grid cells during each time interval. A similar idea may be developed in the future to model moisture transport and to investigate the time scale of atmospheric basins through a spatial-temporal network of global atmospheric moisture.

An important issue in the interpretation of community detection results is the closure degree of the identified communities. According to Figure 5, most of the identified communities in the GAMNs have relatively high precipitation/evaporation recycling ratios (≥50%) and can be viewed as atmospheric basins, but there are no atmospheric basins whose precipitation/evaporation recycling ratios equal 100%. This means that each community in the GAMN has moisture exchanges with others. Several oceanic atmospheric basins even act as important moisture providers (e.g., NIO in JJA and CETP in both seasons) for neighboring communities and atmospheric basins. In this sense, the atmospheric basins defined in this study should be treated as quasi-independent rather than completely closed subsystems in the GAMNs. Furthermore, low precipitation/evaporation recycling ratios were observed at the boundary nodes of some of the atmospheric basins and at nearly all of the nodes in several communities (Figure 4). Low precipitation/evaporation recycling ratios were also observed on the community scale (Figure 5), indicating that some communities should be viewed as relatively open systems with respect to precipitation/evaporation. In a more general sense, since there is no guarantee that all of the nodes of a CN gather around a number of clusters, there may be some nodes and communities that have edges diversely distributed across communities, that is, acting as “intermediate hubs” for other nodes/communities, such as WNP identified in the JJA GAMNs, which collects much of moisture from its neighbors (Figure 5). These intermediate hubs (nodes/communities with low intra-community connectivity) have also been identified in some Infomap-based studies conducted to locate communities in networks in other fields, for example, acting as transition zones in biogeographical networks (Bloomfield et al., 2018) or connector hubs in human brain networks (Bertolero et al., 2018; Power et al., 2013), protein interaction networks (Berenstein et al., 2015), and bus networks (Sun et al., 2016).

4.2. Uncertainties in Data and Atmospheric Moisture Tracking Models

In general, Figures 3–11 indicate relatively acceptable qualitative consistency in the positions, areas, and inter-community relationships of the communities identified in the 22 seasonal GAMNs using ERA and MERRA2. However, besides the differences in positions and areas of the atmospheric basins mentioned in section 3.2, disagreements between the two datasets were also observed in the specific values of the amount of the recycled moisture and the moisture inflows and outflows, especially in those values of the communities located at the Indian Ocean and the tropical Pacific. For example, for the 10-year average cases, the total recycled moisture of NIO, CETP, and the atmospheric basin covering the southern tropical Pacific in JJA are $8.3 \times 10^{12}$ m$^3$, $5.7 \times 10^{12}$ m$^3$, and $8.6 \times 10^{12}$ m$^3$, respectively, according to the ERA results, while these values are $6.8 \times 10^{12}$ m$^3$, $4.6 \times 10^{12}$ m$^3$, and $4.4 \times 10^{12}$ m$^3$, respectively, according to the MERRA2 results; the total moisture transported from NIO to IND-TP and from CETP to WNP are $2.1 \times 10^{12}$ m$^3$ and $2.0 \times 10^{12}$ m$^3$, respectively, according to the ERA results, while these values are $1.6 \times 10^{12}$ m$^3$ and $1.6 \times 10^{12}$ m$^3$, respectively, according to the MERRA2 results. Howard (2018) also found the obvious positive differences in precipitation depicted by ERA and MERRA2 over the central tropical Pacific when evaluating the performance of ERA and MERRA2 in capturing the major characteristics of the ITCZ. Besides, differences in the atmospheric and terrestrial water budget terms between ERA and MERRA2 have also been reported in many other regions (e.g., A. Chen et al., 2018; S. Chen et al., 2019; Hua et al., 2019; Tang...
et al., 2020; Yoon et al., 2019). Given these differences between ERA and MERRA2, cautions should be exercised when referring to the specific values of the recycled moisture and the moisture exchanges in Figure 5, and the performance of more reanalysis products in community detection in the GAMNs deserves a further detailed investigation.

Numerical atmospheric moisture tracking models lay the data foundation for community detection in the GAMNs. As noted in section 2, we chose the WAM-2layer to balance accuracy and computation efficiency of moisture tracking. Besides the “well-mixed” assumption which is also applied in many atmospheric moisture tracking models (e.g., the dynamic recycling model developed by Dominguez et al., 2006 and Martinez & Dominguez, 2014; the quasi-isentropic back trajectory model developed by Dirmeyer & Brubaker, 1999), the WAM-2layer also makes another strong assumption that the moisture exchanges between the upper and lower layers of atmosphere induced by convection, turbulence, rainfall re-evaporation, and other processes can be represented by the magnification of the gross vertical moisture exchanges between the layers. The WAM-2layer has been testified to achieve a satisfactory moisture tracking result compared with a detailed 3-D moisture tracking model developed by Knoche and Kunstmann (2013) in a region with strong vertical wind shear (van der Ent et al., 2013). However, a further comprehensive comparison of the WAM-2layer with other models on the global scale will be very helpful in improving the reliability and quality of the data for community detection in the GAMNs, especially given the development of some state-of-the-art models that track the history of a tagged moisture tracer directly within a weather/climate model, such as the Weather Research and Forecasting water vapor tracer (WRF-WVT; Insua-Costa & Miguez-Macho, 2018), the isotope-enabled Community Atmosphere Model version 5 (iCAM5; Nusbaumer et al., 2017), and the water vapor tracer embedded in the CAM5 (Pan et al., 2017).

4.3. Implications and Future Directions

As noted in section 4.1, an atmospheric basin proposed in this study can be treated as a quasi-independent subsystem in the global atmospheric hydrological cycle, to some extent providing a basic hydrological unit for atmospheric moisture transport, just as a river basin acting as the basic hydrological unit for surface water flow, one that is not closed from an atmospheric perspective (Keune & Miralles, 2019). It should be noted that although this hydrological unit is referred to as being “atmospheric,” it is still treated as a unit on the land/ocean surface since atmospheric moisture links constructed in this study are actually connections between different locations on the land/ocean surface through the atmospheric hydrological cycle. Accordingly, a terrestrial location belongs to two types of hydrological units: a terrestrial basin and an atmospheric basin. The role of the oceans in the global hydrological cycle is worthy of attention since several oceanic atmospheric basins are important moisture providers for other atmospheric basins and communities. The identification of atmospheric basins provides us with a potential approach to build a unified research framework of the land-atmosphere coupled hydrological cycle through the combination of the terrestrial and atmospheric basins. From the perspective of water resource governance and management, identifying atmospheric basins may help concretize the global governance of water resources through regional cooperation regarding water resource issues and jointly-developed strategies on water and land resources of countries located within the same terrestrial and atmospheric basin. For a country that includes more than one atmospheric basin (such as China), the structures of atmospheric hydrological cycles vary in different atmospheric basins, and thus, atmospheric basin partitioning may provide potential references for decision making in water and land resource issues of regions with different structures of regional hydrological cycle.

This study mainly focuses on the identification of atmospheric basins in the global atmospheric hydrological cycle and also touches the issues related with the stability and variation of typical atmospheric basins in 2007–2016. Future work is expected to address the following questions. First, as mentioned in section 3.2, variations in the positions and areas of atmospheric basins can be found in the results of 2007–2016. At present, we attribute the variations to the changes of atmospheric moisture links between different regions. But what drives the changes of atmospheric moisture links is still unclear. And analysis of atmospheric basins in a longer period is also encouraged to figure out whether significant differences exist between the atmospheric basins in early times (e.g., 1980s) and at present. Second, as noted in section 3.3, CETP is confined to the east of the date line in the strong El Niño year (2015) due to weakened atmospheric moisture links between areas located on the opposite sides of the date line. Castillo et al. (2014) investigated the influence of the evolution of the El Niño–Southern Oscillation (ENSO) cycle on moisture sink regions of 12 major...
oceanic moisture source regions and found notable differences in the spatial extents of moisture sink regions between the El Niño and the La Niña years. Therefore, it is believed that atmospheric basins are significantly impacted by the different phases of climate oscillations, such as the ENSO and the North Atlantic Oscillation. And in a more general sense, the relationships between atmospheric basins and atmospheric circulation patterns deserve a systematic and thorough analysis in the future and may help further understand the impact of climate variability on the global atmospheric hydrological cycle. Third, the internal structures of atmospheric basins are worthy of further study. Here we only referred to the Eulerian moisture transport flux fields to get a rough understanding of the internal structures. In fact, every atmospheric basin has complex structures within which hundreds and thousands of internal moisture links exist. How to efficiently depict the internal structures requires further efforts.

5. Conclusion

In this study, we used a Eulerian atmospheric moisture tracking model, the WAM-2layers, driven by ERA and MERRA2 reanalysis data to generate seasonal atmospheric moisture source-sink relationships around the world for JJA and DJF from 2007 to 2016. We viewed atmospheric moisture source-sink relationships from the perspective of a complex network (CN) and constructed global atmospheric moisture networks (GAMNs) for JJA and DJF from 2007 to 2016.

By introducing the CN-based approaches (random walk paradigm and community detection) in the analysis of the GAMN, we identified regional-scale and quasi-independent (high moisture recycling ratios) patterns in the GAMNs that reflect the regional characteristics of moisture transport (e.g., anticyclone, moisture convergence, and monsoonal moisture transport) and defined these patterns as atmospheric basins. Moisture recycling plays the most important role in precipitation/evaporation in an atmospheric basin. Moisture exchanges between atmospheric basins are non-negligible, and several of the identified atmospheric basins provide/receive considerable amounts of moisture to/from their neighbors.

We checked the stability and variation in the atmospheric basins with the significant anticyclone structures, and in the atmospheric basins covering the Asian summer monsoon regions, the North Pacific, and the tropical Pacific. In general, although there are some disagreements in the specific positions and areas of these atmospheric basins between the ERA and MERRA2 results, the two datasets confirm that there are core regions that persist throughout the years (2007–2016) in these atmospheric basins. Furthermore, we observed inter-annual differences in the positions and areas of these atmospheric basins and attributed the differences to the inter-annual differences in the atmospheric moisture links.

Data Availability Statement

ERA-Interim reanalysis data are provided by ECMWF. Specifically, surface data can be downloaded at https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. The following variables should be selected at step 0 at 00, 06, 12, 18 UTC: total column water, total column water vapor, vertical integral of eastward cloud frozen water, vertical integral of eastward cloud liquid water flux, vertical integral of eastward water vapor flux, vertical integral of northward cloud frozen water flux, vertical integral of northward cloud liquid water flux, vertical integral of northward water vapor flux, and surface pressure. Evaporation and total precipitation flux should be selected at steps 3, 6, 9, and 12 at 00 and 12 UTC. Model-level data can be download at https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=ml/. The following variables at levels 14, 24, 30, 34, 37, 40, 43, 46, 48, 50, 53, 55, 56, 57, 58, 59, and 60 should be selected at step 0 at 00, 06, 12, 18 UTC: specific humidity, \( u \) component of wind, and \( v \) component of wind. One should be registered as a user at ECMWF to access data. MERRA-2 data are provided by the NASA Goddard Earth Sciences Data and Information Services Center (GES-DISC) (https://disc.gsfc.nasa.gov/datasets?keywords=%22MERRA-2%22&page=1&source=Models%2FAnalyses%20MERRA-2). Specifically, hourly total precipitable water data can be accessed by selecting variable “TQV” from data collection “inst1_2d_int_Nx”; hourly precipitation and evaporation flux data can be accessed by selecting variable “EVAP” and “PRECTOTCORR” from data collection “tavg1_2d_flux_Nx”; hourly vertically integrated moisture fluxes can be accessed by selecting variable “UFLXQI,” “UFLXQL,” “UFLXQV,” “VFLXQI,” “VFLXML,” and “VFLXQV” from data collection “tavg1_2d_int_Nx”; 3-hr model-level specific humidity, eastward wind, northward wind, and mode-level depth data can be accessed by selecting “QV,”
“U,” and “V”; and “DELP” from data collection “inst3_3d_asm_Nv.” One should be registered as a user at GES DISC to access data. The source codes of the WAM-layers used in this study can be found at https://doi.org/10.5281/zenodo.3725708. Adjacency matrices of the GAMNs are available at https://doi.org/10.5281/zenodo.3970964.

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