PRECIPITATION RECYCLING

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Abstract. The water cycle regulates and reflects natural variability in climate at the regional and global scales. Large-scale human activities that involve changes in land cover, such as tropical deforestation, are likely to modify climate through changes in the water cycle. In order to understand, and hopefully be able to predict, the extent of these potential global and regional changes, we need first to understand how the water cycle works. In the past, most of the research in hydrology focused on the land branch of the water cycle, with little attention given to the atmospheric branch. The study of precipitation recycling, which is defined as the contribution of local evaporation to local precipitation, aims at understanding hydrologic processes in the atmospheric branch of the water cycle. Simply stated, any study on precipitation recycling is about how the atmospheric branch of the water cycle works, namely, what happens to water vapor molecules after they evaporate from the surface, and where will they precipitate? Estimation of precipitation recycling over any large basin, such as the Mississippi or the Amazon, is a necessary step before developing a quantitative description of the regional water cycle. This paper reviews the research on the concept of precipitation recycling and emphasizes the basic role of this process in defining the different components of the atmospheric branch in any regional water cycle. To illustrate the assumptions and limitations involved in estimation of precipitation recycling, we present and discuss a general formula for estimation of precipitation recycling. The recent estimates of annual precipitation recycling ratio from different regions are reviewed and compared. Finally, the dependence of precipitation recycling over any region on the spatial scale is discussed and illustrated by the example of the Amazon basin.

1. INTRODUCTION AND MOTIVATION

The water cycle regulates and reflects the natural variability of weather and climate at the regional and global scales. Large-scale human activities that modify land cover, such as deforestation in the Amazon, drainage of swamps near the sources of the Nile, or diversion of rivers in Russia, will indeed involve significant changes in land surface hydrology. However, it is not obvious how these changes will be reflected in terms of other climate variables, most importantly, in terms of precipitation. In order to understand, and hopefully be able to predict, the impact of these changes on the water cycle and climate, we need first to understand how the water cycle works. Simply stated, any study on precipitation recycling is about how the atmospheric branch of the water cycle works, namely, what happens to water vapor molecules after they evaporate from the surface, and where will they precipitate?

In the past, most of the efforts of hydrologists were focused on understanding the hydrologic processes in the land surface branch of the water cycle, and little attention was given to the processes involved in the atmospheric branch of the water cycle. The recent interest among hydrologists in the study of precipitation recycling is motivated primarily by the need to understand and define accurately the different components of the atmospheric branch in any regional water cycle. Such understanding will ultimately help us to think of the water cycle, including the land surface and atmospheric branches, as a whole. Such an approach is well suited for tackling the large-scale problems that threaten to change the natural course of the water cycle.

The following is a simple description of the water cycle. At the extreme end of large scales, the global picture of the water cycle is simple, as shown in Figure 1a. All water molecules evaporate from the Earth surface, stay in the atmosphere for some time (~10 days), and then precipitate back to the surface. On the extreme end of small scales, the water cycle for any specific point on Earth is also simple (Figure 1b). Water molecules precipitate from the atmosphere on any point, some of the molecules flow on (or beneath) the surface as runoff, and other molecules evaporate back into the atmosphere. Because of horizontal wind advection, the probability that a water molecule evaporates from one point and then precipitates at the same point is close to zero. In contrast to these two limiting cases, the regional cycle of water for any intermediate scale between that of the Earth and that of a single point, is slightly more complicated and is shown by Figure 1c. First, the probability that a water molecule evaporates from within a region

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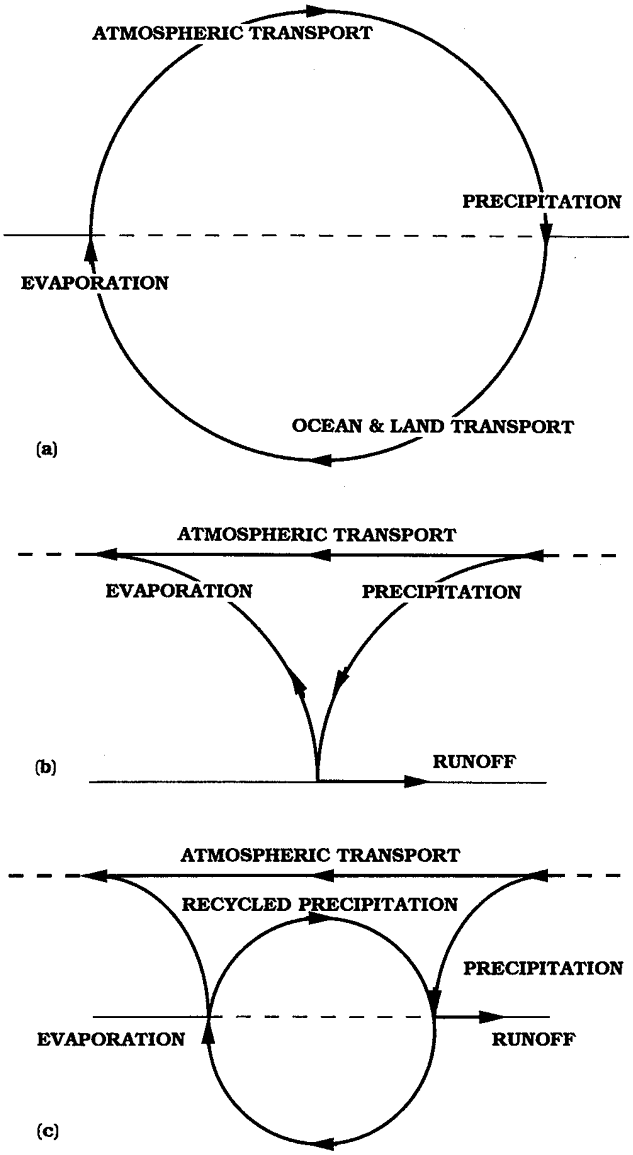

Figure 1. (a) Global, (b) local, and (c) regional hydrologic cycles.

and then precipitates within the same region is no longer zero. Indeed, this probability increases with the scale of the region considered. Second, atmospheric transport mechanisms carry water vapor molecules in and out through the boundaries of any region. The flows in rivers and groundwater reservoirs, into and out of the region, are additional boundary fluxes. The process that is characteristic of the regional water cycle is the formation of precipitation from two components: locally recycled water vapor molecules, and atmospheric water vapor that is transported from outside the region. The process of precipitation formation from two different components is at the heart of our focus on precipitation recycling.

The simple concept that precipitation is partitioned at the land surface into two components, evaporation and runoff, is a well-established idea in hydrology. This concept is the basis for almost every study in surface hydrology. The evaporation-runoff partition of precipitation describes the fate of water molecules that fall from the atmosphere onto the surface. The concept of precipitation recycling describes a similar partition of precipitation. However, this time our focus is not on the fate of precipitation, but rather on the origin of water vapor molecules forming precipitation. In order to describe the origin-based partition of precipitation, we need to classify atmospheric water vapor molecules into the following two species: (1) molecules that are in the atmosphere because of an evaporation event from within the region considered, and (2) molecules that are in the atmosphere as a result of atmospheric transport across the boundary of the region. The first class of species forms an internal water cycle. The second class forms an external water cycle (see Figure 2). The precipitation produced by the internal cycle is defined as recycled precipitation, and the precipitation produced by the external cycle is defined as external precipitation. Since formation of precipitation takes place in the atmosphere, the origin-based partition of precipitation is controlled by atmospheric processes in the same manner that the fate-based partition is regulated by surface processes and properties.

The study of precipitation recycling helps in defining the role of land-atmosphere interactions in regional climate. The primary agent for these interactions is evaporation which supplies water vapor from the land surface to the atmosphere. Evaporation from the land surface contributes water vapor and latent energy to the atmosphere. These two variables are critical ingredients for the processes leading to formation of precipitation. Hence evaporation couples the natural variability in land surface hydrology to atmospheric processes. Depending

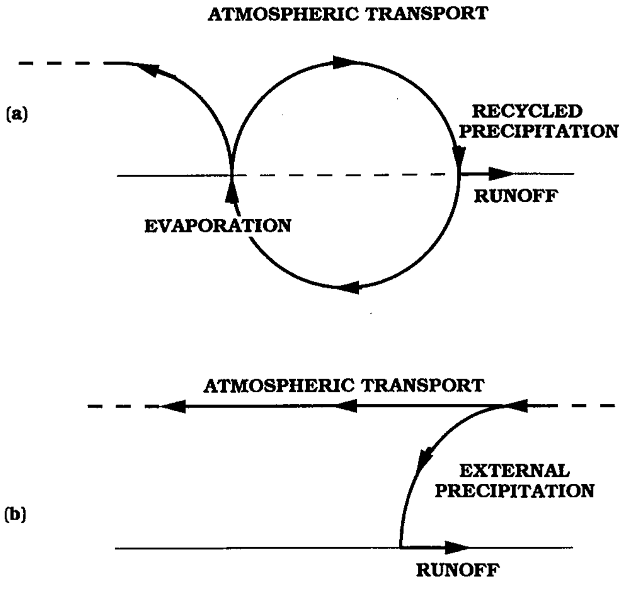

Figure 2. Regional hydrologic cycle: (a) internal component and (b) external component.

on the geographical location, land-atmosphere interactions are potentially important in the formation of precipitation. The relative contribution of recycled precipitation to total precipitation, defined as the recycling ratio, provides one of potentially several diagnostic measures that describe some of these interactions. The recycling ratio is useful in comparing the potential in different regions for interactions between land surface processes and atmospheric processes. For any region with a large recycling ratio, the potential for land-atmosphere interactions is larger than the potential associated with a similar region that has insignificant recycling ratio.

This paper is organized in seven sections. The next section covers some of the motivation for studying precipitation recycling that relates to the role of moisture recycling in land-atmosphere interactions. Section 3 is a brief review of the general studies on the atmospheric water budget without specific reference to the issue of recycling. In contrast, section 4 reviews those studies on the atmospheric water budget that focus on precipitation recycling. Section 5 describes a general formula for estimation of precipitation recycling. Section 6 reviews and compares the different estimates of precipitation recycling from different regions. Section 7 includes a summary and some suggestions for future research directions.

2. PRECIPITATION RECYCLING AND LAND-ATMOSPHERE INTERACTIONS

The precipitation recycling ratio is a diagnostic measure that describes the contribution of local evaporation to local precipitation. This measure is characteristic of the conditions in the current climate equilibrium and has no prognostic value. There is no basis for using any estimate of precipitation recycling in a prognostic statement that predicts the changes in rainfall following changes in evaporation, atmospheric moisture fluxes, or climate in general. The reason is simple: the water cycle has different equilibria in the different climates, and the equilibrium in the current climate is in general different from the equilibria of the water cycle in other climates. The recycling ratio is likely to change with any change in climate, and hence significant errors may result from assuming the recycling ratio to be a constant. A similar argument could be used against assuming a constant runoff ratio in predicting the change in runoff that may result from any climate change [*Dooge*, 1992]. However, the precipitation recycling ratio provides a diagnostic measure of the potential for land-atmosphere interactions in the current climate equilibrium. Different forms of these interactions are likely to take place at the different climatic regimes and spatial-temporal scales. In the following we discuss the role of moisture recycling in three important processes that involve land-atmosphere interactions.

2.1. Precipitation Recycling and Local Convective Storms

The rising air motion that leads to the formation of rainfall can be associated with (1) large-scale atmospheric forcings such as those provided by orographic lifting, frontal systems in midlatitudes, and monsoon circulations in the tropics and/or (2) local instability in the vertical distribution of atmospheric temperature and atmospheric humidity. The degree of this instability is usually characterized by convective available potential energy (CAPE). Surface conditions such as temperature and humidity affect to a significant degree the magnitude of CAPE. Hence these conditions are important in the processes that are associated with local instabilities in the convective storms. These storms occur during summer in mid-latitudes and throughout most of the year in tropical regions. The triggering mechanism leading to the energy release and formation of rainfall in convective storms is a nonlinear process that is controlled partly by surface conditions. This factor enhances the role of surface conditions in the dynamics of these systems.

The studies by *Zawadzki and Ro* [1978] and *Zawadzki et al.* [1981] explored the relationship of convective storms and the mesoscale thermodynamic variables. *Williams and Renno* [1993] analyzed surface and upper air observations from several regions and found significant correlation between wet-bulb temperature and CAPE. This relation is characterized by a threshold of wet-bulb temperature that has to be reached for any significant amount of CAPE to exist. *Eltahir and Pal* [1996] related surface conditions and the subsequent rainfall in convective storms. *Betts et al.* [1994] studied the coupling between land surface processes and the dynamics of rainfall at local and regional scales. In regions with high levels of moisture recycling, variability in local evaporation is likely to influence significantly the magnitudes of surface humidity and surface temperature. The magnitude of moist static energy (uniquely related to wet-bulb temperature) and its partition into sensible and latent energy are determined by the magnitudes of surface humidity and surface temperature. Both factors are important in governing the dynamics of local convective storms. They influence the likelihood of occurrence of moist convection as well as the magnitudes of CAPE and local rainfall [*Williams and Renno*, 1993; *Eltahir and Pal*, 1996]. Hence estimates of precipitation recycling should help in identifying regions where local evaporation is likely to play a significant role in the dynamics of convective storms.

2.2. Precipitation Recycling and Regional Atmospheric Circulations

Precipitation over large regions, such as the Mississippi basin or the Amazon basin, is supplied by two sources: local evaporation and horizontal fluxes of atmospheric water vapor. The latter is dependent on regional atmospheric circulations. Any changes in land cover that occur over large enough areas are likely to

TABLE 1. Predictions of the Impact on the Water Cycle Due to Large-Scale Deforestation in the Amazon Region

	Change, mm/d		
Study	*Precipitation*	*Evaporation*	*Atmospheric Moisture Convergence*
Nobre et al. [1991]	−1.8	−1.4	−0.4
Dickinson and Kennedy [1992]	−1.4	−0.7	−0.7
Lean and Rowntree [1993]	−0.8	−0.6	−0.2

Values are averages over the area of the Amazon basin.

result in changes in the regional patterns of evaporation. However, these same changes in land cover may also trigger significant changes in the regional atmospheric circulation. Hence the changes in precipitation that may result from any large-scale modification of land cover, such as those associated with a hypothetical deforestation of the entire Amazon basin are attributable to changes in local recycling of moisture as well as changes in the regional circulation.

Several recent studies investigated the response of the tropical atmosphere to changes in land cover (deforestation) over the Amazon region. Table 1 compares the results of several numerical experiments on the Amazon deforestation problem. The predictions of the changes in moisture fluxes satisfy mass balance, in the sense that the change in precipitation is equivalent to the sum of the change in evaporation and the change in atmospheric moisture convergence. The changes in atmospheric moisture convergence are of the same order of magnitude as the changes in evaporation. These results suggest that the changes in land cover introduce significant nonlinear feedbacks that amplify the linear response of the land-atmosphere system to deforestation. The process of precipitation recycling is at the heart of these interactions. The reduction of evaporation, which occurs as a direct result of deforestation, reduces atmospheric humidity and surface moist static energy. As was discussed in section 2.1, this reduction in moist static energy is likely to reduce local rainfall. This negative change in local rainfall triggers a feedback process that modifies the atmospheric circulation, resulting in further reduction of the atmospheric moisture convergence and regional rainfall [*Eltahir and Bras*, 1993].

2.3. Precipitation Recycling and Mesoscale Circulations

In recent years there has been significant interest in the impact of land cover variability on atmospheric circulations at the mesoscale, [*Anthes*, 1984; *Avissar and Pielke*, 1989; *Dalu and Pielke*, 1993; *Rabin et al.*, 1990]. The essence of these land-atmosphere interactions is the idea that any significant spatial variability in land surface characteristics should result in a similar pattern of land surface fluxes of heat and moisture. When the gradients in these fluxes are large enough, circulations of significant magnitude, described as land breeze, may develop at the mesoscale. The essential ingredient for these interactions is the small-scale spatial variability in land-surface characteristics and processes.

In contrast, precipitation recycling is concerned with the contribution of evaporation from large areas to continental precipitation. Hence the development of mesoscale circulations is a good example for a class of land-atmosphere interactions where the concept of precipitation recycling is of little relevance.

3. REVIEW OF STUDIES ON THE ATMOSPHERIC WATER BUDGET

The studies on atmospheric water budget are primarily concerned with the estimation of atmospheric water vapor amounts and fluxes. These fluxes include precipitation, evaporation, and horizontal fluxes of water vapor. Precipitation is routinely observed by the global network of surface stations. The horizontal fluxes of water vapor can be computed from the direct measurements of wind, temperature, and humidity that are collected by the global network of upper air observation stations. However, direct measurements of regional evaporation are nonexistent, and reliable estimates of the same variable require extensive observations of the surface characteristics and conditions that are usually not available at regional and global scales. For these reasons, the principle of mass conservation is often applied to retrieve evaporation as a residual in the atmospheric water balance, using observations of precipitation, water vapor fluxes, and the change in storage of atmospheric water vapor as input [*Rasmusson*, 1966, 1967, 1968, 1971].

The atmospheric water budget has been studied extensively at the global scale [*Peixoto*, 1973; *Peixoto et al.*, 1982; *Peixoto and Oort*, 1992; *Chen and Pfandtner*, 1993; *Oki et al.*, 1995] and the regional scale [*Benton et al.*, 1950; *Benton and Estoque*, 1954; *Rasmusson*, 1966, 1967, 1968, 1971; *Molion*, 1975; *Peixoto et al.*, 1982; *Roads et al.* 1994]. While *Bryan and Oort* [1984] investigated the seasonal variability of the global atmospheric water vapor, *Chen et al.* [1995] studied the low-frequency variability of the same variable. The study of *Rosen and Omolayo* [1981] focused on the northern hemisphere and determined the exchange of atmospheric water vapor between land and ocean. Most of these studies on atmospheric water budget involve extensive analysis of rawinsonde data [*Savijarvi*, 1988; *Elliot and Gaffen*, 1991]; however, more recent studies use assimilated data sets such as those produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [*Oki et al.*, 1995; *Eltahir and Bras*, 1994].

Several studies focused on the atmospheric branch of the water cycle over North America [*Benton et al.*, 1950; *Benton and Estoque*, 1954; *Rasmusson*, 1966, 1967, 1968, 1971]. The study of *Benton et al.* [1950] focused on the water balance of the Mississippi basin, considering both the atmospheric and the land branches of the water cycle. *Benton and Estoque* [1954] studied the transfer of water vapor over the North American continent for the year 1949. They evaluated the monthly and seasonal patterns of moisture flow and argued for a close relation between these patterns and the distribution of precipitation. In the same study, Benton and Estoque estimated evapotranspiration as the difference between observed precipitation and atmospheric moisture convergence. They compared these estimates of evapotranspiration with other independent standard estimates of the same variable, finding only small differences.

The study of *Rasmusson* [1967] focused on atmospheric water vapor transport for North America using data covering the period from May 1961 to April 1963. Monthly water vapor fluxes were computed for vertical cross sections on certain boundaries of the region. These cross sections indicated significant details in the distribution of water vapor flux. Subsequent studies of *Rasmusson* [1968, 1971] used a more extensive data set covering the period from May 1958 to April 1963. The study included a large-scale water balance for the region of North America as well as water balance computations for several regions within the North American continent. Monthly values of evapotranspiration and change in storage of soil moisture were computed on the basis of observed values of atmospheric water vapor convergence, precipitation, and streamflow.

In most of the studies on atmospheric water budget, two sources of precipitation are recognized, namely, atmospheric advection of water vapor and local evaporation. However, many of these studies do not estimate the relative contribution to precipitation from each of these two sources and hence do not address the issue of precipitation recycling. The studies on precipitation recycling that are reviewed in this article take the standard analysis of atmospheric water budget one step farther by attempting to define and estimate the relative contributions to precipitation from local evaporation and horizontal advection of atmospheric water vapor.

4. REVIEW OF STUDIES ON PRECIPITATION RECYCLING

4.1. Early Studies of Precipitation Recycling

The early studies on precipitation recycling focused on the continental landmass of North America. *Holzman* [1937, p. 14] cites the words of S. Aughey, who wrote in 1880 about the physical geography of Nebraska, "year by year as cultivation of the soil is extended, more of the rain that falls is absorbed and retained to be given off by evaporation or to produce springs. This of course must give increasing moisture and rainfall." This is one of the earliest speculations in the literature, about the role of evaporation from land surfaces in regional rainfall and climate. Aughey suggests that local moisture recycling has a significant contribution to atmospheric moisture and rainfall. This theory was widely accepted until the early decades of the present century. No rigorous proof was provided, and indeed the data available were not enough for such a purpose.

In the early years of the present century, more hydrologic data became available, and various estimates of regional precipitation, evaporation, and runoff were obtained. It was estimated that around 30% of total precipitation over continental areas returns to the oceans by surface runoff and the remaining 70% evaporates back to the atmosphere. These new findings led to the conclusion that 70% of total precipitation over the continents is contributed by evaporation from land areas. These conclusions are based on a simple and inaccurate picture of the water cycle, in which atmospheric moisture inflow to any region is equal to runoff and hence recycled precipitation is equivalent to evaporation. However, the principle of mass conservation, applied to the water cycle in Figure 1c, suggests that runoff is equivalent to the convergence of atmospheric moisture. In general, the latter statement is different from saying that runoff is equivalent to atmospheric moisture inflow.

Several studies supported the theory that evaporation from land surfaces has a significant effect on regional rainfall and climate. *Jensen* [1935] analyzed annual rainfall series from the midwestern United States to study drought in that region. The observation that rainfall deficiency in eastern and central Nebraska was significantly larger than rainfall deficiency in western Nebraska led him to speculate that the relatively high levels of rainfall in western Nebraska are due to the advent of irrigation in that region. He further suggested that dams should be built to impound runoff and hence increase evaporation and rainfall. In a similar study, *Ives* [1936] described observed desert floods in Sonoyta valley in Mexico and classified floods into primary and secondary according to the origin of the moisture in rainfall. Primary floods are caused by rainfall formed by moisture that comes from outside the valley, while secondary floods are caused by the rainfall formed from moisture that comes from within the valley. This classification was based on purely subjective visual description of the conditions in the valley.

A different view in the topic of precipitation recycling was presented by *Holzman* [1937]. He criticized the theory that continental evaporation contributes significantly to atmospheric moisture or rainfall and pointed to the lack of rigorous proof supporting this theory. In contrast to most of the previous research, which was limited to analysis of surface meteorological data, Holzman used upper air meteorological data to estimate atmospheric water vapor amounts and upper air wind. The paper argues that the contribution of evaporation to atmospheric moisture and rainfall is not significant owing to the great mobility of atmospheric air masses. *Holzman* [1937] emphasized the important role of rainfall producing mechanisms and suggested that no direct relation exists between atmospheric moisture over any region and rainfall. He concluded that most of the supply of moisture for precipitation over the United States is derived from maritime air masses that obtain their moisture mainly from evaporation over the oceans, with only a very small part attributable to continental evaporation. The principal amount of moisture returned to the atmosphere by continental evaporation is absorbed by dry continental air masses that in general do not produce rainfall over continents.

In direct contrast to *Holzman*'s [1937] study, *Horton* [1943] estimated the contribution of the different moisture sources to precipitation in eastern United States. He studied the variability of chlorine content in runoff and deduced that the contribution of oceanic water in rainfall varies from 100% at the Atlantic coast to about 5% at 300 miles west of New York City. This finding led *Horton* [1943, p. 764] to conclude that "little or no vapor of truly oceanic origin may ever reach small tributary-areas at the headwaters of large rivers." The comparison of the conclusions from all these studies points to the clear lack of a generally accepted theory or understanding of precipitation recycling.

The water balance and precipitation recycling over the Mississippi basin were described by *Benton et al.* [1950]. Benton et al. followed an approach similar to that of *Holzman* [1937] in relating the water cycle to the air mass cycle. They classified air masses as either maritime, originating from the Gulf of Mexico or the Pacific Ocean, or continental, originating from Canada, the Arctic or the southwest, and analyzed precipitation and upper air meteorological data at Huntington, West Virginia, for 1 year. The results of the water balance suggest that 90% of precipitation comes from maritime air masses and 10% is derived from continental air masses. Precipitation over the basin is equivalent to about 20% of moisture advection into the basin. *Benton et al.* [1950, p. 61] concluded that "modification of the evapotranspiration regime even over a wide spread area can have comparatively little direct effect on the average quantity of precipitation recorded over that or neighboring regions." It is interesting to note that although 80% of precipitation evaporates back to the atmosphere, the contribution of precipitation recycling is estimated as very small.

In a rather humorous paper, *McDonald* [1962] criticized the suggestions that local precipitation may be increased by increasing local evaporation. He emphasized two basic misconceptions in the previous studies on precipitation recycling: they underestimated two factors, (1) the important role of rainfall-producing mechanisms and (2) the large scales involved in the hydrologic cycle.

4.2. Precipitation Recycling and the Dynamics of Regional Rainfall

The rate of evaporation at any location depends to some extent on the availability of water stored near the surface following previous rainfall events. Hence if evaporation contributes significantly to the formation of rainfall, it is plausible to think that future rainfall amounts are related to previous rainfall. The significance of this feedback mechanism depends on the control exerted by the land surface on evaporation and the rainfall-producing mechanism. There were early speculations in the literature about this potential feedback in regional rainfall due to precipitation recycling. *McNish* [1936, p. 126] discussed the statistical nature of some meteorological time series and offered the following mechanism as a physical cause of correlation in rainfall over the central part of a continent: "a year during which the rainfall has been very great will result in the accumulation of considerable ground-water which by its subsequent evaporation through the soil will supply humidity to the air giving rise to further rainfall and tending to perpetuate the "wet cycle" until the development of some other condition causes a change in this trend." This theory was not supported by any observations.

The Bahr Elghazal basin is located near the Nile sources of equatorial Africa. It represents an interesting closed hydrologic system which includes a large area of swamps. All the rain which falls in that basin, equivalent to about 1 m/yr, is lost through evaporation. Large-scale water conservation projects are being planned for draining the Bahr Elghazal swamps. *Chan and Eagleson* [1980] speculated that draining the swamps may have impacts on the regional climate. *Eltahir* [1989] suggested a feedback mechanism relevant to regions with large swampy areas or shallow lakes. This mechanism emphasizes the role of precipitation recycling. A wet year increases the storage volume of the swamp and hence extends its surface area, resulting in increased evaporation in that year and the following years. The increase in evaporation may result in increased rainfall over the swamp and in the surrounding regions. A wet (dry) year favors wet (dry) following years. *Eltahir* [1989] analyzed rainfall records from the regions surrounding the swamps and concluded that the water balance dynamics of the Bahr Elghazal swamps and the observed serial correlation in annual rainfall over the surrounding regions are consistent with this feedback mechanism.

The role of precipitation recycling in regional rainfall is at the center of the debate about the impact of irrigation projects on the local climate and rainfall. It is argued that development of a new irrigation project should increase local evaporation and hence increase rainfall. One case study that focuses on the impact of irrigation projects on rainfall is the Columbia Basin Project in Washington State. The size of the project is 200,000 hectares. It was developed in the period 1950–1965 and the water supplied for irrigation is about 3 km^3/yr. *Stidd* [1975] analyzed summer (July–August) rainfall measured at about a hundred stations located within 240 km from the center of the project. The stations within the Columbia basin were classified as target stations; these are located, roughly, within 200 km from the center. The rest of the stations were the control stations. The measure used in the analysis was the ratio of mean summer rainfall for the period 1959–1973 to the normal, which is estimated by the mean for the period 1931–1950. It was found that this measure computed from the target stations is significantly larger than that for the control stations. A reasonable explanation is that the moisture added by irrigation enhanced evaporation and resulted in increased rainfall.

The role of precipitation recycling in the dynamics of continental soil moisture conditions has been studied using modeling approaches. The process of recycling is parameterized in term of evaporation, which is a function of soil moisture state. *Rodriguez-Iturbe et al.* [1991a] presented a model describing the interannual soil moisture dynamics at the regional scale. The model assumes that recycled precipitation is partly a function of evaporation and assumes advection of atmospheric water vapor to be constant. Evaporation is nonlinearly related to the degree of saturation of the active soil depth. Infiltration is treated in a similar way. The analytic solution of the stochastic soil moisture differential equation results in a bimodal distribution for the spatially averaged soil saturation. *Rodriguez-Iturbe et al.* [1991a] argue that this bimodal distribution may explain some of the features observed in rainfall time series in the Sahel region of Africa, namely, the prolonged wet and dry periods. In a companion paper, *Rodriguez-Iturbe et al.* [1991b] analyzed the behavior of the interseasonal soil moisture dynamics. The nonlinear water balance equation exhibits a chaotic behavior that implies limited predictability of the soil moisture state.

5. A GENERAL FORMULA FOR ESTIMATION OF THE PRECIPITATION RECYCLING RATIO

In this section we derive a general formula for estimation of precipitation recycling. The formula was developed by *Eltahir and Bras* [1994] and relates the recycling ratio to the relevant atmospheric variables. The purpose in presenting this formula is to illustrate the underlying assumptions and limitations that are involved in the studies of precipitation recycling. The formula of *Budyko* [1974], which has been used in several other studies, will also be discussed. The emphasis in the following sections is on presenting the basic principles and specific assumptions involved in estimation of precipitation recycling.

5.1. Conservation of Atmospheric Water Vapor Mass

The recycling formula is based on the principle of mass conservation. Two species of water vapor molecules are considered: molecules that are in the atmosphere because of evaporation from within the region considered, and molecules that are in the atmosphere as a result of atmospheric transport across the boundary of the region. The definition of the word "region" includes all the area under study. For a finite control volume of the atmosphere located at any point within the region, conservation of mass of the two species requires the following:

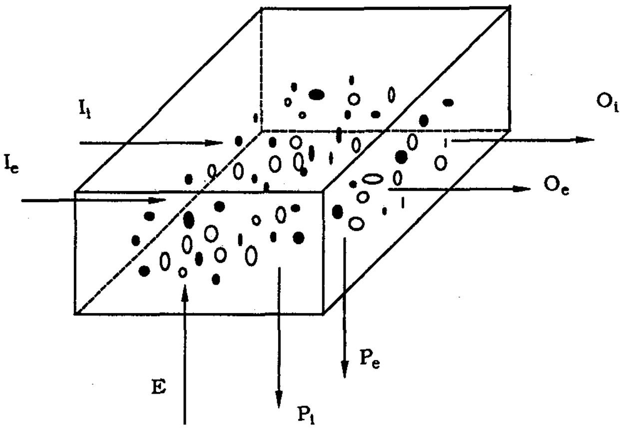

Figure 3. Control volume for atmospheric fluxes of water vapor.

$$
\begin{aligned}
\partial N_i/\partial t &= I_i + E - P_i - O_i \\
\partial N_e/\partial t &= I_e - P_e - O_e
\end{aligned}
\tag{1}
$$

where subscript i denotes molecules that evaporate within the region (internal molecules) and e denotes molecules that evaporate outside the region (external molecules). The variables that appear in the equations (1) are defined as follows: N is proportional to the number of water vapor molecules, I and O are inflow and outflow, P is precipitation, and E is evaporation (see Figure 3). All the variables, N, I, O, P, and E, are functions of space and time defined on a horizontal grid. Figure 3 describes the fluxes for any of the grid cells. For simplicity, the dependence on space and time is dropped from the equations. The units of all the fluxes correspond to volume of water per unit time. Each of I and O is a summation of the components of flux in the two horizontal directions.

5.2. Assumptions Leading to the Recycling Formula

In deriving the general recycling formula, we make two assumptions. The first assumption states that water vapor is well mixed in the planetary boundary layer (PBL) of the Earth's atmosphere. The PBL is of the order of 1 km deep and contains most of the water vapor in the atmosphere. Observations of the vertical distribution of water vapor and other conserved tracers show a practically uniform distribution through the PBL up to the level where the air from the PBL mixes with the upper air (for observations in midlatitudes, see *Crum and Stull* [1987]; for observations from the Amazon region see *Harriss et al.* [1988] and companion papers describing the Amazon Boundary Layer Experiment (ABLE)). Mixing of water vapor in the PBL is primarily

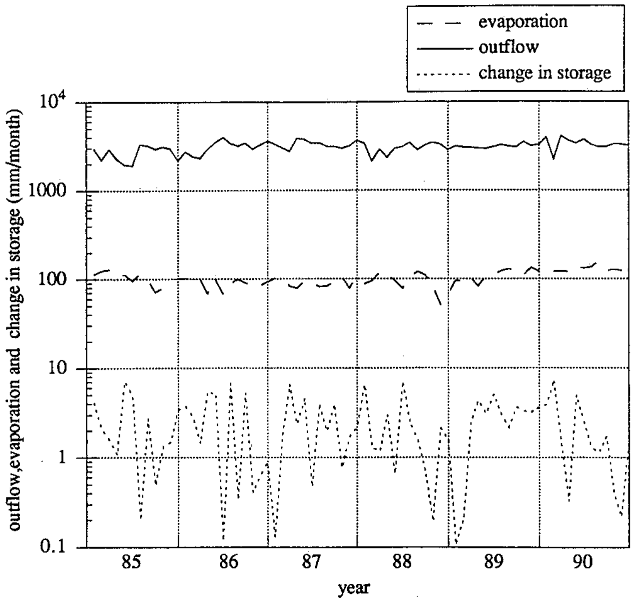

Figure 4. Comparison of evaporation, atmospheric water vapor flux, and change in storage of atmospheric water vapor. The data correspond to a single grid cell (250 km × 250 km), from the Amazon basin [*Eltahir and Bras*, 1994].

achieved by dry thermal convection. This process is very efficient in mixing water vapor and other pollutants. *Lamb* [1982] compiled the results of many field experiments studying air pollutants released at the surface; the data indicate that mixing in the PBL occurs on very short timescales. It takes about 15 min for water vapor molecules evaporating at the surface to mix in the vertical for up to a depth of 1 km. Above the boundary layer, it is frequently observed that the air forming clouds mixes with the surrounding environment [see *Paluch*, 1979]. On the basis of these observations, we make the assumption that water vapor molecules from the two species defined above are well mixed, which implies that

$$\rho = \frac{P_i}{(P_i + P_e)} = \frac{N_i}{(N_i + N_e)} = \frac{O_i}{(O_i + O_e)} \qquad (2)$$

where ρ is defined as the precipitation recycling ratio. At any location within the region, ρ estimates the ratio of recycled precipitation to the total precipitation falling at that location. Recycled precipitation consists of molecules of water vapor that were in the atmosphere as a result of an evaporation event at that location or somewhere else in the region under study. The assumption of a well-mixed atmosphere implies that the composition of water molecules in atmospheric outflow and precipitation is the same as the composition of water vapor molecules in the water vapor within the control volume. This condition is described by equation (2).

The second assumption states that at sufficiently long timescales the change in storage of atmospheric water vapor is small in comparison with fluxes of atmospheric water vapor, including evaporation. Figure 4 shows a comparison between the monthly flux of atmospheric water vapor, evaporation, and the change in storage of atmospheric water vapor at a single location in the Amazon basin. It is evident from this comparison that at the monthly timescale, the rate of change of storage of water vapor is very small in comparison with atmospheric water vapor fluxes. This observation combined with the assumption of a well-mixed atmosphere suggests that the change of storage of either of the species N_i or N_e is small in comparison with its flux. Therefore the derivatives in equation (1) are relatively small and hence assumed equivalent to zero. Rearranging (1) results in

$$I_i + E = O_i + P_i \qquad (3a)$$

$$I_e = O_e + P_e \qquad (3b)$$

5.3. A General Formula for the Recycling Ratio

Substituting for O_i, P_i, O_e, and P_e from (2) into (3) results in

$$I_i + E = \rho(O_i + O_e) + \rho(P_i + P_e) \qquad (4a)$$

$$I_e = (1 - \rho)(O_i + O_e) + (1 - \rho)(P_i + P_e) \qquad (4b)$$

Dividing (4a) by (4b) and rearranging results in

$$\rho = \frac{(I_i + E)}{(I_i + E + I_e)} \qquad (5)$$

Equation (5) is the formula for estimating the precipitation recycling ratio. This formula can be used for estimating the spatial distribution of the precipitation recycling ratio at the monthly timescale. In order to obtain lumped estimates, or annual estimates, the recycling ratios have to be aggregated with observed precipitation serving as the weighting factors in this averaging process.

5.4. The Formula of Budyko

A popular approach for estimating precipitation recycling over large regions was developed by *Budyko* [1974]. Assuming that the region of interest is located parallel to the streamline of atmospheric flow, precipitation recycling is considered as a one-dimensional process along the streamline. The Budyko formula provides a lumped estimate of recycling over the large area. This estimate is described by the parameter β, which is defined as the ratio of total precipitation to external precipitation,

$$\beta = 1 + (eL/2I) \qquad (6)$$

where e is evaporation rate per unit area and I is the flux of external water vapor at the upstream boundary of the region, equivalent to depth of atmospheric water vapor multiplied by effective wind. This formula is derived by making the same two assumptions stated in the previous section. In addition, evaporation, recycled precipitation, and external precipitation are assumed constants, with no variability along the streamline.

To relate the two parameters that describe precipitation recycling, we note that $\beta = 1/(1 - \rho)$ and $\rho = 1 - (1/\beta)$. It is important to emphasize that equation (5) describes the process at each point in space, while (6) is an integrated estimate of recycling over a large area. Hence when the two approaches are compared, we refer to an average value of ρ. In a recent study, *Brubaker et al.* [1993] modified Budyko's model to account for the fact that the spatial orientation of the region under study may not lie parallel to a streamline. The results based on this approach, as well as other approaches, are presented in the following section.

6. ESTIMATES OF ANNUAL PRECIPITATION RECYCLING FOR DIFFERENT REGIONS

This section presents and compares different estimates of precipitation recycling from several studies. The focus is on lumped estimates of the annual precipitation recycling ratio. These estimates are shown in Table 2. The recent estimates of annual recycling in the Amazon region from the two studies of *Eltahir and Bras* [1994] and *Brubaker et al.* [1993] seem to agree on an estimate of about 25 to 35%. This estimate is smaller than the old estimate of about 50% [see *Molion*, 1975; *Marques et al.*, 1977], which is frequently quoted as evidence for the high recycling rate in the Amazon. The estimate of about 50% is obtained as the ratio of total evaporation to total precipitation. *Eltahir and Bras* [1994] illustrated why the ratio of evaporation to precipitation would overestimate precipitation recycling. In fact, if precipitation recycling could be estimated by the ratio of evaporation to precipitation, then the Amazon basin would have one of the lowest recycling rates in comparison to other regions, since the ratio of evaporation to precipitation is about 56% for the Amazon, while the same ratio is 78% for the Mississippi basin.

TABLE 2. Estimates of Annual Precipitation Recycling Ratio

Region	*Scale,* km*	*Estimated Recycling Ratio, %*	*Reference*
Amazon	2500	56	*Molion* [1975]
Amazon†	2300	25	*Brubaker et al.* [1993]
Amazon‡	2500	25	*Eltahir and Bras* [1994]
Amazon‡	2500	35	*Eltahir and Bras* [1994]
Mississippi	1800	10	*Benton et al.* [1950]
Mississippi†	1400	24	*Brubaker et al.* [1993]
Eurasia§	2200	11	*Budyko* [1974]
Eurasia†	1300	13	*Brubaker et al.* [1993]
Sahel†	1500	35	*Brubaker et al.* [1993]

*Square root of area.

†All the annual estimates of the recycling ratio from *Brubaker et al.* [1993] are computed using the monthly estimates of recycling ratio and the monthly precipitation data described by that study.

‡The two estimates from *Eltahir and Bras* [1994] are computed using evaporation data supplied by the European Centre for Medium-Range Weather Forecasts (ECMWF); while the first estimate (25%) is based on flux data from ECMWF, the second estimate (35%) is based on flux data from the Geophysical Fluid Dynamics Laboratory for the same region.

§This recycling ratio is computed by transforming an estimate of $\beta = 1.12$ from *Budyko* [1974]. In this case the linear scale is the parameter L of the Budyko formula. The scale corresponding to the square root of area should be smaller.

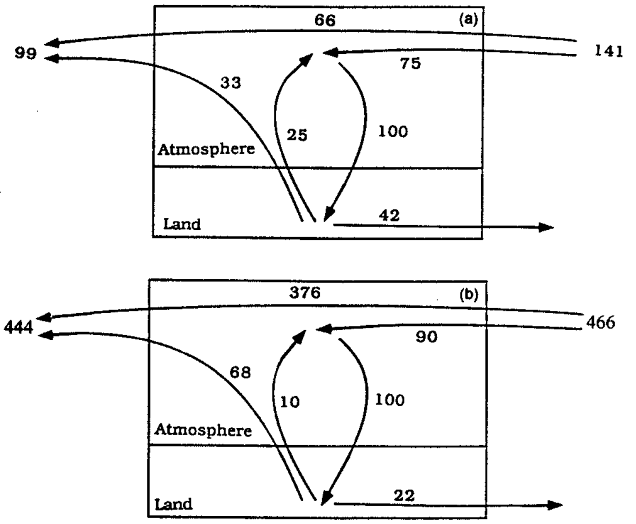

Figure 5. Regional water cycles: (a) the Amazon basin (annual precipitation = 1.95 m = 100 units) and (b) the Mississippi basin (annual precipitation = 0.75 m = 100 units). From *Eltahir and Bras* [1994].

The results for the Eurasian region from the studies of Budyko and Brubaker et al. are quite similar, except for the difference in scale. Given that the two scales presented in Table 2 were obtained differently, it seems reasonable to argue that the estimates of the recycling ratio by the two studies are not significantly different. The estimate of *Brubaker et al.* [1993] for the recycling ratio in the Mississippi basin (~24%) is significantly higher than that of *Benton et al.* [1950] (~10%) for the same region. The former study estimates a higher recycling ratio for a smaller area of the same region. These differences are due in part to the different evaporation estimates used in the two studies; about 1100 mm/yr in the Brubaker et al. study compared with about 600 mm/yr in the Benton et al. study. However, it is important to note that the east to west gradient of annual evaporation in the Mississippi basin is quite significant (~500 mm/1000 km) [see *Brutsaert*, 1982, Figure 1.1]. Under such conditions, a distributed recycling model similar to the one presented in section 5 could be more accurate in estimation of the recycling ratio.

As was stated in the introduction of this paper, any estimates of precipitation recycling are useful for defining the components of the regional water cycle and for comparing different regions. Figure 5 is taken from the recent study by *Eltahir and Bras* [1994] and describes the regional water cycles over the Mississippi basin and the

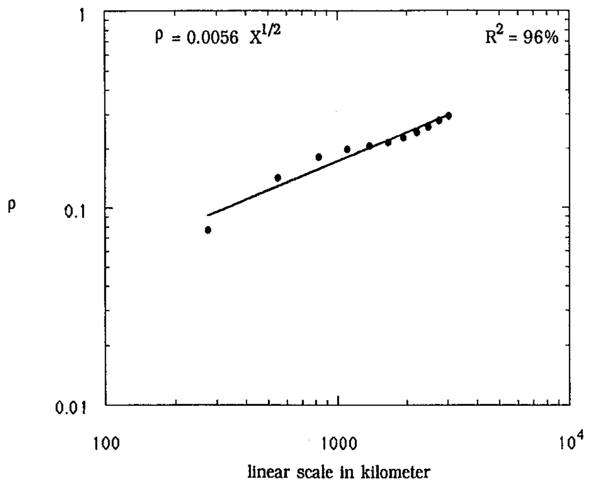

Figure 6. Scaling of the annual precipitation recycling ratio in the Amazon basin [*Eltahir*, 1993].

Amazon basin. The estimates for the Mississippi basin are based on the results of *Benton et al.* [1950]. It is interesting to compare the two regional cycles. Although evaporation constitutes 78% of precipitation in the Mississippi, compared with 56% for the Amazon, the recycling ratio for the Mississippi basin is smaller than that of the Amazon basin by about a factor of 2. This difference is due largely to the difference in atmospheric water vapor fluxes between the two regions (466 units for the Mississippi compared with 141 for the Amazon). Aside from the nonlinear effects of water vapor on rainfall-producing mechanisms, the comparison in Figure 5 points to a larger potential for land-atmosphere interactions in the Amazon basin compared with the Mississippi basin.

6.1. Scale Dependence of the Recycling Phenomenon

The precipitation recycling ratio depends on the geographical location, the temporal scale, and the spatial scale considered and may vary seasonally. At the global scale the recycling ratio is 1, while for any point on Earth the same ratio is close to 0. The question is then, how does the recycling ratio vary in any region between these two limits? The Budyko formula, presented in section 5, suggests a linear relation between β and the scale of the region, L (see equation (6)). However, the recycling ratio for any large area is given by

$$\rho = \frac{eL}{eL + 2I} \tag{7}$$

For regions where the external supply of moisture is much greater than local evaporation ($2I \gg eL$); it follows that the recycling ratio is linearly related to the spatial scale L. On the other hand, for regions where local evaporation is much greater than external supply of moisture ($eL \gg 2I$), the recycling ratio is almost independent of L. In the first limiting case the scaling exponent is close to 1, while in the second limiting case the scaling exponent is close to 0 (the scaling exponent is the exponent of L in the relation of ρ and L). Hence according to this formula, the scaling exponent of the recycling ratio lies somewhere between 0 and 1 and depends to some extent on the relative magnitudes of local evaporation and atmospheric flux of water vapor.

The dependence of the recycling ratio on spatial scale can be studied using the general formula of section 5. *Eltahir* [1993] used that formula in estimating the recycling ratio for areas of different sizes located within the Amazon basin. The results are shown in Figure 6 for the range of scales between 250 km and the scale of the Amazon basin, ~2500 km. The estimated scaling exponent is about 0.5. This exponent is characteristic of the conditions in the Amazon region. The scaling exponents for other regions are not known.

7. SUMMARY AND CONCLUSIONS

Precipitation recycling is defined as the contribution of local evaporation to local precipitation. The motivation for studying this process stems from the central role of the water cycle in the climate of the Earth. In order to assess the impact of human activities on the water cycle and climate, we need first to understand the hydrologic processes over the land surface and in the atmosphere. Until recently, most of the research in hydrology focused on the land surface branch of the water cycle. The study of precipitation recycling shifts some of that focus toward the other important processes that drive the atmospheric branch of the water cycle.

The concept of precipitation recycling is useful in defining the different components in the atmospheric branch of any regional hydrologic cycle. The estimation of precipitation recycling ratio provides a diagnostic measure of the potential for interactions between land surface processes and atmospheric processes and hence can be used for comparing different regions. The role of precipitation recycling in land-atmosphere interactions is discussed with reference to convective storms, mesoscale circulations, and regional circulations. While the role moisture recycling is important in the dynamics of local convective storms and regional-scale atmospheric circulations, the same process may not be relevant to the dynamics of land breeze circulations at the mesoscale.

Recent research on the role of precipitation recycling in rainfall processes is reviewed in the context of the early ideas on this topic. A general formula for estimation of precipitation recycling is derived and presented to illustrate the underlying assumptions and limitations that are involved in the studies of precipitation recycling. A simple recycling formula can be developed by applying the principle of mass conservation and assuming that atmospheric water vapor is well mixed. Recent estimates of precipitation recycling for different regions are presented and compared. Significant agreement is found between the different studies on the estimates of recycling for two regions: the Amazon basin and Eurasia. Some differences are noted between the different studies on the estimate for the Mississippi basin. The dependence of the recycling ratio on spatial scale is discussed in general and illustrated with an example from the Amazon region where the recycling ratio is found to be proportional to the square root of the linear spatial scale.

Most of the research in precipitation recycling focused on North America and the Amazon regions. There is a need for future research to focus on other regions. In particular, we need to develop new estimates for arid regions, where the water cycle may be more vulnerable to climate change as a result of anthropogenic effects. The spatial scaling of the recycling ratio has been estimated for the Amazon region, but we need to investigate the scaling of this process over other regions. Finally, we need to focus on developing of new analytical formulae for estimating precipitation recycling. These formulae should try to avoid the assumptions of spatial uniformity that are involved in the approach of Budyko and have been presented in this paper. Some of the ongoing research in this area addresses these issues.

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