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Sources of moisture for rainfall in west Africa

Cuiling Gong and Elfatih Eltahir

Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge

Abstract. The objective of this study is to identify the sources of moisture for rainfall in west Africa. A model of precipitation recycling is developed and applied to the region of west Africa to obtain quantitative estimates of the moisture contributed by local evaporation as well as the moisture contributed by the zonal and meridional fluxes from the surrounding regions. We estimated the recycling ratio for the entire region by specifying three subregions where evaporation is treated as the source of moisture: west Africa, central Africa, and the tropical Atlantic Ocean. We find that evaporation from the tropical Atlantic Ocean, west Africa, and central Africa contribute about 23, 27, and 17% of rainfall in west Africa, respectively. Moisture fluxes from the tropical Atlantic are almost in phase with rainfall in west Africa. However, we find that moisture supply from central Africa is strongly regulated and limited by the westerly flow associated with the monsoon circulation. Hence the large-scale monsoon circulation is not only the main forcing of rainfall over west Africa, but the dynamics of this circulation exert significant control on where the moisture comes from.

1. Introduction

Rainfall over any land region is contributed by two sources: (1) water vapor that is advected into the region from the surrounding areas, and (2) water vapor that is supplied by evaporation from the same region. The objective in this paper is to identify the sources of moisture for rainfall in west Africa and to obtain quantitative estimates of the moisture contributions by evaporation from within the region and by fluxes from the surrounding regions. West Africa is defined as the region between 5°N and 15°N and from 10°W to 15°E (see Figure 1). A model of precipitation recycling is developed and used to estimate these contributions. The precipitation recycling ratio is defined as the contribution of evaporation in a specified region to precipitation in the same region or the surrounding areas. The importance of studying the precipitation recycling is that the recycling estimates would enable us to define one aspect of the regional hydrological cycle.

The paper is organized as follows. A review of early work related to this study is summarized in section 2. The recycling model is described in section 3. The data are described in section 4, and results of the study are presented in section 5. The findings and discussion are given in section 6.

2. Review of Early Work

The issue of sources of moisture has been explored for a long time. The early work was done by *Benton et al.* [1950] who pointed out that both the vertical motions in the atmosphere and horizontal motions that carry water vapor across the continents from oceans are important for producing significant precipitation. Benton et al. estimated the sources of precipitation over the Mississippi basin and concluded that 90% of moisture is contributed by advection from outside the basin.

Budyko [1974] developed a simple one-dimensional model to estimate the moisture recycling in a territory. In his model, the water content of the atmosphere varies in response to the loss of water as precipitation and the gain from evaporation along a streamline. Budyko's model provides a lumped estimate of recycling along a single streamline. The calculations of the water balance components for the European territory of the former Soviet Union show that only 11% of the precipitation is formed from the local evaporation. He concluded that even on the most extensive continents where the relative role of local evaporation is the greatest the main portion of precipitation is formed from water vapor of external origin and not local.

Lettau et al. [1979] used the method of climatonomy to model coherently both the atmospheric and land phases of the water cycle. The model estimates the recycling ratio for the Amazon basin to vary from 15 to 32% in the region between 50° and 75°W in the Amazon basin. *Salati et al.* [1979] and *Brezgunov* [1991] analyzed the recycling processes by measuring the distribution of the concentration of stable oxygen isotope in precipitation. Their analysis was based on the fact that the concentration of isotopes in precipitation varies as the source of moisture changes. However, isotopic analysis can only give qualitative information about the origins of precipitation.

Koster et al. [1986] investigated the origin of water precipitating in different geographic regions using the NASA Goddard Institute for Space Studies (GISS) general circulation model (GCM) in which they incorporated a finite difference scheme developed by *Russell and Lerner* [1981] to solve a tracer transport equation. Water evaporating from various source regions is "tagged" and then followed as a tracer. Russell and Lerner concluded that in the Sahel region the contributions of water vapor in summer from the tropical Atlantic, which is the part of the Atlantic Ocean extending from 0° to 35°N, and Africa/Asia are 60 and 30%, respectively.

Lamb [1983] studied west African water vapor variations during the rainy season by analyzing the observations in very deficient and near-average rainy seasons. He concluded that sub-Saharan drought is not associated with the northward supply of unusually dry surface air to west Africa from the tropical Atlantic. Westerly and southwesterly directions of the advective water vapor flux within the low-level onshore flow are more predominant.

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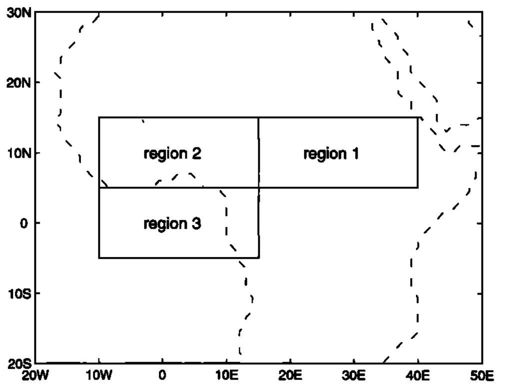

Figure 1. The domain of the study area and three specified regions: region 1 is central Africa, region 2 is west Africa, and region 3 is the tropical Atlantic Ocean.

Druyan and Koster [1989] studied the sources of sub-Saharan precipitation using the GISS climate model. Their GCM simulations focus on July Sahel precipitation. They found that the tropical North Atlantic Ocean contributes most of the rainfall in the western Sahel and that local evaporation is the second largest contributor to rainfall in July over the same region.

Brubaker et al. [1993] modified *Budyko*'s [1974] model to estimate the recycling ratio for regions that do not lie parallel to a streamline. The recycling ratio was defined as the ratio of the precipitation contributed from the local evaporation to the total precipitation of the specified control volume. The land regions studied included Eurasia, North America, South America, and Africa. They found that the contribution of regional evaporation to regional precipitation varies substantially with location and seasons. The recycling ratio in west Africa estimated from their model varies from 10 to 48% in different months. Similar to Budyko's model, their model is still a lumped model which does not treat the spatial variation of the relevant variables.

Savenije [1995] suggested the use of the salinity of the rainfall to estimate the rate of moisture recycling. It is assumed that the amount of salt of marine origin is uniformly distributed in the moisture content of the atmosphere. He concluded that the recycling of moisture in the Sahel is responsible for more than 90% of the rainfall. The reason for such a high recycling ratio is that only meridional advection is considered; the zonal advection of moisture was ignored in this model.

Eltahir and Bras [1994] developed a recycling model that accounts for both spatial and seasonal variabilities of the process. *Eltahir and Bras* [1994] applied this model to the Amazon basin and estimated that about 25% of rainfall is contributed by the local evaporation. The model of *Eltahir and Bras* [1994] estimates the contribution of evaporation in any source region to precipitation in the same region. Although we use a model similar to that of *Eltahir and Bras* [1994], we extend that model and estimate the contribution of evaporation in any source region to precipitation not only in the same region but also in the surrounding areas. The model used in this study is capable of estimating the contributions to precipitation in west Africa from evaporation in the Atlantic Ocean and central Africa and from local evaporation.

3. Recycling Model

This recycling model is based on mass balance. First, the area under consideration as a source of moisture is defined. Second, regions, in which moisture may potentially precipitate, are specified as shown in Figure 2c. Figure 2a and 2b show the following two types of control volumes in the atmosphere: one is above the source region; the other is above the surrounding areas. The dimension of the control volume depends on the resolution of the observations. For this application, the horizontal dimensions are 2.5 × 2.5° in zonal and meridional directions, and the vertical extent is from the land surface to a 100-mbar level. Since above 100-mbar level, water vapor content is very low, water vapor exchange at the top of the control volume is negligible. Applying the law of mass conservation to the control volumes results in the following equations: for control volumes that are inside the source region (type A),

$$\frac{\partial N_i}{\partial t} = I_i + E_i - O_i - P_i \tag{1}$$

$$\frac{\partial N_o}{\partial t} = I_o - O_o - P_o \tag{2}$$

for control volumes that are outside the source region (type B),

$$\frac{\partial N_i}{\partial t} = I_i - O_i - P_i \tag{3}$$

$$\frac{\partial N_o}{\partial t} = I_o + E_o - O_o - P_o \tag{4}$$

where E is evaporation; N is the storage of water vapor molecules in the control volume; I and O are the inflow and outflow of moisture; P is precipitation; subscripts i and o represent the origins of the water vapor molecules: i denotes water vapor molecules that evaporate inside the source region,

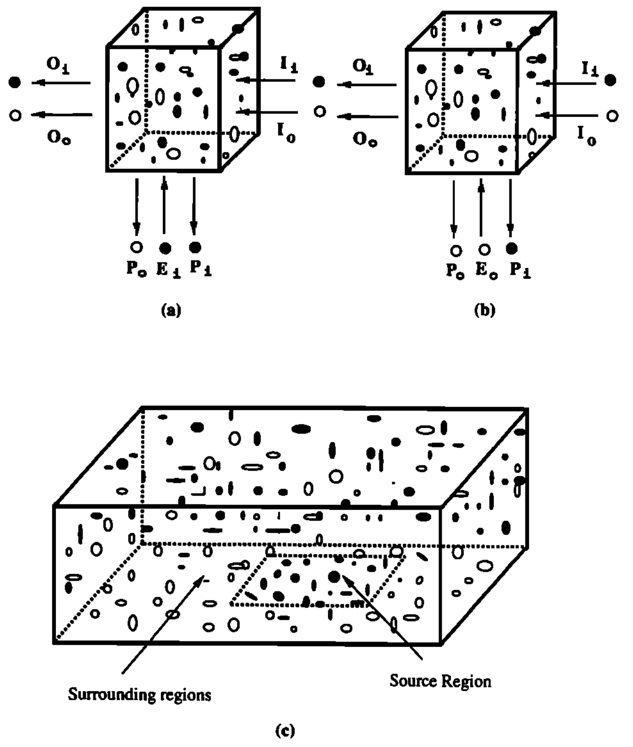

Figure 2. (a) Control volume in the source region, (b) control volume in a surrounding region, and (c) definition of source and surrounding regions. (Note that water vapor molecules evaporated from the source region and surrounding regions are represented by solid and open circles, respectively.)

and o denotes water vapor molecules that evaporate outside the source region. Note that the inflow and outflow include both zonal and meridional fluxes.

The two following assumptions will now be made: (1) the atmospheric water vapor is well mixed within the planetary boundary layer; in other words, water vapor molecules that evaporate from the surface and those advected into the control volume are well mixed; (2) the rate of change of storage of water vapor within a control volume is negligible compared to the fluxes into the control volume at the monthly timescale. The first assumption is supported by observations of *Crum and Stull* [1987] for the midlatitudes and observations of *Harris et al.* [1988] for the Amazon basin. *Budyko* [1974] also pointed out that the molecules of water vapor of local and external origins are completely mixed in the atmosphere because of turbulent mixing. To support the second assumption, *Eltahir and Bras* [1994] computed the monthly flux of water vapor and the rate of change in storage of water vapor at a single location in the Amazon basin at the monthly timescale and found that the rate of change in storage of water vapor is quite small compared to the water vapor fluxes [*Eltahir and Bras*, 1994, Figure 2].

On the basis of the first assumption, any water vapor that leaves the control volume has the same composition as the moisture in the control volume; therefore we have the following equation:

$$\rho = \frac{P_i}{P_i + P_o} = \frac{O_i}{O_i + O_o} = \frac{N_i}{N_i + N_o} \qquad (5)$$

where ρ is defined as the precipitation recycling ratio for the local evaporation. *Budyko* [1974] made a similar assumption of mixing in the boundary layer.

Applying the second assumption to the mass conservation (1)–(5) we get the following equations: for control volumes of type A,

$$I_i + E_i = O_i + P_i = \rho(O_i + O_o) + \rho(P_i + P_o) \qquad (6)$$

$$I_o = O_o + P_o = (1 - \rho)(O_i + O_o) + (1 - \rho)(P_i + P_o) \qquad (7)$$

for control volumes of type B,

$$I_i = O_i + P_i = \rho(O_i + O_o) + \rho(P_i + P_o) \qquad (8)$$

$$I_o + E_o = O_o + P_o = (1 - \rho)(O_i + O_o) + (1 - \rho)(P_i + P_o) \qquad (9)$$

Dividing (6) by (7) and rearranging the equation, we get a simplified expression of recycling ratio for type A control volumes:

$$\rho = \frac{I_i + E_i}{I_i + E_i + I_o} \qquad (10)$$

which is the ratio of the sum of the part of inflow with origin in the source region and evaporation in the source region to the sum of the total inflow and evaporation. Similarly, for type B control volumes, the recycling ratio for contributions of evaporation from the surrounding areas is defined by

$$\rho = \frac{I_i}{I_i + E_o + I_o} \qquad (11)$$

In this case, naturally local evaporation does not appear in the numerator. Note that these definitions of recycling ratio impose no restrictions on the spatial distributions of evaporation and precipitation; therefore the spatial variability of the recycled precipitation can be calculated. The procedures for applying the model are summarized in the following:

1. Divide the whole area into small cells corresponding to the resolution of the data. Estimate water vapor fluxes in zonal and meridional directions and evaporation in each cell.
2. The recycling ratios are estimated by iteration. First, an initial value is guessed and assigned to each cell. Then outflow is partitioned into O_i and O_o using (5). Note that the cells are connected with each other; therefore the outflow in cell (i, j) is equal to the inflow in cell $(i + 1, j)$ in the zonal direction. Similarly, the meridional outflow has the same characteristics. I_i and I_o can be estimated directly from O_i and O_o in the surrounding cells, and a new estimate of ρ can be obtained using (10) or (11).
3. Compare the new estimate of ρ with the previous one. If the difference is small enough, the new estimate is taken as the final result; otherwise, the iteration is repeated until convergence is reached.

The advantage of the model is that the recycling ratio in one cell takes into account information in the surrounding cells. Note that the outflows in the surrounding cells are partitioned by the recycling ratios in those cells and inflows in one cell are equal to outflows in the surrounding cells; therefore the recycling ratio in one cell is related to the recycling ratios in all cells in the area.

The areal average of recycling ratio for a particular month can be estimated by using precipitation as a weighting factor.

$$\rho_a = \frac{\Sigma P(i, j)\rho(i, j)}{\Sigma P(i, j)} \qquad (12)$$

where $P(i, j)$ is the precipitation in cell (i, j) and $\rho(i, j)$ is the recycling ratio in the same cell.

The yearly or seasonal average of recycling ratio at any cell (i, j) can be obtained using the following equation:

$$\rho_y(i, j) = \frac{\Sigma P(i, j, k)\rho(i, j, k)}{\Sigma P(i, j, k)} \qquad (13)$$

where $P(i, j, k)$ is the monthly precipitation in cell (i, j), and $\rho(i, j, k)$ is the monthly recycling ratio in the same cell.

4. Data

A subset of the European Center for Medium-Range Weather Forecasts (ECMWF) global data is used to estimate water vapor fluxes and evaporation. The data are produced by the data assimilation system, which uses observations from the surface meteorological stations, upper air measurements, and satellite data as input. The data set includes temperature, relative humidity, wind, and latent heat flux. The wind, temperature, and humidity data have spatial resolution of 2.5° × 2.5° in zonal and meridional directions and 15 pressure levels in the vertical direction. There are two analysis cycles daily. The latent heat flux data have a resolution of 1.125° × 1.125° in zonal and meridional directions. There are two forecasts daily between 1985 and 1990 and four forecasts daily after 1990. The temporal coverage of the data is from January 1985 to December 1995.

The domain of the current study area is between 10°S and 30°N and from 20°W to 50°E. The following three regions, in which the precipitation recycling is to be estimated, are specified: west Africa (region 2) is defined as the region between 5°N and 15°N and from 10°W to 15°E; central Africa (region

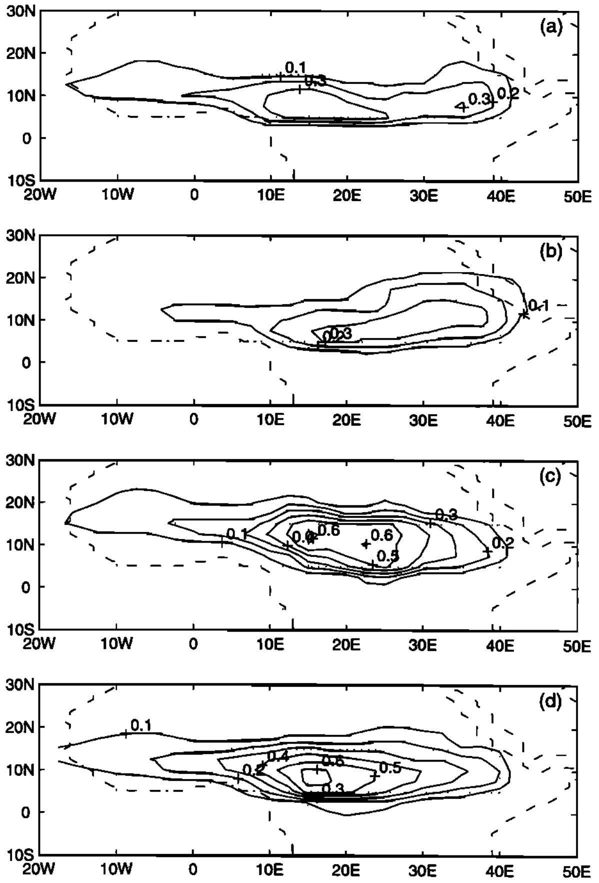

Figure 3. Spatial distribution of the precipitation recycling ratio with the source region specified as central Africa for (a) June, (b) July, (c) August, and (d) September.

1), between 5°N and 15°N and from 15°E to 40°E; and the tropical Atlantic Ocean (region 3), between 5°S and 5°N and from 10°W to 15°E. Figure 1 shows the location of these regions. Note that the number of cells are the same in these regions. Data from January 1992 to December 1994 are selected for the analysis since they contain more input from satellite data and hence are more reliable than those in previous years.

The monthly surface evaporation is estimated from latent heat fluxes:

$$E(i, j) = \frac{L(i, j)}{\lambda} \tag{14}$$

where λ is the latent heat of vaporization (= 2.5×10^6 J/kg) and $L(i, j)$ is the latent heat flux.

The monthly atmospheric water vapor flux is computed from the wind, temperature, and humidity data in the upper atmosphere and on the land surface. The fluxes in zonal and meridional directions are computed using the following equations:

$$F_1 = \frac{\varepsilon L_1}{g} \sum_{i=1}^{n} (Rh)_i e_s(T_i) U_i d(\ln P_i) \tag{15}$$

$$F_2 = \frac{\varepsilon L_2}{g} \sum_{i=1}^{n} (Rh)_i e_s(T_i) V_i d(\ln P_i) \tag{16}$$

where ε is the ratio of molecular weight of water vapor to that of dry air; U and V are the zonal and meridional wind velocities; T is temperature; P is pressure; e_s is the saturation vapor pressure; R_h is the relative humidity; g is the gravitational acceleration; L_1 and L_2 are the distances in zonal and meridional directions; the subscript n represents the pressure levels which range from the surface to 100 mbar. Note that hydrostatic distribution of pressure is assumed in deriving the above equations. The fluxes and evaporation at the monthly timescale are estimated by adding the data within each month.

The precipitation data are used as weighting factors in the estimation of the regional recycling ratio. The precipitation data for west Africa are taken from the Shea Climatological Atlas 1950–1979 [*Shea*, 1986] data set, which is based on rain gauge data. This data set has a spatial resolution of 2.5° × 2.5° in zonal and meridional directions.

5. Results of Study

5.1. Precipitation Recycling Ratio

Recycling ratios are computed only for the rainy season from June to October since there is very little rainfall in the dry season. The estimates of evaporation and fluxes presented are expressed in monthly averages for a period of 3 years from January 1992 to December 1994. According to the National Center for Atmospheric Research report [*Trenberth and Olson*, 1988] describing this data set, the coverage by observations from west Africa is quite low, which may cause some errors in the estimation of the recycling ratio.

The evaporation is estimated using (14), and moisture fluxes in the zonal and meridional directions are calculated using (15) and (16) for June, July, August, and September. The monthly precipitation recycling ratios are then calculated based on the estimates of evaporation and water vapor fluxes in those 4 months. In order to identify the sources of moisture, we specify three source regions as described in section 4. Figure 3 shows the distribution of the recycling ratio in the entire study area with the source region specified as central Africa. Figures 3a, 3b, 3c, and 3d show the results in June, July, August, and September, respectively. These figures show that the evaporation in central Africa contributes to precipitation in both central and west Africa in all 4 months. The recycling ratios increase from June to August and start to decrease in September, which is consistent with the evaporation observations. Figure 4 shows the recycling ratio distribution with the source region specified as west Africa. Figure 4 shows that the evaporation in this region contributes more to the local precipitation but has little contribution to the precipitation in central Africa and the tropical Atlantic. Similarly, Figure 5 shows the recycling ratio with the source region specified as the tropical Atlantic Ocean. Clearly, the evaporation in the tropical Atlantic Ocean has important contributions to precipitation in west Africa. The contribution of evaporation increases from June to August as shown in Figure 5a, 5b, and 5c and starts to decrease in September as shown in Figure 5d.

The areal average precipitation recycling ratios averaged throughout the rainy season are estimated using an equation similar to (13). The total yearly precipitation is replaced by the total precipitation throughout the rainy season. The climatology of precipitation is used as weighting factors in estimating the areal and seasonal average of the recycling ratios. The results are presented in Table 1. The first row in Table 1 indicates that evaporation in central Africa contributes 35% of rainfall in central Africa, 17% of rainfall in west Africa, and 7% of rainfall in tropical Atlantic Ocean in the rainy season.

The other two rows can be interpreted similarly. The areal average recycling ratio in west Africa during the rainy season is 23% when the source region is specified as the tropical Atlantic Ocean, which is larger than the 17% contributed by central Africa. This result is consistent with the decrease of moisture supply from the east during the rainy season and increase of moisture supply from the south during the same period.

Since most of the rainfall is received during the rainy season, June–October, the recycling ratio for the rainy season can be used as an approximate measure of the yearly recycling ratio. The spatial distribution of the recycling ratio in the rainy season with the source region specified as west Africa is plotted in Figure 6. The figure shows that the recycling ratio in the rainy season in west Africa varies from 10 to 40%.

5.2. Scaling Analysis

The objective of this analysis is to test how the recycling ratio scales as the area of the source region varies in west Africa. In general, the recycling ratio is a function of the hydroclimatological conditions of the region and the size of the source region under study. For example, the scaling relation will be different if we choose source regions with the same size in west Africa and in the Amazon basin because of the differences of the hydroclimatological conditions. Therefore the scaling relation can be used as an indicator of the regional hydroclimatological conditions.

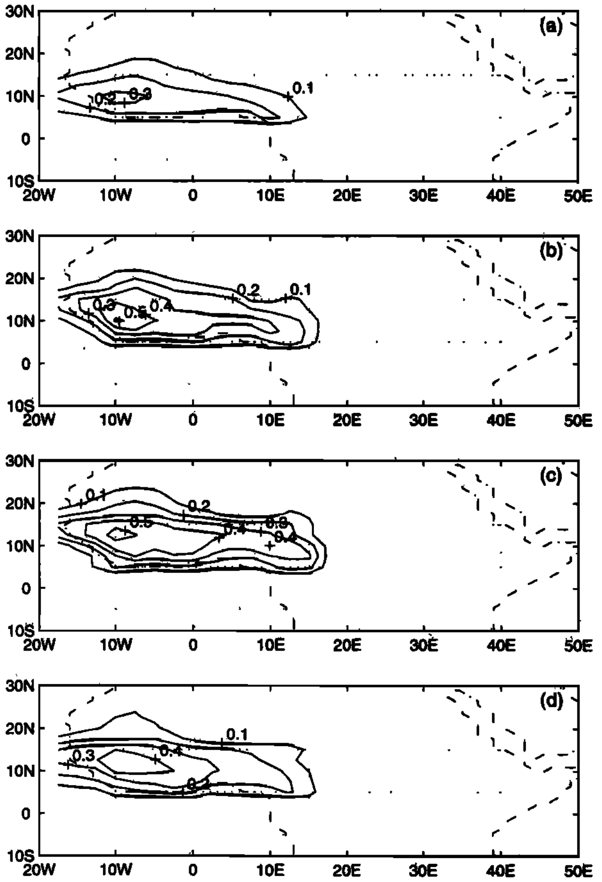

Figure 4. Same as Figure 3, but source region is west Africa.

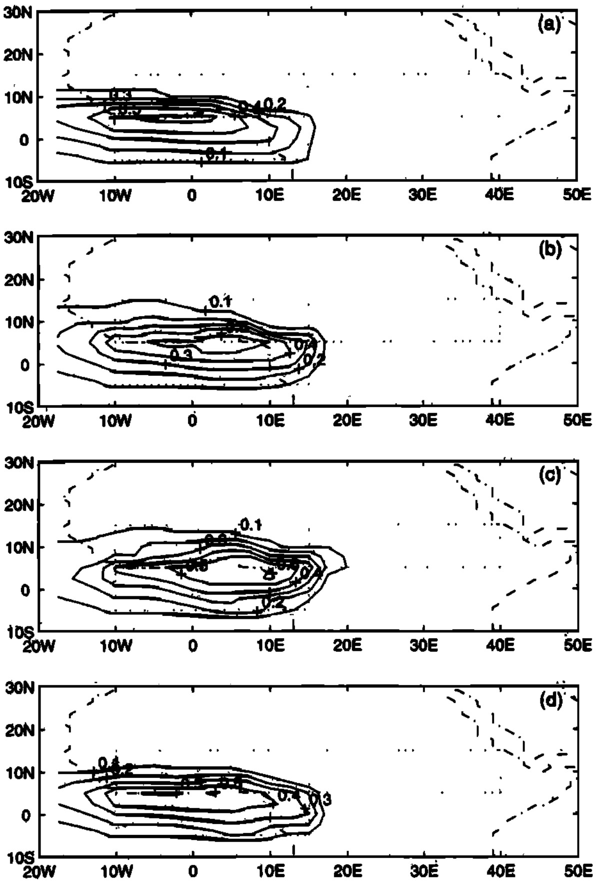

Figure 5. Same as Figure 3, but source region is tropical Atlantic Ocean.

The entire area of west Africa is divided into small square cells of equal sizes and with the length of each side equivalent to the specified scale. The smallest scale we can use for this analysis is the resolution of the ECMWF data (~250 km), and the largest scale is the entire area (~3300 km). Each cell is treated as a single well-mixed box so that I_i is equal to zero. Equation (10) becomes

$$\rho = \frac{E}{E + I} \tag{17}$$

where E is the total evaporation of the cell and I is the total inflow flux of the cell.

The recycling ratio is estimated in each cell and then averaged over all the cells with the same scale. Data used for this scaling analysis are based on the evaporation and flux data in August 1992. The result of the scaling study is shown in Figure 7. The slope of the line reflects the regional hydrologic conditions. For this particular study, the relation between the recycling ratio and area of the source region can be described by

$$\rho = 0.0053X^{0.57}; \qquad R^2 = 0.96 \tag{18}$$

Table 1. Areal Precipitation Recycling Ratios in the Rainy Season

	Central Africa	West Africa	Atlantic Ocean
Central Africa	0.35	0.17	0.07
West Africa	0.02	0.27	0.07
Atlantic Ocean	0.02	0.23	0.39

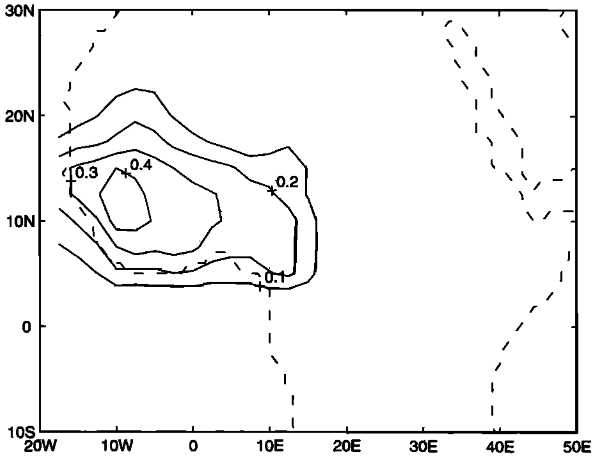

Figure 6. Distribution of the precipitation recycling ratio in the rainy season with the source region specified as region 2.

where X is the length scale of the square cells and R^2 is the coefficient of determination. Compared to the Amazon basin, where the relation between the annual recycling ratio and area of the source region is described by $\rho = 0.0056X^{0.5}$ [*Eltahir*, 1993], the recycling ratio is slightly higher in west Africa in August when the scale of the cells is the same.

5.3. Fluxes Across the Boundaries of West Africa

The temporal variations of the fluxes across the eastern, southern, and northern boundaries of west Africa are also studied. The monthly fluxes across the three boundaries from January 1992 to December 1994 are plotted in Figures 8a, 8b, and 8c, respectively. The fluxes across the southern and eastern boundaries are much larger than those across the northern boundary. Comparing the precipitation shown in Figure 8d and the fluxes variations, we can see that the incoming fluxes from the southern boundary of the region are in phase with precipitation, while fluxes from the eastern and northern boundaries are not in phase with the precipitation.

Rainfall has a direct impact on the magnitude of evaporation. Figure 8e shows that evaporation is closely associated with rainfall (see Figure 8d). Moisture supply and rainfall in west Africa relate to each other closely and exhibit similar seasonal variation. On one hand, atmospheric moisture provides the source for rainfall and controls the maximum amount of rainfall. During the dry season, moisture supply to west Africa is very low as shown in Figures 8a and 8b; rainfall shown in Figure 8d is low too. On the other hand, rainfall is associated with atmospheric circulations, which control where the moisture fluxes come from. Rainfall regulates the moisture supply from the Atlantic Ocean and central Africa. In the early months of the rainy season, significant moisture is supplied to west Africa from the east, and the convective rainfall heats the upper troposphere, which induces large-scale meridional circulation. Once the large-scale monsoon circulation develops around August the cross-equatorial southerly flow induces strong westerlies, which shut off the easterlies partially or even totally depending upon the strength of the monsoon. As a result, moisture supply from central Africa decreases significantly in monsoon months: August and September. Figure 8 shows this feature clearly during 1994. In the same period the moisture supply from the tropical Atlantic Ocean increases significantly, which is almost in phase with the rainfall.

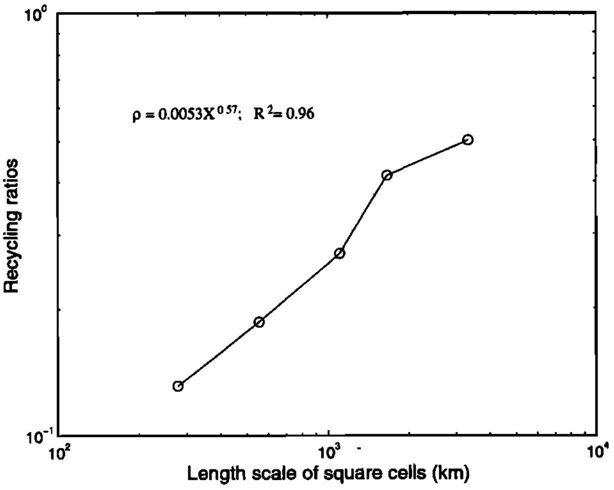

Figure 7. Relation between the regional precipitation recycling ratio and the size of the study region.

6. Conclusions

The precipitation in west Africa is mainly contributed by local evaporation and evaporation in the areas to the east and

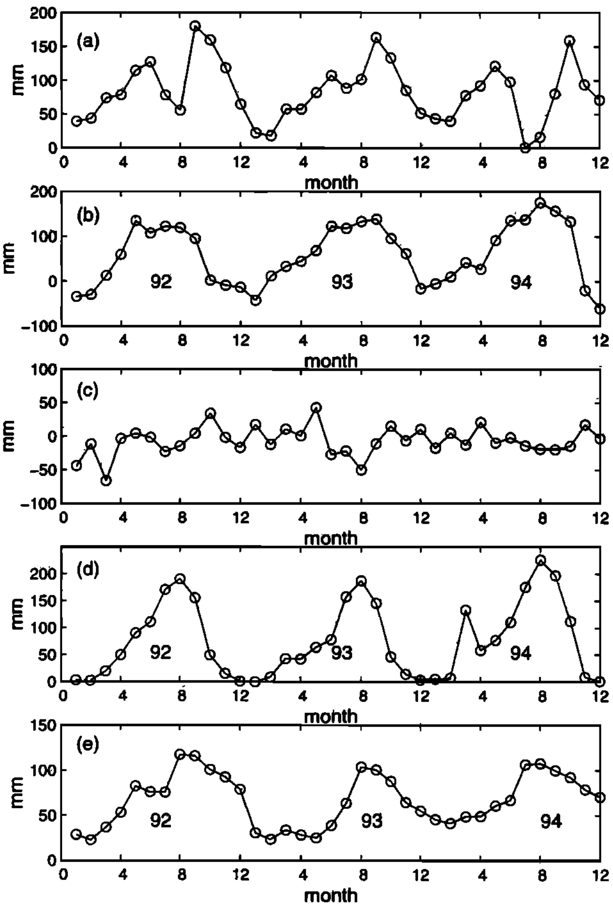

Figure 8. Water vapor fluxes coming from (a) eastern, (b) southern, and (c) northern borders of west Africa; the time series of (d) monthly precipitation and (e) monthly evaporation from 1992 to 1994 in the region of west Africa.

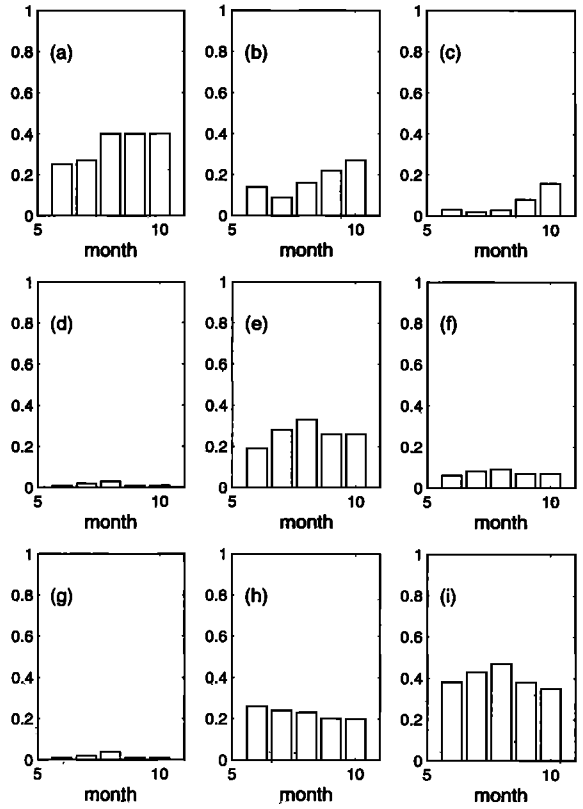

Figure 9. Areal monthly average of the relative contributions of evaporation from region 1 to precipitation in (a) region 1, (b) region 2, and (c) region 3; areal monthly average of the relative contributions of evaporation from region 2 to precipitation in (d) region 1, (e) region 2, and (f) region 3; areal monthly average of the relative contributions of evaporation from region 3 to precipitation in (g) region 1, (h) region 2, and (i) region 3.

to the south of the region. These three components contribute about 70% of the total precipitation in west Africa. Evaporation from the two African land regions, combined, contributes more rainfall to west Africa than the tropical Atlantic Ocean, 44% in comparison to 23%. However, the tropical Atlantic Ocean contributes nearly as much rainfall as local evaporation in west Africa.

The local evaporation in west Africa contributes about 27% of the precipitation, which indicates a significant potential for interactions between the local surface hydrology and climate. On the basis of the scaling analysis we find that contribution of the local evaporation to rainfall in west Africa and the Amazon basin changes by different magnitude as the area increases by the same amount. Although the magnitude of this difference is small, the contribution of local evaporation increases faster in west Africa as the area increases.

The findings of this study could be summarized by Figure 9. It shows the seasonal variation of the relative contributions of evaporation from any of the regions of west Africa, central Africa, and the tropical Atlantic Ocean to rainfall in any of these three regions. The diagonal figures, 9a, 9e, and 9i, show contributions by local evaporation, while the off-diagonal figures describe contributions of advected moisture. For example, Figure 9b shows the contribution of the evaporation in central Africa to rainfall in west Africa. It shows that this contribution drops during the monsoon months because of the decrease of moisture supply to west Africa from the east. Evaporation in west Africa increases as the monsoon develops; therefore the local recycling ratio increases during the same period, as shown in Figure 9e. Moisture supply from the tropical Atlantic Ocean increases in the monsoon months, but since the local evaporation increases during the same period, the relative contribution of evaporation from the tropical Atlantic Ocean to rainfall in west Africa remains the same or slightly decreases, which is shown in Figure 9h. The nature of the atmospheric circulation around west Africa is such that evaporation in west Africa or in the tropical Atlantic Ocean has negligible contribution to precipitation in central Africa. Figures 9d and 9g show this feature clearly. A similar argument explains the small contributions of evaporation in central and west Africa to rainfall in the Atlantic Ocean as shown in Figures 9c and 9f.

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E. Eltahir and C. Gong, Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139.

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