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Estimating Precipitation Recycling in Sudan using a BulkModel

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Abstract: The objective of this study was to estimate precipitation recycling ratio (PRR) in Sudan. The numerical bulk model of Eltahir and Brass was used. It was adopted to fit the moisture flux in the domain. The data was retrieved from the European Re-Analysis (ERA-40) of the European Centre for Medium and long-range Weather Forecast (ECMWF) archive. Surface evaporation, horizontal wind speed and specific humidity for 11 levels between the ground surface and the tropopause were used. The grid resolution was $2.5° \times 2.5°$ latitude by longitude. The period was the rainy season for the years 1984, 1988 and 2001. These years represent a dry, a wet and a normal year respectively. By calculating the vertical integrals for moisture fluxes the troposphere was reduced to a 2-dimansional domain. PRR values indicated a strong coupling between the ground surface characteristics and the rain patterns. Precipitation recycling ratio was found to be 19% in July, 21% in August and 27% in September. The contribution of the evaporation in South Sudan to the local rains exceeded 25%. It approached zero north of latitude 15°N. While evaporation from South Sudan was recycled, evaporation from North Sudan was not entrained in rain-producing systems due to air subsidence. This raised the question about the benefit of storing water in the desert.

Keywords:*Precipitation recycling; Moisture feedback; Vertical integral*

1. INTRODUCTION

Rainfall variability is a result of different forcings. One of them is due to land feedback mechanisms.Studying precipitation recycling over land areas provides useful information on the possible interactions between land and the atmosphere.
Precipitation Recycling Ratio (PRR) is defined as the ratio of precipitation due to local evaporation to the total precipitation, [1] [2]. Mathematically it is given by:

$$\rho = \frac{P_l}{P_t} = \frac{P_l}{P_l + P_a} \quad (1)$$

Where ρ is the precipitation recycling ratio, P_l is the precipitation due to local water vapour, P_a is the precipitation due to advected water vapor and P_t is the total precipitation. Precipitation recycling ratio defines the process by which local evaporative source of water contributes to precipitation before leaving the local region. It depends greatly on the scale of the domain under consideration. For a small spot the local contribution shrinks to zero. On the other hand global-scale recycling extends to 1.0 as the recycled precipitation equals the total precipitation.

Precipitation recycling studies have two different approaches; a physical approach and a meteorological approach. The former is based on the fact that heavy isotopes favor the liquid phase to the gaseous one. During condensation processes atmospheric water vapor is gradually depleted of heavy isotopes of oxygen as it moves downstream. Consequently water collected downstream contains heavier isotopes than the water collected upstream [3].

Meteorological approaches, on the other hand, consider the dynamics, thermodynamic and physical processes within the air masses. They covered all possible dimensions of atmospheric motion [4][5][6][2][1][7]. Moisture fluxes and their interactions with sources and sinks are the backbones of these studies. More recent models adopted dynamic approach-

es on daily atmospheric interactions[8][9][10].
This study is giving numerical values of the amount of rainfall that comes as a result of the local evaporation in Sudan and South Sudan.

2. METHOD

Eltahir and Brass's model [1], as shown in equation 2 was used to estimate precipitation recycling ratio.

$$\rho = \frac{I_l + E}{I_l + I_a + E} \quad (2)$$

ρ is the precipitation recycling ratio, I_l is the water vapor flux of local origin, I_a is the water vapor flux of advected origin and E is the evaporation rate.
The period of study was for the rainy seasons of the years 1984, 1988 and 2001. The rainy season was considered to extend from April to October in South Sudan and between June and October in North Sudan [11]. Monthly means of the horizontal wind components and the water vapor mixing ratio parameters were retrieved from the archive of the ERA-40 reanalysis of the European Centre for Medium and long-range Weather Forecast (ECMWF) for the following pressure levels;1000, 925, 850, 775, 700, 600, 500, 400, 300, 200, 100 hPa leading to 10 layers.

The data was the average of the 00 and 12 UTC launches or calculations. Precipitation recycling ratio PRR was calculated at grid spaces of $2.5° \times 2.5°$ (latitude x longitude) within the box: 02.5°N, 17.5°N, 22.5°E and 37.5°E. Surface pressure was given by the Sudan Meteorological Authority.

The vertical integral of water vapor flux in the x-axis and y-axis were calculated using equations (3) and (4), respectively. X represents the moisture flux in the zonal direction while Y represents the meridional moisture flux.

$$X = \frac{1}{g}\int_{p_s}^{p_t} qudp = \frac{1}{g}\sum_{k=1}^{N} q_k u_k \left(\Delta p\right)_k \quad (3)$$

$$Y = \frac{1}{g}\int_{p_s}^{p_t} qvdp = \frac{1}{g}\sum_{k=1}^{N} q_k u_k \left(\Delta p\right)_k \quad (4)$$

Here *q:* is the specific humidity, *g*: is the acceleration due to gravity, *u* and *v*are the wind speeds in the *x* and *y* axes and k represents the layer number. This vertical integral of moisture flux reduced the 3-dimentional distribution of the moisture into a 2-dimentional representation.

It was assumed that tropospheric moisture was well mixed. Each flux component was composed of local and advected species of water vapor molecules. Over the area under consideration, moisture flux was expected from all four directions.

Equation 2was re-written in the form:

$$\rho = \frac{E^*}{E^* + I_l + I_a} + \frac{I_l}{E^* + I_l + I_a} \quad (5)$$

The evaporation rate (E^*) here was that along a strip of width 1 metre across the entire grid cell. Instead of the trial-and-error method used by [1], moisture fluxes were partitioned into local and advected components.

For an array of grid points: the total in-flux was represented by:

$$\begin{aligned} I_{i,j} &= \left(I_a + I_l\right)_{i,j} \\ &= X_{i-1,j} + X_{i+1,j} + Y_{i,j-1} + Y_{i,j+1} \end{aligned} \quad (6)$$

The moisture flux was partitioned according to the recycling ratio at the neighboring grid points. At the edges of the domain most of the moisture was of advected origin. So the local contribution was taken as zero. The local influx becomes:

$$\begin{aligned} \left(I_l\right)_{i,j} &= \rho_{i-1,j} \times X_{i-1,j} + \rho_{i+1,j} \times X_{i+1,j} \\ &+ \rho_{i,j-1} \times Y_{i,j-1} + \rho_{i,j+1} Y_{i,j+1} \end{aligned} \quad (7)$$

The inward moisture flux at each grid point depended on the value of ρ at the source of the moisture flux. PRR was calculated for each current separately. The final value of PRR was the summation of all these values.

To estimate the contribution of the area south of latitude 10.0°N, to the rains of northern Sudan, PRR was calculated for a sub-domain north of latitude 10.0°N.The difference in the value of PRR at each point represented the contribution of the area south of latitude 10.0°N to the precipitation of North Sudan.

3. RESULTS AND DISCUSSION

The area average of PRR south of latitude 10.0°N were shown on table 1. The local contribution to the rains of South Sudan increased steadily from April to July. August showed a small decrease in this contribution. Possibly because of the increase of the horizontal flux, [2]. September showed the maximum local contribution. It was a result of the large local evaporation when trees and swamps supply the atmosphere by water vapour.

In the area north of latitude 10.0°N, PRR was 0.12 in July, 0.19 in August and 0.10 in September. In the northern sub-domain the maximum local contribution was in August.

Table 1: Area-average of PRR for the area south of latitude 10.0°N.

Month	**Apr**	**May**	**Jun**	**Jul**
PRR	0.16	0.19	0.25	0.27
Month	**Aug**	**Sep**	**Oct**	
PRR	0.23	0.34	0.23	

Figure 1a shows the spatial distribution of PRR in July 2001 when, rain activity extended to latitude 17.0°N. The zone of maximum PRR extended from the western parts of South Sudan along a north-eastern axis towards (10.0°N, 35.0°E). The general pattern of the precipitation recycling ratio showed an extension of high values between longitudes 30.0°E and32.5°E in Northern Sudan.PRR for the month of August 2001 is shown in figure 1b. A maximum value (40%) was

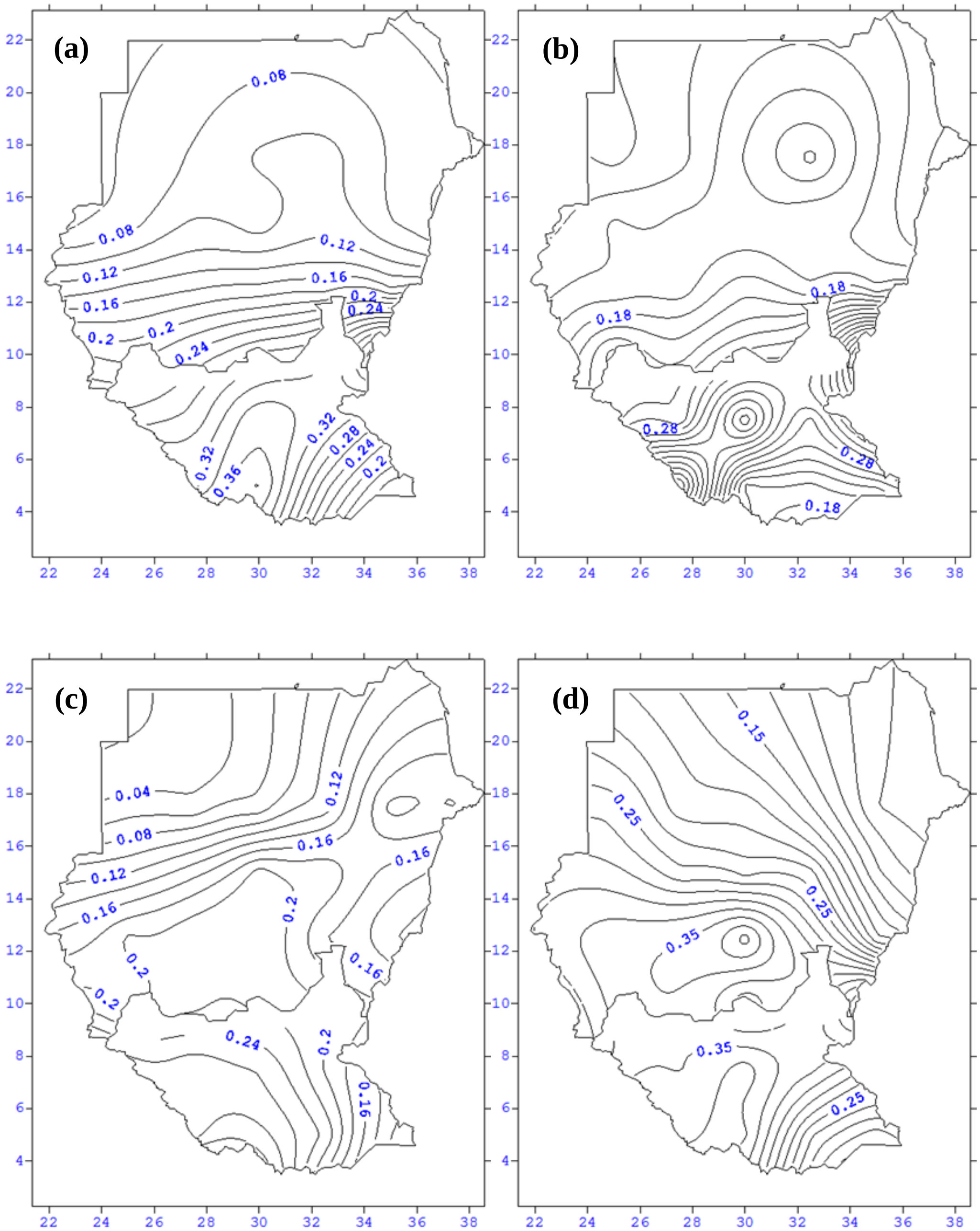

Fig. 1: The spatial distribution of Precipitation Recycling Ratio in (a) Jul 2001, (b) August 2001, (c) August 1984, (d) August 1988

observed on the western part of South Sudan. A second maximum value was located to the east around (10.0°N, 35.0°E) with a value exceeding 50%. In North Sudan higher values were observed between longitudes 30.0°E and 32.5°E with values around 20%. The increase in PRR was a result of the efficiency of the rain-producing systems and the availability of local water exposed to air that enhanced evaporation.Table 2 shows that the recycled precipitation on the western areas of South Sudan (Lat 5.0ºN and 10.0ºN)ranged between 20% and 30% along longitude 30.0ºE. It was around 18% over central Sudan (latitude 12.5ºN)

Table 2: Precipitation Recycling Ratio (PRR) along longitude 30.0E during August 2001.

Latitude	2.5	5	7.5	10
PRR	0.15	0.20	0.30	0.22
Latitude	12.5	15	17.5	20
PRR	0.18	0.15	0.16	0.13

Figure 1c shows the spatial distribution of the precipitation ratio for August 1984. That year was one of the driest years on this area, [12]. The maximum PRR values were observed on the centre of the domain. PRRs were smaller than those for August 2001.There was no maximum value at the border between the Republic of Sudan and Ethiopia. The precipitation recycling ratio at point (10.0ºN, 35.0ºN) dropped from amaximum value of 53% in August 2001to 12% in August 1984.

Table 3 shows the contribution of the evaporation in Southern Sudan to the evaporation at latitude 12.5ºN. The highest value was below 6%. In many locations it was around zero. At latitude 15.0ºN it was zero for all cases. A possible explanation of this stems on the weak surface winds in the southern areas. The evaporation water vapour molecules find enough time to enter the convective systems to fall as precipitation.

Table 3: The contribution of the evaporation of the southern area to the rainfall at latitude 12.5°N for different Augusts.

Longitude	**22.5**	**25**	**27.5**	**30**	**32.5**	**35**	**37.5**
Aug 1984	0.2	0.4	0.8	1.7	1.5	0.0	0.0
Aug 1988	0.9	1.5	2.8	5.6	5.0	0.5	0.0
Aug 2001	0.7	1.7	2.8	2.7	3.4	3.4	5.1

The swamps of South Sudan provide the atmosphere with large amounts of water vapor. The large recycling ratio near the Sudanese-Ethiopian border (figures 1, 2 and 4) was a result of this fact. The south-westerly current passed over the swamps of South Sudan, picked up water vapor and carried it to these downstream areas. PRR, in general increases downstream [4], [1]. However in Sudan there is more than one moisture conveyor. In the lower layers the south-westerly currents dominate. But in the middle layers a reversed moisture laden current moves from east to west.

The large values of PRR to the west of the Nile course were attributed to the easterly moist current on the mid-tropospheric layers. PRR at northern areas was small in spite of the longer distance moved by the humid southerly winds. Subsidence on the pole-ward-side of the easterly jet stream weakened the entrainment of the local evaporation into the rain-producing systems.

The amount of the recycled rain at the end of the rainy season was larger than that at the beginning of the rainy season, (table 1). This was due to the fact that the contribution of the underlying surface to the moisture budget differed at these two periods, being larger at the end of the rainy season when the trees resumed their leaves and the area of the leaves became larger. [13].

4. CONCLUSION

Local evaporation contributed to the rains of Sudan by ratios reaching 20% or more at some periods and some locations. Precipitation recycling ratio (PRR) was bigger than its values at the beginning of the rainy season, which indicate the importance of the local evaporation. Suppression of local evaporation by deforestation or canalization of the swamps will affect local evaporation and consequently the local rains may decrease. Atmospheric moisture currents affect the spatial distribution of the precipitation recycling ratios. PRR is largest on the central and western parts of the domain instead of the northern areas. This is attributed to the fact that on the northern areas subsidence is largest. Another cause is east-to-west track of the rain-producing disturbances on the middle and upper layers. [2][10]. Evaporation from surface water sources in northern Sudan is large.However there is no lifting mechanism produce rain-producing clouds. in other words the contribution of the evaporation in the northern areas (e.g., Marawi dam) is negligible.

The contribution of the evaporation of South Sudan to the rains of North Sudan was small. It was confined to the border strip and it hardly affects the central and northern areas. The maximum values were around 5% which is comparable to the natural variability of the rains.

The study showed that the coupling of land surface processes to the atmospheric ones is important. More studies and workshops are encouraged to explore the feedback mechanisms between the lower atmosphere and underlying surfaces.

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