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Moisture Flux over Sudan during the Rainy Season

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Abstract: The objective of this study is to evaluate the tropospheric moisture fluxes into and out of Sudan during the rainy season. The data was retrieved from the European Re-analysis (ERA-40) of the European Centre for Medium and long-range Weather Forecast (ECMWF) archive. Horizontal wind speed and specific humidity for levels of significance between the ground surface and the tropopause were used. Vertical integrals for moisture fluxes between the ground surface and the tropopause were calculated at spacing of 2.5°. The moisture fluxes were calculated around the box bound by 2.5°N, 20.0°N, 22.5°E and 37.5°E. Depending on the moisture flux three distinct layers were found within the troposphere. The bulk of moisture entered Sudan from south and west. In the dry year of 1984 the moisture out flux of moisture nearly balanced the influx, leaving the area in a situation of weak convergence which did not favor rain production. The drought of 1984 was attributed to the absence of rain-producing systems rather than to lack of atmospheric moisture. The study concluded that high moisture content is necessary but is not sufficient to produce rain in the absence of converging wind flows. To improve rain predictions and forecast, adequate monitoring of tropospheric moisture and winds is needed.

Keywords: *Moisture flux; Monsoonal flow; Rain-producing systems; Sudan*

1. INTRODUCTION

Transport of moisture into a region where it can be entrained into a precipitating weather system depends on the atmospheric dynamics as well as on the moisture content. Moisture flux is the amount of water that passes across a unit area. It is a result of multiplication of two parameters: specific humidity (mass of water vapourin one kilogram of air) and wind speed that carries these water molecules (F=qV). Kidson[1] studied upper air over Africa using radiosonde observations. He found that at latitude 10°N the mixing ratio dropped from about 18 gm per kilogram of air at the surface to about 2 gm at the 500hPa level to about 0.2 gm at the 300hPa level. A similar distribution was found on the products of the General Circulation Models, [2][3].
Wind speed is measured by balloons and radiosondes beside the remote sensing techniques of satellite imagery and radars. Dodd and James [4] found that the peak magnitude of the global zonal-mean of water vapor flux is $178 kg m^{-1} s^{-1}$ at latitude 10˚N. Trenberth and Guillemot [5] showed that the main global moisture transports were east-west with strong westward components in the tropics and eastward components in the middle latitudes with few exceptions.

The objective of this work is to study the moisture fluxes over Sudan during the rainy season. Although many studies were conducted about the hydrological parameters on the ground surface at this area, the atmospheric branch of the hydrological cycle received little attention. Remote sensing techniques and products of General Circulation Models provided good information for these tropical areas [6][7].The study area is Sudan and South Sudan. A rectangle bounded by 2.5°N, 20.0°N, 22.5°E and 37.5°E is used.

2. METHODOLOGY

Moisture fluxes into and out of the domain of study were constructed. Vertically integrated moisture fluxes were calculated. The integration was made over the area throughout the troposphere. Three main assumptions were needed to do this integration. Firstly the flow was considered hydrostatic (the vertical extent is much less than the horizontal extent). Secondly the liquid and solid water contents were considered negligible. Thirdly water vapor above the tropopause was negligible.

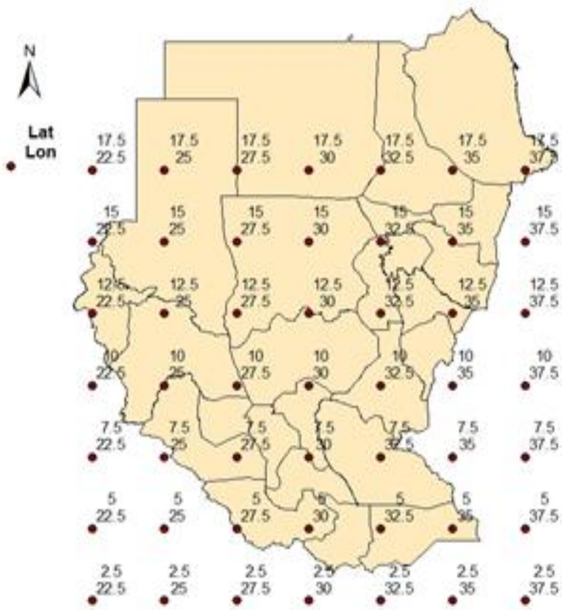

Fig 1: Map of Sudan and South Sudan showing the grid points used in the study. The figures represent the latitude and longitude of the location.

The vertical integral of water vapor flux in the x-axis is given by:

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

The vertical integral of water vapor flux in the y-axis is given by:

$$Y = \frac{1}{g}\int_{p_s}^{p_t} qvdp = \frac{1}{g}\sum_{k=1}^{N} q_k u_k \left(\Delta p\right)_k \qquad (2)$$

Here *q*: is the specific humidity,*g*: is the gravity, *u* and *v*are the wind speeds in the *x* and *y* axes; k represents the layer number, and *K* is the total number of layers[8]. Equations (1) and (2) were used to estimate the vertical integral of moisture flux using the retrieved data. The data belonged to the ECMWF ERA-40 reanalysis. It was retrieved for 30 locations along the boundaries of the domain 2.5°N to 20.0°N and 22.5°E to 37.5°E. There were 11 isobaric levels: 1000, 925, 850, 775, 700, 600, 500, 400, 300, 200 and 100 hPa. For each level specific humidity, zonal and meridional wind components were retrieved. Surface pressure values were collected from the archive of Sudan Meteorological Authority. The physical parameters at the ground surface were extrapolated following Oki, [8]. The average specific moisture for each level and the average wind for each layer were calculated first independently. The resultant values were integrated throughout the depth of the troposphere to obtain the vertical integral of the moisture flux.

The total moisture flux was the summation of the absolute value of the moisture of each layer. The average value of the flux for each side was constructed to estimate the inward and outward fluxes.

3. RESULTS AND DISCUSSION

The specific humidity dropped exponentially with height at all locations. The mid-monsoon period had got the highest moisture content in the lower levels. The high moisture content at the lower levels was a result of the moisture advection by low level winds,the proximity to the water sources on the ground level and to the ability of the warm air to carry water vapor. The post-monsoon period had got more moisture compared to the pre-monsoon one. This was attributed to the reservoir of soil moisture and to vegetation

3.1 *Vertical moisture profile*

Specific humidity dropped from about 15 gm per cubic metre at ground level to around zero at a height of 9 km (~300 hPa).The zonal wind was westerly at the lower tropospheric layers which represented a typical monsoonal flow to a depth of 3 km. The Tropical Easterly Jet stream (TEJ) dominated the high tropospheric layers over this area. The speed of this easterly flow increased steadily with height from about 2 m/s on the lower levels to about 30 m/s at the 100 hPa level. The zonal moisture flux showed a powerful westerly monsoonal flux with a peak value at a height of 1.5 km (~850 hPa). An easterly moisture flux was evident in the mid-tropospheric layer around 5.5 km (~ 500 hPalevel). The wind speed increased in an order of one magnitude while the specific humidity decreased in about two orders of magnitude. The increase in wind speed could not compensate the drop in the specific humidity. The vertical profile of the moisture flux was controlled by the value of the specific humidity rather than by the value of the wind speed. The three vertical profiles showed that there were three distinct layers. The monsoonal layer at the lower levels was the most evident. The easterly flow can be divided into two layers: the lower one which extended between 5 and 9 km (600 and 300hPa), and the layer between 300hPa and the tropopause. The main difference between them was the moisture content and flux. The strong southerly meridional flux was observed at the lower layers. At higher levels the winds oscillated around the zero.

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3.2*Flux across the eastern border*

Figures 3 shows the vertical integral of the zonal moisture fluxes along longitudes 40.0°E and 42.5°E from the equator until latitude 20.0°N in August 2001. The flux along longitude 40.0°E was easterly except at the extreme northern parts of the domain around latitude 17.5°N where it was westerly. Along longitude 42.5°E the flow was westerly. This indicated that little moisture was flowing from the east into the domain. The main reason behind this was the powerful eastward Somali jet stream over the Arabian Sea.

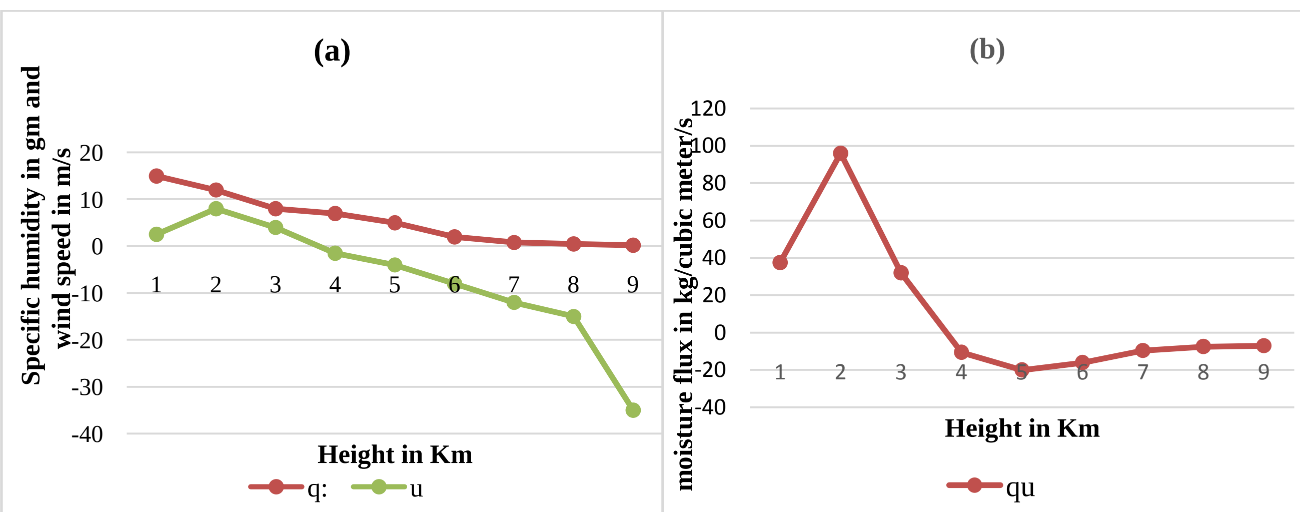

Fig.2: a) Vertical profile of : specific humidity (q in gm) and zonal wind speed (u in m/s), b) Vertical profile of zonal moisture flux

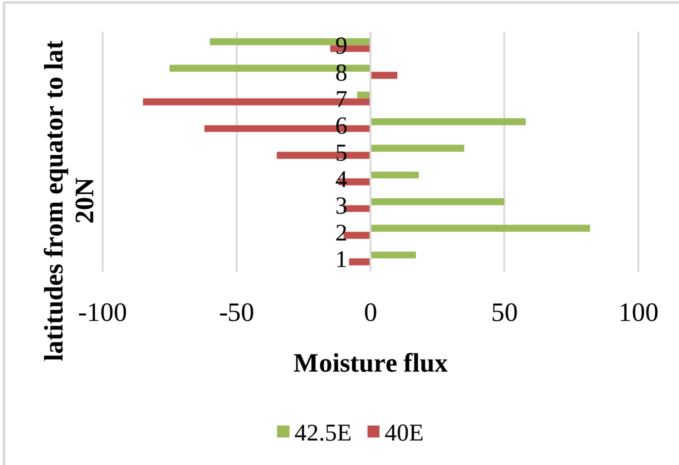

Fig. 3: The vertical integral of the zonal flux along latitudes 40.0°E and 42.5°E in August 2001. The y-axis represents the grid points at a space of 2.5º from the equator to latitude 20.0ºN

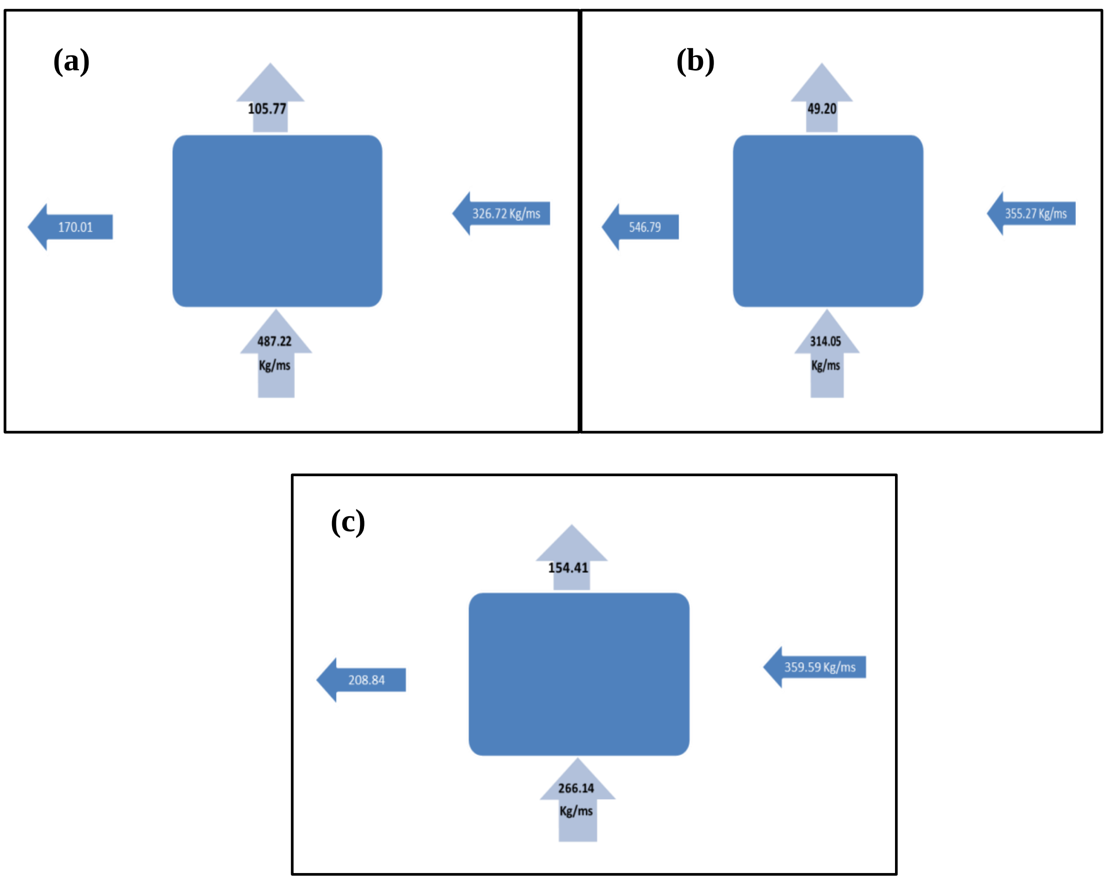

Fig. 4: a) Horizontal moisture flux for August 2001, b) Horizontal moisture flux in August 1984, c) Horizontal moisture flux in August 1988.

3.3 *lateral moisture fluxes*

The budget of the atmospheric water can be represented by the following mathematical formula [8]:

$$\Delta S = E - P + \left(F_{in} - F_{out}\right) \qquad (3)$$

The left-hand -side of this equation represents the moisture storage in an air column. The right-hand-side represents the atmospheric processes that lead to moisture accumulation in the air column. For long time periods (a month or more) the change in storage and evaporation are negligible and precipitation becomes directly proportional to the horizontal moisture fluxes: influx of moisture and out flux of moisture [8].

$$P \alpha \left(F_{in} - F_{out}\right) \qquad (4)$$

Figure 4a shows the moisture flux in August 2001. 487 kg of water vapor entered from the south, 327 kg from the east, while 170 kg left on the west and 106 kg left on the north. The out flux was 34% of the influx. The moisture converged within the area was 66% of the influx.

It should be noted that August 1984 (figure 4b) witnessed large inward moisture fluxes from the eastern and southern sides, (355 kg and 314 kg respectively). Nevertheless the outgoing flux on the western side was very large (547 kg). This left the whole area on a situation of weak moisture convergence. The ratio of the out flux to the influx was 89%. The converged moisture was .08% of the influx. This indicated the weakness of the rain-producing system in converting the available moisture to precipitation.

Furthermore it could be seen that August 1988 (figure 4c) was characterized by weak southerly moisture flux (266 kg) in spite of the strong easterly inward flux (360 kg). The weak outgoing flux (209 kg) on the western side left the area on a convergence situation. The percentage of the out flux to the influx was 58% and the percentage of the converged moisture to the influx was 42%.

During the monsoon period large amounts of moisture entered the study area from the south and from the lower layers on the west. Small amounts of moisture were observed to enter from the east. Atmospheric moisture left the domain from the western middle layers. The dry year of 1984 witnessed a large influx and also a large out flux of moisture nearly 90% of which over-flown the area without being converted into precipitation. On the other hand in August 1988 less water vapor entered the domain. The efficient rain-producing systems left 58% of which to overfly the domain.

4. CONCLUSION

Water vapor entered the domain from the south and lower levels on the west. Very little amount of moisture enters from the east and no moisture entered from the north. The water vapor exit was on the middle layers on the western side. Large influx of water vapor did not mean large amount of rainfall, as the out flux might be similarly large leaving the area in a state of weak moisture convergence. On the contrary powerful rain-producing systems might converge less influx moisture into rain.Finally, it should be noted that the moist easterly current in the middle layer was not originated over the Indian Ocean. It was a reversed flow of the moist south-westerly monsoonal flow.

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