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Research Article

Synoptic Conditions Responsible for Rainfall and Dry Situations above Khartoum Area-Sudan (1994-2003)

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(Received: October 01, 2015; Accepted: March 12, 2016)

Abstract-Synoptic conditions including rainfall and dryness over Khartoum have been investigated by using Principal Components Analysis (PCA) and Two-Step Cluster analysis methods. The synoptic observation data has been collected from the Khartoum station during the period 1994-2003. First, PCA has been used as a data reduction technique and six PC scores which described 72.03% of the total variance were retained by using eigenvalues greater than one. The PC1 was strongly positively correlated with relative humidity (and the related dew point temperature) and cloud cover, while the other PCs have a weak correlation with all variables. Second, these modes are treated as a new file for Classification Analysis technique. Finally, nine synoptic types were determined in this area.

These types are showing reasonable results and reflecting the synoptic features which, oscillate over this area e.g. unstable southwesterly monsoon wind dominates over the areas south of the Inter-Tropical Convergence Zone (ITCZ) position inducing thunderstorm rainfall during the rainy season.

Index terms: Synoptic conditions, Khartoum station, PCA , Two-step Cluster, ITCZ.

I. INTRODUCTION

Khartoum station is located at 15° 40´ and 32° 32´ E, in the Central Sudan mainly in the semi arid zone. This zone experiences its maximum rainfall in August, from heavy squall line thunderstorms. These squall lines are basically, a part of the large-scale of the West African Monsoon (WAM) system, but it initiates at much higher altitudes than the continuous monsoon rains that start south of 12-10°N. The upper-level jets, especially, the African Easterly Jet (AEJ), are important in starting and driving the westward movement of these linear depression lines.

The meridional shifts in the position of the easterly jet can produce rather large rainfall anomalies [1]. And these squall lines which may develop as high as 16 km, receive moisture from the low-level WAM flow in which their bases embedded. As evidence, Robert [2] noticed that, Khartoum station (32°E) is one of the stations that are located in the passage of these lines, as they propagate westward. Hypothetically, the study area is relatively drier than the areas that lie in the east and the west at the same latitudinal limits [3]. Therefore, it has been considered to investigate both rainfall and dryness conditions through a decade.

The main purpose of this paper is to determine synoptic conditions that responsible for rainfall and dryness situations over Khartoum area, by using Principal Component Analysis (PCA), based on the hourly observation data, and two-step cluster analysis techniques. Firstly, these data have been summarized into a small number of components known as, component scores, and secondly; these scores are subjected to a two-step cluster analysis. The outline from this analysis is nine surface synoptic types, over this area, which is able to address synoptic features, which are producing either the rainfall or dryness conditions during a period of time commencing from 1994 to 2003.

II. MATERIALS AND METHODS

Surface Observation Data

Synoptic observation data are collected from the Khartoum Meteorological Station. These data contain nine elements namely: air temperature, dew point temperature, wet-bulb temperature, relative humidity, mean sea level pressure, wind direction and speed, cloud cover, and daily rainfall. These elements were observed four times/day (00, 06, 12, and 18 UTC corresponding to +3 LT), excepted for rainfall which, was collected once a day during the study period 1994-2003. The missing data is about, 0.06% only from all the data. In order to have a data matrix file, it is necessary for these data to be regulated.

Since these data contain of different units of measurements, an 8 days of moving average (known as Mean Square Error (MSE)) was used to remove the seasonal cycle or seasonality, following David *et al* [4], who utilized this method in the economic studies. This procedure is known as deseasonalization.

Methodology

Principal Components Analysis (PCA) is a multivariate technique, which is widely used in Meteorology and Climatology, in order to reduce a number of variables into a smaller set of uncorrelated variables, with the aim of better understanding and interpreting structure of the data. The technique reorganizes the original data matrix into a new set of principal components (hereafter PC) that are linearly independent and ordered by the amount of the variance of the original data they explain.

Since the purpose of this study is a synoptic-typing classification, a choice of decomposition of a P-mode was done. These data have to be standardized by using a correlation matrix, when different variables in the dataset are measured using different units (mm, mb, percent, degree…etc), and a file of 33 variables with 3650 cases has been created. Comparatively, principal components (PCs) of the original variables account for as much as large of the total variance, while the first PC explains the largest variations and smaller for the subsequent PCs.

In this application PCA (unrotated) was utilized for two reasons: (a) to produce an entirely orthogonal dataset and (b) to reduce the size of the matrix without much loss of information. The number of PCs in this study was identified by choosing eigenvalue values greater than one, which is commonly used as a cutoff point for which PCs are retained [5, 6]. This method suggests retaining PCs, which always explain more than 70% of the total variance from the original variables.

The PCA results have described the component loadings which are showing the relationships between the components and the original variables. A large component loading indicates the greater importance of the meteorological parameter in explaining that PC, where, the component scores discover the relationship between the meteorological variables for each day and the PC. Thus, days with similar meteorological conditions can display similar component scores.

The next step, there are three clustering procedures must be done in this section; based on the resulting component scores as the main data file for clustering method. First, hierarchical and agglomerative have been used to determine the initial clusters. Second, by using Ward's criterion, the scores were regrouped according to their similarities. Third, Euclidean distance measurement was used because it has the ability to amalgamate the scores with each others, and this procedure is repeated until one cluster remains. Further, the intermediate results of hierarchical clustering have to be illustrated by using the dendogram. But no dendogram here is depicted due to the high number of scores included. For convenience, for solving this problem a two-step clustering technique has been utilized because it has the ability to analyze the large data files [7]. And exactly, the optimal number of clusters was determined by illustrating agglomeration coefficients in the Scree Plot. This method suggested that nine emergent clusters were identified. After that, the initial clusters used as an input data file for the K-means, non-hierarchical cluster method, which was applied to produce the final solution, by classifying the days which are belonged to each cluster [8]. After this procedure, a daily catalogue for these clusters was created to be used for further investigations. Ultimately, we have nine surface synoptic types.

III. RESULTS AND DISCUSSION

PCA Results

Table (1) shows that the first 6 PC scores explain 72.03% of the total variance. PC1 explains 43.352% of the variance and it has the highest positive correlation with relative humidity, wet-bulb temperature, and cloud cover. These results indicate that the first PC loadings' is showing the rainfall conditions over Khartoum area, which are driven by the northern migration of the Inter-Tropical Convergence Zone (ITCZ) during the rainy season; whereas, the second PC loadings has weak correlation with all variables. This fact corresponding to Richman and Lamb [9] results for all rainfall stations, which were showing either positively correlated to each other or had near-zero correlations. Generally, three PCs are weakly correlated with rainfall conditions such as PC1, PC5 and PC6 with values about 0.20, 0.50 and 0.30 respectively. However, the rest of PCs namely; PC2, PC3 and PC4 depict dry conditions rather than rainfall conditions.

The component scores reflect the temporal behavior of primary circulation modes and can be used as multivariate parameters of daily synoptic circulation. The PC1 occurs during winter months (December-January-February); when it has low negative scores appears in summer months (June-July and August). While PC2 was distinguished from the first one, by its frequent occurrence twice a day and it is dominant during April 1998 and in April and May 2001 as well as during July and August in the same year.

Table (1): Eigen values for the first six components

Components	Initial Eigenvalues		
PCs	Total	%variance	%cumulative
1	14.306	43.352	43.352
2	4.014	12.164	55.516
3	2.094	6.346	61.862
4	1.297	3.931	65.794
5	1.056	3.199	68.993
6	1.003	3.040	72.033

Classification Results

Cluster analysis produces nine surface synoptic types over the Central Sudan. These types will be described according to their monthly frequent occurrences with a concentration on the more frequent months.

Type 1

It appears in autumn (September-October) and in June. It is characterized as dry with high temperature values (Figure, 1). Wind blows in a southwesterly direction explaining the retreat of the ITCZ (Figure, 2); low pressure system has been shown (Figure, 5). It has moderate relative humidity (that means also moderate wet-bulb temperature and dew point temperature (see, figures, 6, 7 and 8 respectively); with moderate cloud cover representing more than 5 oktas during the day (Figure 9) but there is no rainfall available. It is clear that during the above-mentioned period the rainfall system is retreating southwards. Since, the southwesterly wind is dominating during this period of time allows this type to be characterized as *the calmest, warm, with moderate humidity, high clouds and moist air masses so it is recognized as* ***the calmest type.***

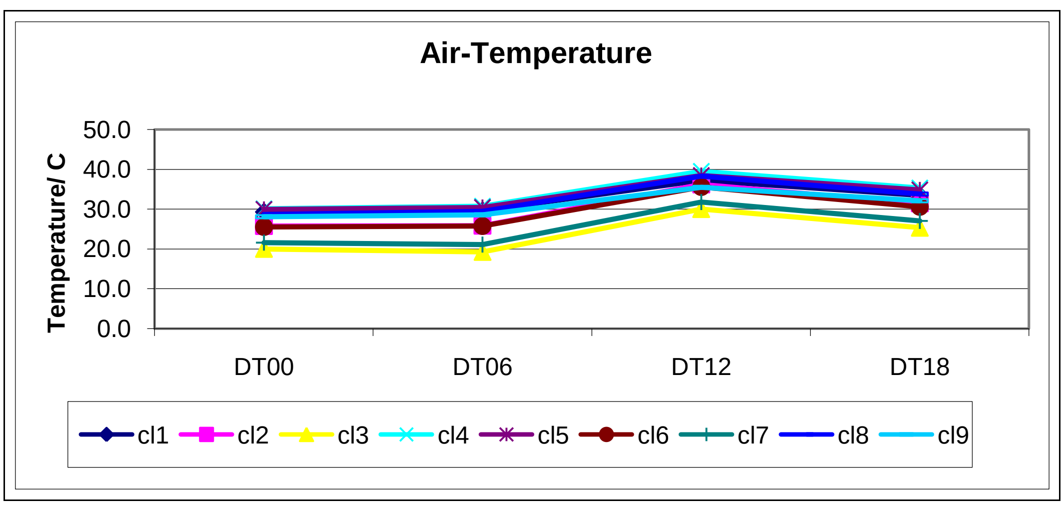

Fig. 1: Air temperature in the nine surface types

Type 2

It is observed during spring (March-April) and in November. It was appearing in a transitional period. Wind flows in a counterclockwise as NW direction with the highest speed about 8m/s (Figure, 2), (known as samoom in Sudan) originating in the Sahara desert. It is described as dry and thundery; with very low relative humidity. It is known as a transitional type, *with low pressure values, most changeable, dry and dusty*.

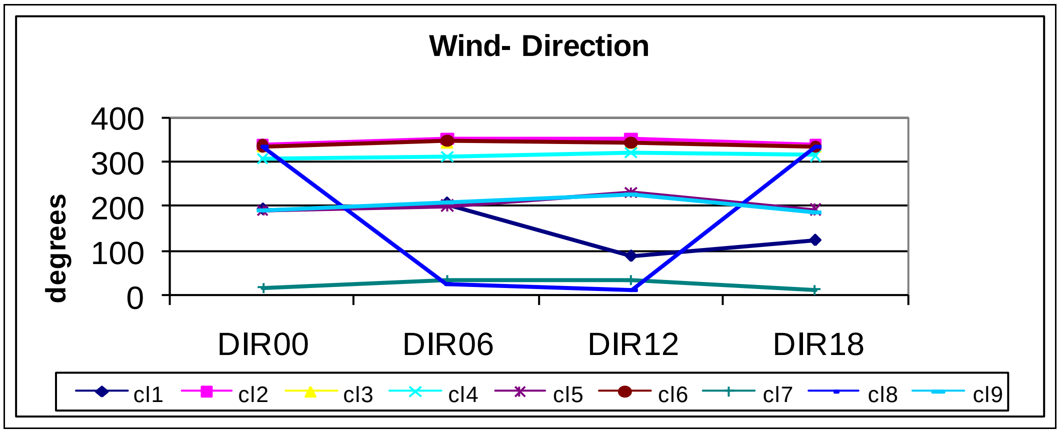

Fig. 2: Wind direction in the nine surface types

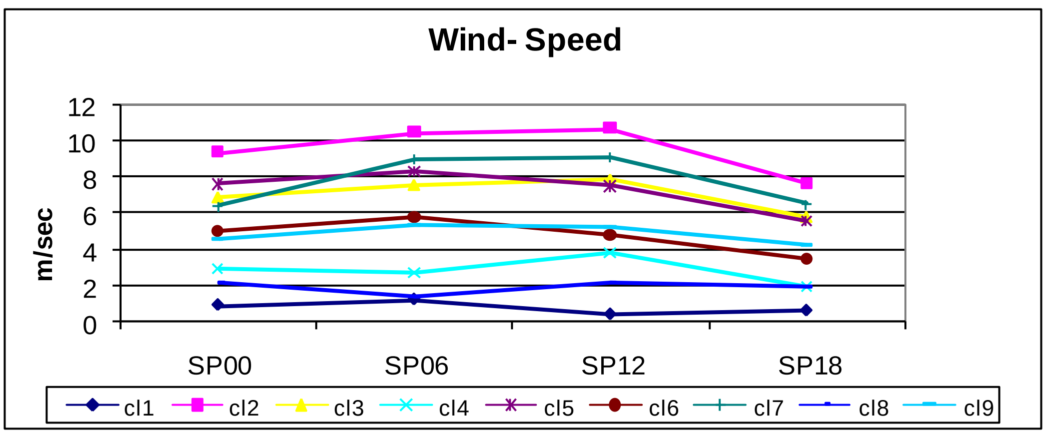

Fig. 3: Wind speed in the nine surface types

Type 3

It is depicted during winter months (December-February [DJF]). It includes the majority of the days during the whole study period. It is the coolest and direr one with clear skies. The lowest temperature values registered (Figure 1), due to the passage of severe cold fronts associated with the Mediterranean depressions. Therefore, this it is defined as winter type and it distinguished by its *drier, cloudless skies and wind components aim at northwesterly direction with moderate speed.*

Type 4

It is observed in spring mainly in May and early summer in June. Dry season in Sudan sometimes continues until May/June. Wind is sweeps inside this area from the NW direction with the highest speed. Even, it is cloudy during the daylight, but with very little rain (Figure 10). These situations are suitable for higher temperatures to reach 40°C in midday (Figure 1). It is recognized as *cloudy, dusty and warm type*. Thus, it is known as convergent-frontal type.

Type 5

It is a summer type. It is frequent in June, July and August with a peak in July. The highest temperature values are recorded during the course of the day as well as high relative humidity (also the highest dew

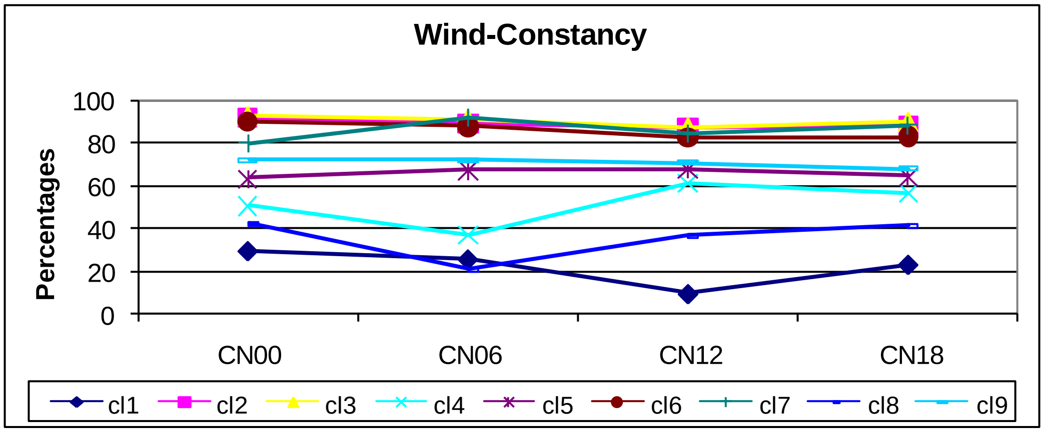

Fig. 4: wind constancy in the nine surface types

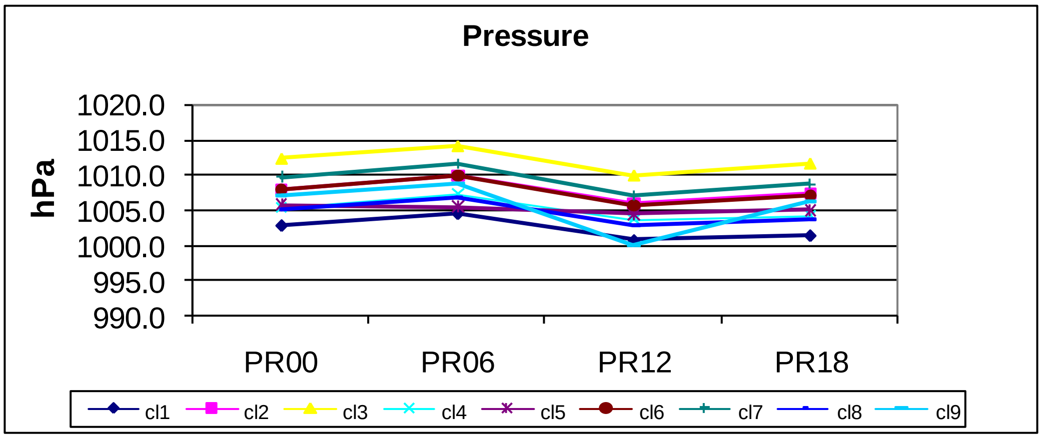

Fig. 5: pressure values in the nine surface types

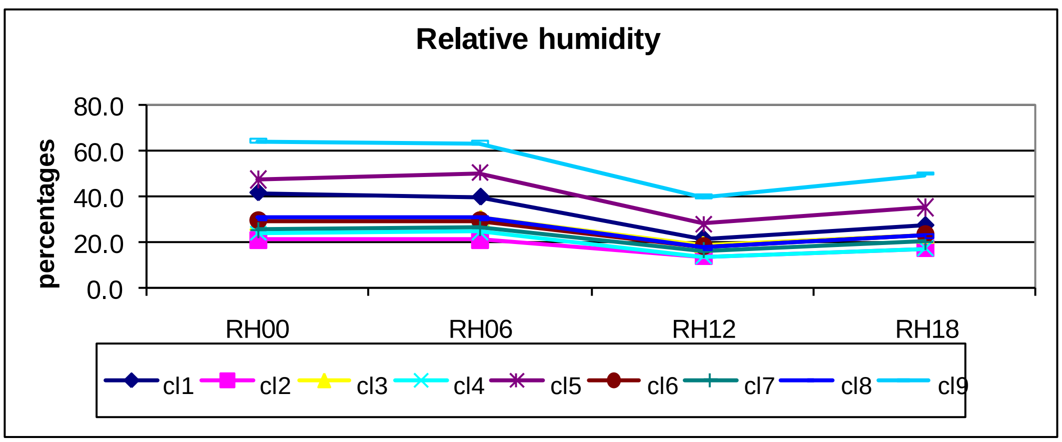

Fig. 6: Percentages of Relative Humidity in the nine surface types

point temperature and the wet - bulb temperature is around 23 °C during the day) and these conditions are capable of typifying the moist currents arriving from south to north, represented by the SW monsoon flow (Figure 2). These conditions supported cloud cover to be more than 6 oktas (Figure 9). These moist currents are including the ITD zone and the TEJ which has been related to the rainfall system in Sudan (Figure 10). Also this system is allowed the convective storms to develop. Finally, the rainfall is organized in Squall line system. Even it appears in summer, it has rainfall but with a short duration not more than one month. These conditions lead this type to be *warmer, cloudy, more humid, rainy and dusty with uniform pressure system* (Figure 5).

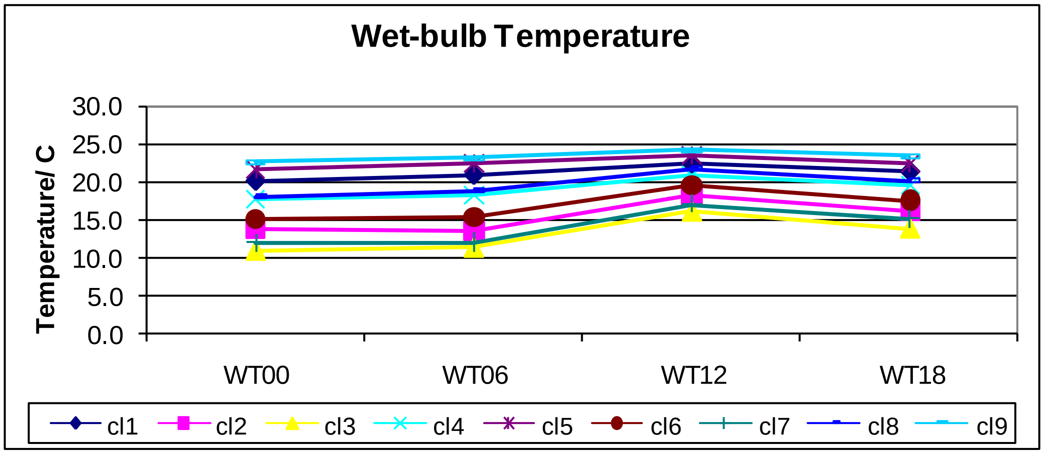

Fig. 7: Wet-bulb temperature in the nine surface types

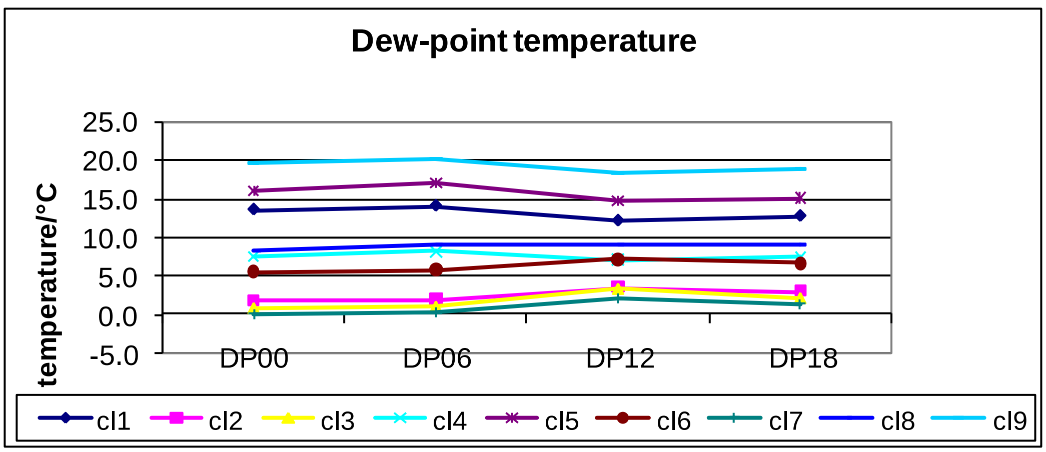

Fig. 8: dew point temperature in the nine surface types

Type 6

It is most frequent during November and December. The dry situations prevail from northern part of Sudan, due to NW dry wind (the same conditions were discussed in type 3). Owing to these dry conditions, relative humidity attains it's the lowest percentages throughout the day (see figure 6). Generally, in November, the Sudan as the other North African countries are experienced the highest maximum temperature order of 37-38ºC is met around 15ºN. During the nighttime air temperatures exceeding 20ºC mainly over the northeast of Sudan region; and it is one of the warmest areas in the tropical Africa [10]. Thus, it is characterized as the *driest one, with clear skies*, known as a northwesterly type.

Type 7

Also it is like type 3, appears in January, February and March. It has a remarkable point in March. The wind takes NE direction with high speed (figure 3). It contains the lowest number of days during the study period. It is characterized as *drier and cooler* compared with the other types. It is known as *winder,-driest one and windy type*.

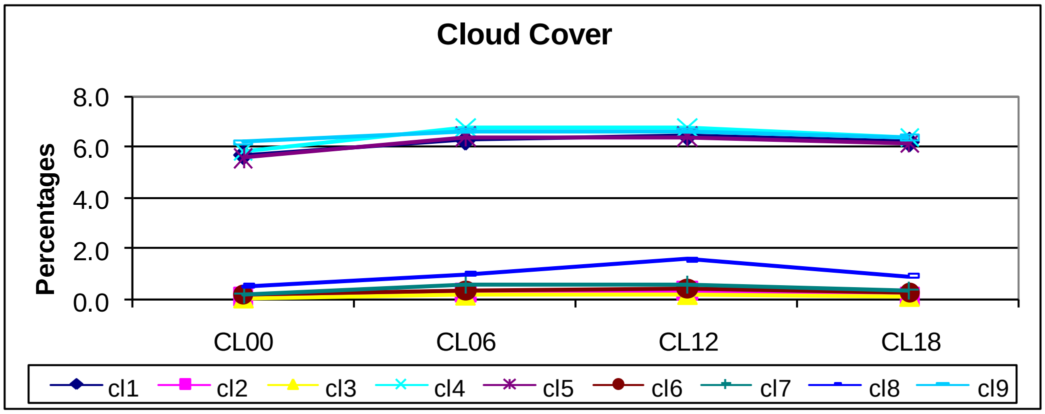

Fig. 9: Cloud cover in (oktas) in the nine surface synoptic types

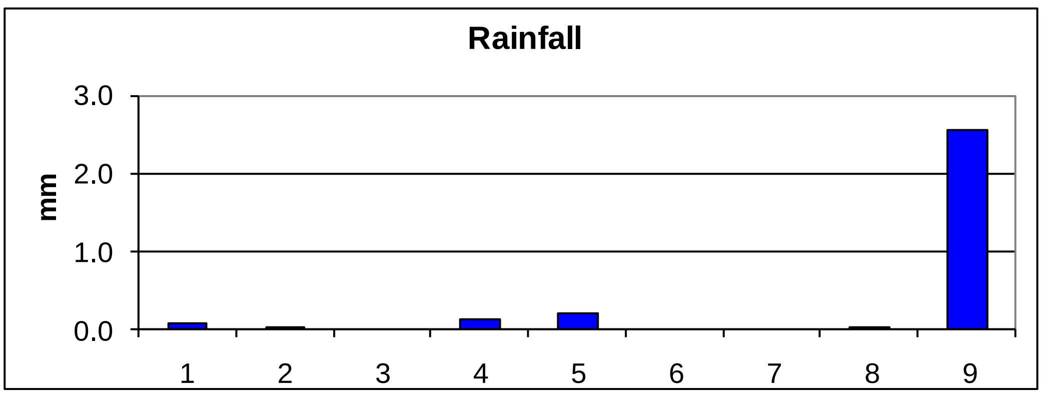

Fig. 10: Rainfall Averages in the nine surface types

Type 8

It appears in spring (April and May) and early summer in June; with the remarkable point in April. In comparison, it takes the same characteristics as in type 4. Wind flows from the northwest in the morning and at night while it reverses to northeast during the daylight. The temperature is very high; around 38°C in midday, suggested that type 8 is primarily a warm-season feature (figure 1). It is characterized as *clear, warm and almost calm, and defined as a warm-transition feature.*

Type 9

It is the most important type, because it is related with the rainy season in Khartoum area. It appears in July, August and September. It is most frequent in August. Wind blows in a counterclockwise direction known as monsoon wind and it is responsible for rainfall in Sudan. This wind blows inland from a southwest direction, it originates from the South Atlantic Ocean with moderate speed not more than 5 m/s (figure 3). Rainfall mechanisms over Sudan resulting in the Inter-Tropical Discontinuity Zone (herein, ITCZ) and it usually reaches its peak in August. In this type rainfall duration is about 121 rainy days (Figure 10). However, there are few days with maximum averages. For instance, two days are found namely, 29 July and 6 September 1995 with an average rainfall of about 45.2 and 45.9 mm respectively; and on 10 September 1996, there is the highest average about 57.3 mm; on 9 July and on 7 October 1997, there are two days with averages about 40.5 and 40.8 mm respectively. Finally, on the 1st September 1998 there is an average of rainfall about 44 mm.

This type coincides with the third rainy zone which lies in the southern part of the surface ITCZ and on the cyclonic shear side of the easterly jet. And it is described by its maximum rainfall in which squall lines are frequent and African waves activity is centered, much rainfall is associated with the passage of these lines. For these reasons, it is known as Rainfall Maoism type.

IV. CONCLUSION

The PCA results revealed six PC scores, which have been accounted with 72.03% of the total variance. The first PC-loading has documented the rainfall conditions. While the second one is showing a lack correlation with all variables since the goal of this study is to have small components with the highest variance; to be used in cluster analysis.

The temporal variability is summarized in the first two components-scores only. Noteworthy, the seasonal signals are well established in PC 1 and the event with consecutive occurrences appears in the second leading mode. Finally, nine surface synoptic types over the Khartoum area are classified. The nine types may be grouped according to the rainfall conditions. Group 1 includes type 1, 4, 5, and 9; these four types show a considerable amount of cloud cover and the moist wind blows in a SW direction, except for type 4, which has northwest direction even it is cloudy. Group 2 contains the remaining five types; all these types characterized by dry wind blowing either from the northwest or northeast direction, as in type 8 joins between these two winds.

Type 9 is the rainiest one; includes about three months with daily rainfall. These results corresponding with that found by Nicholson ,who broadly divided North African annual rainfall into zonally oriented belts with increasing convergence in rainfall from 50-100 cm along 10-15°N to 100-200 cm from 10 °N to the equator. And he cited that nearly 80% of the annual rainfall, over Sudan regions, is provided by the summer monsoon period during June to September. However, it is clearer from Figure (10) that the rainy period is less than six months during a decade of time, so this area is affected by the Sahara dry conditions rather than the tropical wet conditions.

As evidence, during the study period there are two years showed different synoptic situations, which were produced either wet or dry seasons. In 1994 the West Africa-Sahel zone-experienced one of the wettest years since the early 1960s whereas, however, in 1997 the Sudan experienced one of the famous recent drought years, resulting in low agricultural production, and affected millions of rural poor farmers, with series degradation of the environment

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