Macrothink Institute™

Environmental Management and Sustainable Development
ISSN 2164-7682
2014, Vol. 3, No. 2

Rainfall Analysis over Mauritius Using Principal Component Analysis

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Received: August 1, 2014 Accepted: August 19, 2014

doi:10.5296/emsd.v3i2.6290 URL: http://dx.doi.org/10.5296/emsd.v3i2.6290

Abstract

Principal Component Analysis (PCA) is one of the most popular dimensionality-reduction techniques used for the purpose of classification. It has gained popularity because of its ease of use and optimal nature in a mean square error sense. This paper focuses on an analysis of PCA as a classification tool for rainfall images. Rainfall maps were generated using monthly precipitation data from 226 stations over Mauritius for the years 1992 to 1995 and also for the mean monthly rainfall for the years 1961 to 1990. Three different methods of applying PCA were then used on the rainfall maps and each method generated principal components reflecting the relevant percentage of variability. To interpret these components, a study of the various rainfall bearing climate systems and the wind-field active in Mauritius proved to be necessary to enable their association of the most significant principal components. The effect of altitude on rainfall has been found to have most dominant effect on rainfall. Other climate systems such as the ITCZ, cyclones, anticyclones, cold fronts and the perturbation of easterlies were also found to have specific rainfall patterns associated with them.

Keywords: Rainfall, Principal Component Analysis, Climate Systems, Wind Regime

1. Introduction

The Republic of Mauritius is situated in the Indian Ocean with the main island, located at approximately 20 ^{0}S and 57 ^{0}E, about 1844 km^2 in size as shown in Figure 1. The island is roughly a main hill with a central plateau (caldera). The climate in general can be characterized as a pleasant moderate tropical climate with annual mean temperatures of about 22^0 C and normal annual rainfall of 2120 mm. Despite the small area of the island, there are substantial variations in rainfall as well as other climatic characteristics due to differences in elevation (Figure 2), distance from coast, windward-leeward locations apart from the influences from cold fronts, Inter Tropical Convergence Zone (ITCZ) and occasional storms (Padya, 1989). Two seasons are observed, namely, summer from November to April (warm and wet) and winter from May to October (cold and dry).

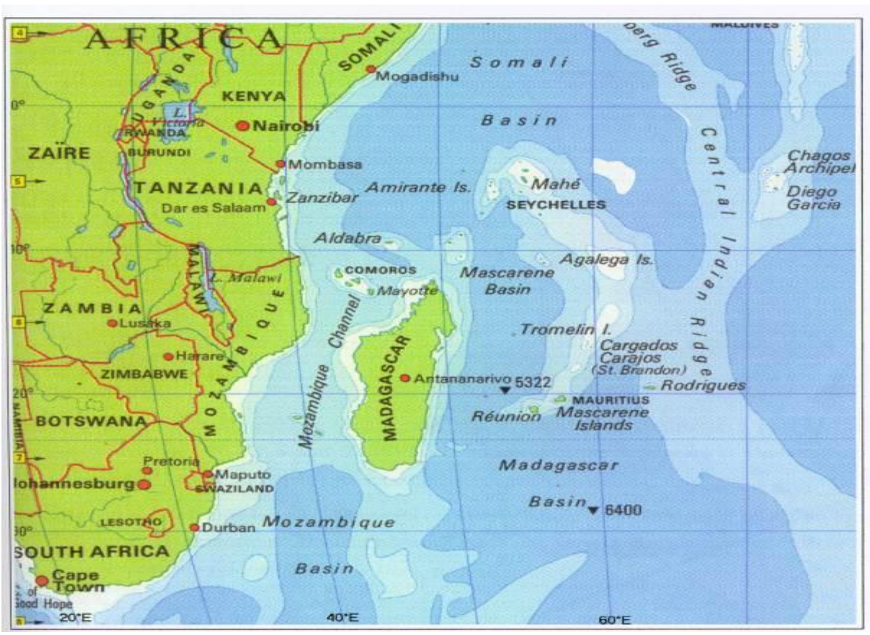

Figure 1. Location of Mauritius

The design and estimation of water systems and certain related agricultural development including agro-climatic suitability of potential crops in a particular country requires a thorough knowledge of rainfall distribution pattern since the latter varies sensitively with geographical locations and prevailing weather conditions. In this paper, PCA has been applied to rainfall data. The Surfer 8.0 software was used to make the contour maps while Matlab codes were written to carry out PCA. The main aim of this paper is to investigate whether the climate systems of Mauritius have significant contributions to rainfall over Mauritius. This enables the association of various rainfall patterns generated by applying PCA to particular climate systems. This technique has been widely applied in this field (Fernandez Mills, 1995, Singh, 2006, Liu et al., 2000). The paper is organized as follows: section 2 describes the weather system in Mauritius; section 3 gives a brief description on the theory of Principal Component Analysis; in section 4, we give a description of the methodology used in the paper. Section 5 presents the results and discussion and section 6 wraps up our concluding remarks.

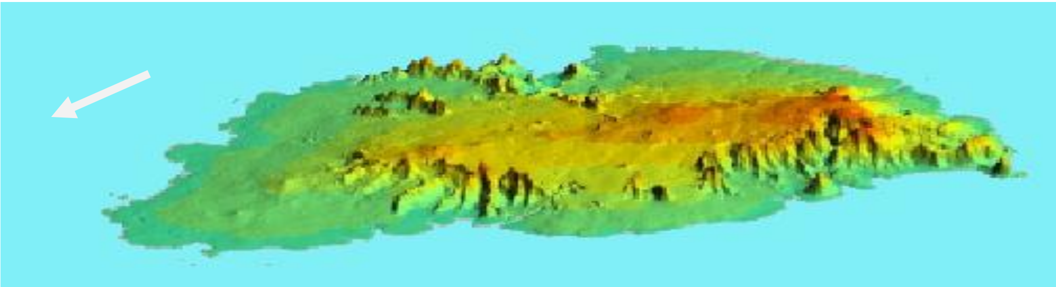

Figure 2. Elevation map of Mauritius with 3D perspective (arrow indicates North direction)

(Outermost green represents coastal areas and brown areas high grounds not exceeding 822 m)

2. Weather Systems in Mauritius

The monthly mean rainfall pattern for the years 1961 to 1990 is given in Figure 3. The northern part of Mauritius is characterized by dry months from August to October and wet months from November to April. The wet months account for about 70% of the mean annual rainfall. The western part shows the effect of depletion of water vapour on the windward slopes and the descent of the air on the leeward slopes. In fact, 78% of the rainfall in the west occurs in the summer months November to April while July to September are the driest. The eastern and the southern regions have fairly similar rainfall patterns as almost throughout the year they receive the oceanic air with its moisture content intact and benefit from the forced uplift resulting from its passage over the sloping lands and hills (Padya, 1989). Below, in sections 2.1 to 2.8, we describe various climate systems prevailing over Mauritius during a typical year with a typical synoptic chart for the region shown in Figure 4.

2.1 Windfield over Mauritius

Located at the edge of the tropics, Mauritius is as a rule within the belt of the trade winds. Mauritius is mainly dominated by two wind regimes: the South East Trade Winds (easterlies) and the North West Monsoon Winds (westerlies). On a few occasions, the westerlies occur mainly in the summer months when the ITCZ lies to the south of Mauritius. The months April to May are dominated mainly by Easterlies. By the end of June, the easterlies show an

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ISSN 2164-7682
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expansion southwards (Padya, 1989).

2.2 Cyclones

Cyclones generally spawn over the warm waters of the Indian Ocean between latitudes 5 °S and 10 °S in the summer months November to March and rarely in April. They move generally in the south-west directions with speeds attaining 20-25 km/h. On average, 2-2 cyclones will pass within 100 km from Mauritius annually.

2.3 Intertropical Convergence Zone (ITCZ)

The ITCZ is a meteorological boundary between the summer and winter hemispheres. It is also a boundary where the North West monsoon winds (westerlies) and the South East Trade winds (Easterlies) converge. There is very little transfer of mass and energy across the ITCZ in the atmosphere. The view generally held is that the ITCZ arranges itself in such a way that the thermal processes taking place in the atmosphere mostly achieve equilibrium on each side of it. The ITCZ affects the weather in Mauritius during its southerly seasonal migration in the summer months of January to February and sometimes in December and March as well.

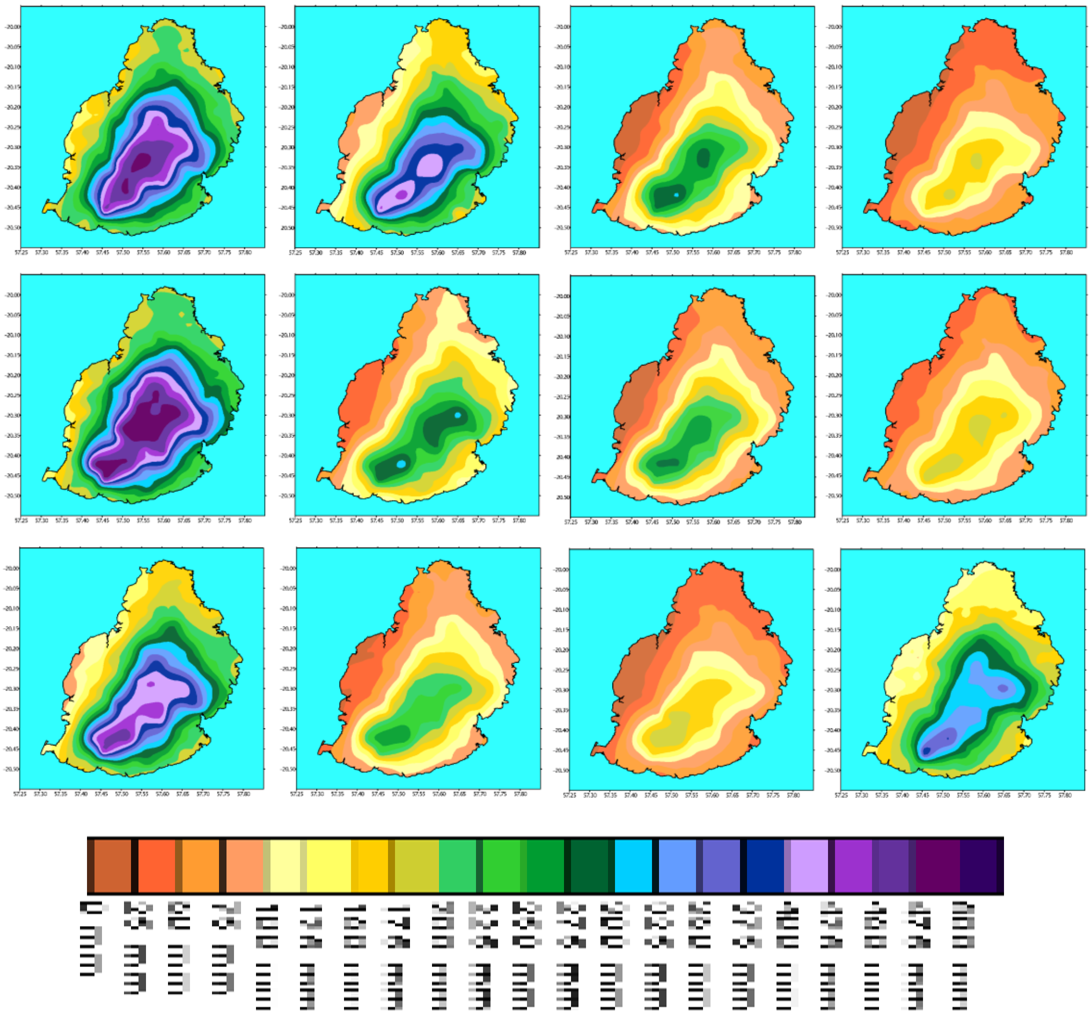


Figure 3. Long-term monthly mean rainfall pattern 1961-1990

2.4 Cold Fronts

In the southern Indian Ocean, two air-mass sources have been recognized, with boundary at around 45 °S on the average: the Maritime Tropical to the north over the warmer seas and the Maritime Polar over the cooler waters to the south of the Oceanic convergence. The boundary between the air masses themselves, as distinct from that between the source regions, is constantly moving. A general northward movement of the boundary between maritime polar and maritime tropical constitutes an active advancing cold front. Such outbreaks of colder air originating in the far south often reach Mauritius, except in the warmer part of summer.

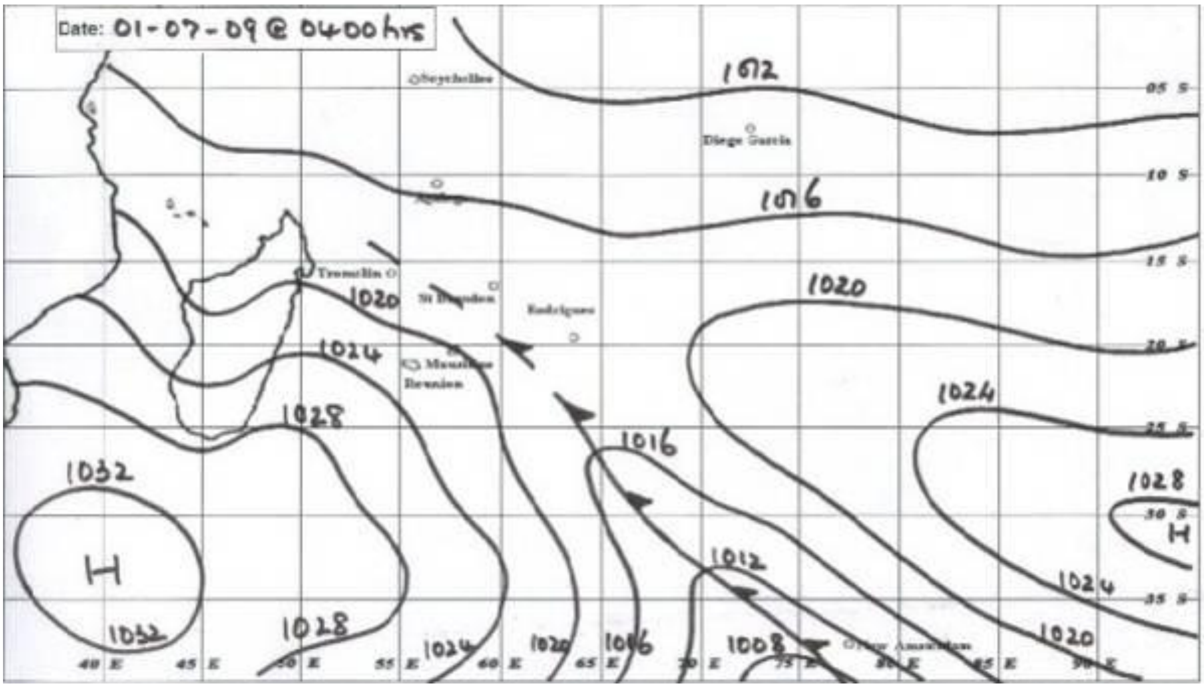


Figure 4. A typical synoptic chart for Mauritius (HPa)

2.5 Anticyclones

At the longitude of Mauritius, the sub-tropical belts of anticyclones are situated near 30 °S in winter, retracting pole-ward to about 35 °S in summer. The strongest anticyclones, which occur in winter, have central pressure exceeding 1040 HPa.

2.6 Sea Breeze

The classical explanation of the sea-breeze is that the heated land heats the layer of air close to the ground surface and causes the warm air to rise until its ascent and resulting expansion cools it sufficiently to destroy its buoyancy. As this process continues, there is formed, above the land surface, a deeper and deeper warm layer. There comes a stage when the temperature of the surface layers has risen sufficiently to produce a significantly higher pressure at some upper level over the land than over the sea. The pressure difference initiates a flow from land to sea in the upper levels. A reverse flow from the sea to the land takes place at the surface. In Mauritius, there is, as a rule, a "prevailing" east-south-east wind subject to its own synoptic space and time variation. Over the east and south coastal areas, therefore, the sea-breeze will help to accelerate the low-level trades and will also affect their direction. On the east, in particular, the sea-breeze is felt as a strengthening of the wind by mid-morning, which continues as long as the land is kept warmer than the sea by insolation. Sometimes the whole stretch of sloping land in the south and south-east from three to four kilometers inland to the centre of the island is shaded by clouds the whole day and precipitation is experienced.

2.7 Easterly Waves Perturbations in the Lower Troposphere

This kind of perturbation, sometimes giving rise to heavy rainfall over parts of Mauritius, can occur more frequently in summer, irrespective of the depth of the surface easterlies. Perturbations of the lower tropospheric easterlies, even when they are shallow, having a distinct wave-like character, are quite commonly encountered in the south-west Indian Ocean, between 70 °E and 50 °E, at the latitude of Mauritius. Their speeds are often of the order 5-8 ms^{-1}, i.e. close to the speed of the winds in the lower levels.

2.8 Cloud Masses and Upper Level Lows

Quite often the region of Mauritius and its neighbourhood experiences cloudy and rainy conditions without an identifiable synoptic system being detected. In such cases, the satellite pictures show the cloud systems to be a small patches of 2 degrees or so in diameter of a line of cloud with an almost meridional (north-south) orientation, or again a large mass ten degrees in width. These cloud masses may have varying degrees of activity. Some cases of heavy rainfall and active thunderstorms have occurred with these synoptically unexplained weather systems.

3. Principal Components Analysis

Principal Component Analysis (PCA) is a useful statistical technique that has found its application in many fields such as face recognition and image compression, and it is a common technique for finding patterns in data of high dimensions (Bedi and Bindra (1980); Bärring (1988); Overland and Preisendorfer (1982); Richman (1986)). It is a way of identifying patterns in data, and expressing the data in such a way so as to highlight their similarities and differences (Daultrey, 1976). Several factors that have led to the popularity of PCA include its simplicity, ease of use, as part of popular remote-sensing and statistical packages, and optimal nature in terms of mean square error (Preisendorfer, 1988). Some of the most commonly used remote-sensing software packages for data analysis and interpretation, such as ENVI™ (2002) and EMRAS IMAGINE™ (1999), use PCA for data analysis.

3.1 Overview of PCA

PCA transforms or projects the features from the original domain to a new domain (known as PCA domain) where the features are arranged in the order of their variance. The features in the transformed domain are formed by the linear combination of the original features and are uncorrelated. Dimensionality-reduction is achieved in the PCA domain by retaining only those features that contain a significant amount of information. Geometrically, this process can be looked upon as a rotation of the axes of the original vector space to form a set of orthogonal axes for the PCA space as illustrated in Figure 5.

3.2 Application of PCA to Images

We now outline the way in which PCA is applied to images; first showing how images are usually represented, and then showing how to apply PCA on images. An image is represented by an M x N matrix with each matrix value corresponding to a pixel intensity level. To apply PCA, the image matrix must be reshaped to a 1 x MN matrix, where the rows of the pixels in the image are placed one after the other so that a one-dimensional image is formed.

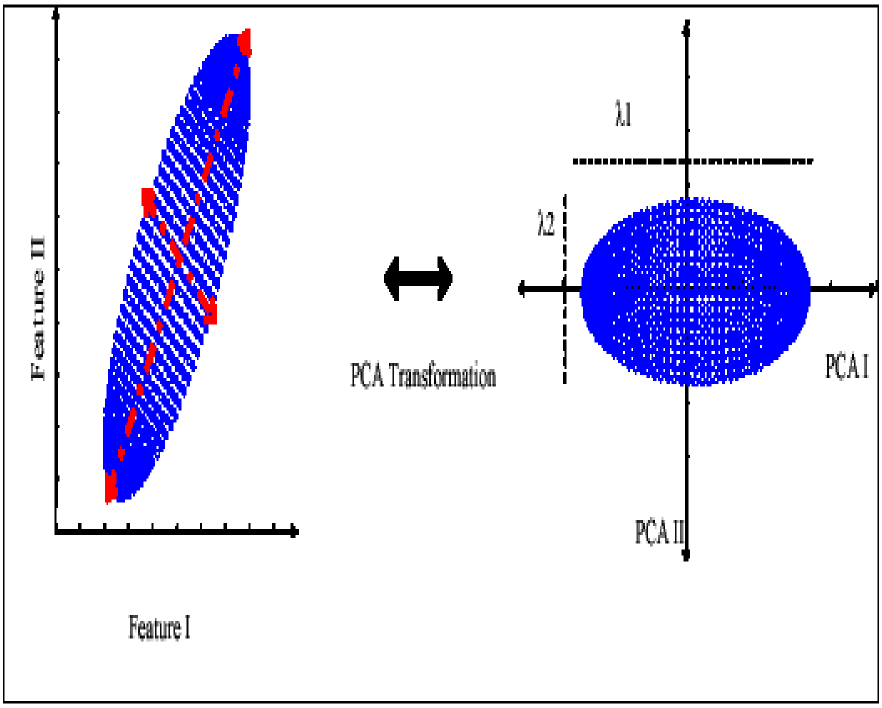
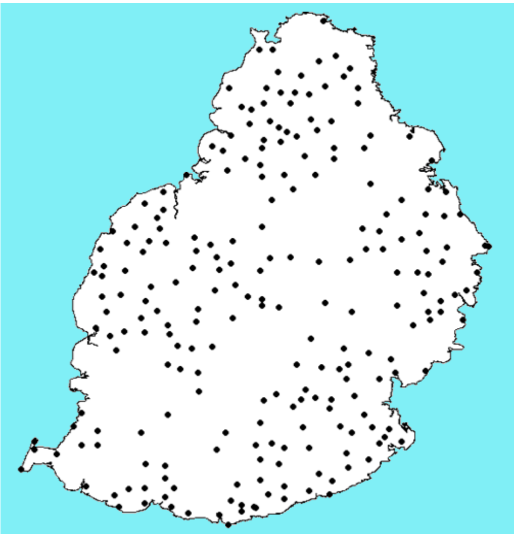


Figure 5. PCA space

4. Methodology

In this section, we focus on the methods of application of PCA on the available data by using relevant softwares. The data from 226 rainfall stations around Mauritius for the years 1992 to 1995 were used in our PCA analysis. We also consider the monthly normals for the period 1961 to 1990. The stations over the island are spread over the whole island (Figure 6). From this data, contour plots were generated using the Surfer™ 8.04 software. The rainfall levels have been normalized using the formula: $R_N = \ln(1 + 10R)$, where R_N is the normalised rainfall level and R is the original rainfall level in millimeters. The normalisation has been carried out so that, when a similar scale for rainfall level is used for all the images, they contain a reasonable amount of different grey level intensity as shown in Figure 7. The contour maps are then exported as bitmap images for processing in Matlab™ 6.5 software. Figure 8 shows a flowchart describing the various steps in implementing the PCA.



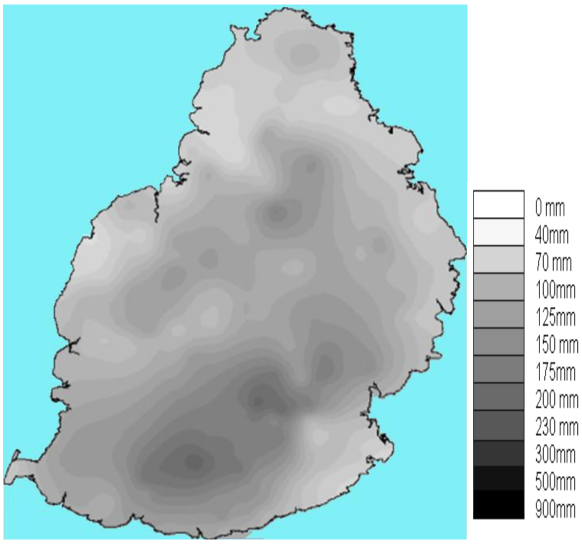


Figure 6 (left). Distribution of 226 rainfall stations over Mauritius

Figure 7 (right). Monthly rainfall pattern over Mauritius for January 1992

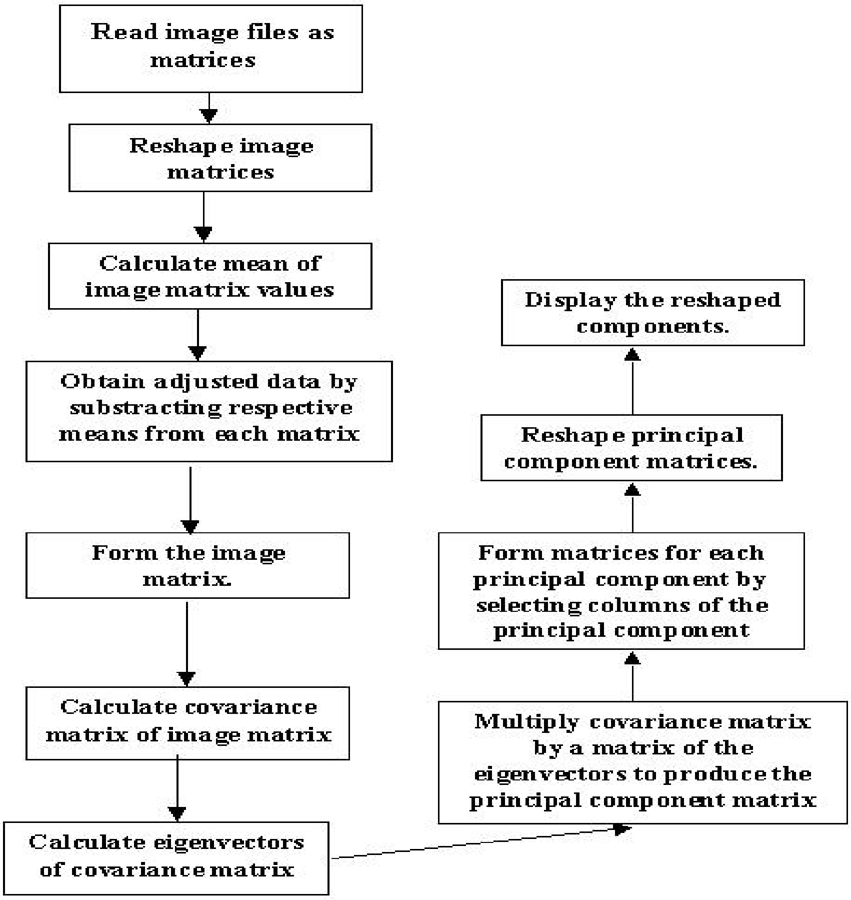


Figure 8. Flowchart of algorithm used to implement PCA

4.1 Method 1

The aim of method 1 is to identify the different climate systems operating in the different months throughout the year. In this method, the data of monthly precipitation for the years 1992 to 1995 were used. The method is illustrated by the flowchart in Figure 9; 48 images of rainfall maps (one for each month) were generated, the images were then divided in 12 groups according to the month and PCA was applied to each set.

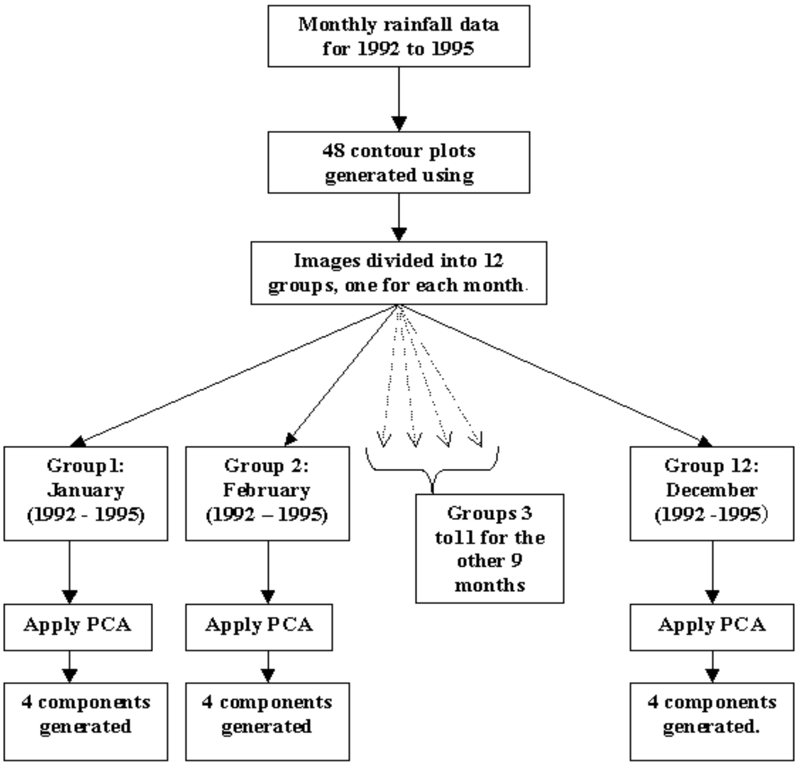


Figure 9. Flowchart describing method 1

4.2 Method 2

The aim of this method is to extract the most common rainfall patterns that affect the climate system in Mauritius. Data for the mean monthly rainfall for the period 1961 to 1990 were used. The method is illustrated by the flowchart in Figure 10.

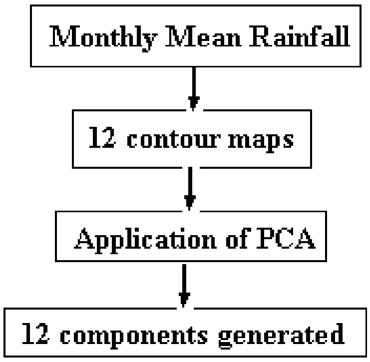


Figure 10. Flowchart describing method 2

4.3 Method 3

The aim of this method is to highlight the climate systems that have been most active during the years 1992-1995. This method is fairly similar to method 2 except that the data used is the monthly precipitation for the years 1992 – 1995. The method is illustrated in the flowchart in Figure 11 which uses the data for 1992; the process is repeated for the years 1993, 1994 and 1995.

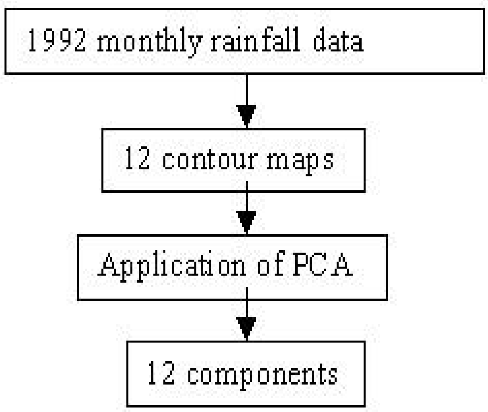


Figure 11. Flowchart describing method 3

5. Results & Discussions

5.1 Method 1

PCA has been applied on twelve sets of four images each (one for each month). The rainfall contour plots for the month of January, which is a typical summer month, for the years 1992 to 1995 are shown in Figure 12(a) while Figure 12(b) gives those for June which is a typical winter month. Method 1 allowed the assessment of the contribution of different climate systems to rainfall throughout the year. The first principal component of each set of results enabled to monitor the intensity of rainfall on the central plateau in the different months. PCA analysis of the full set reveals the following. The months February and March were found to be the rainiest while October and November the driest, consistent with observations. Moreover, the periods, during which Mauritius is dominated by different wind regimes, were found to have different rainfall patterns on the coasts. During the summer months, January to March, the effect of the westerlies and sea breeze were prominent. On the west and northwest coasts, the westerlies pushed the sea breeze further inland so that rainfall was found deeper into the island. On the east coast they prevented the entrance of the sea breeze, and therefore no precipitation occurred. Next, we compared the effect of cyclone and the ITCZ during the summer months and that of cold fronts and anticyclones during the winter months. In both cases, there was rainfall throughout the island but cyclones and the ITCZ brought much more intense falls.

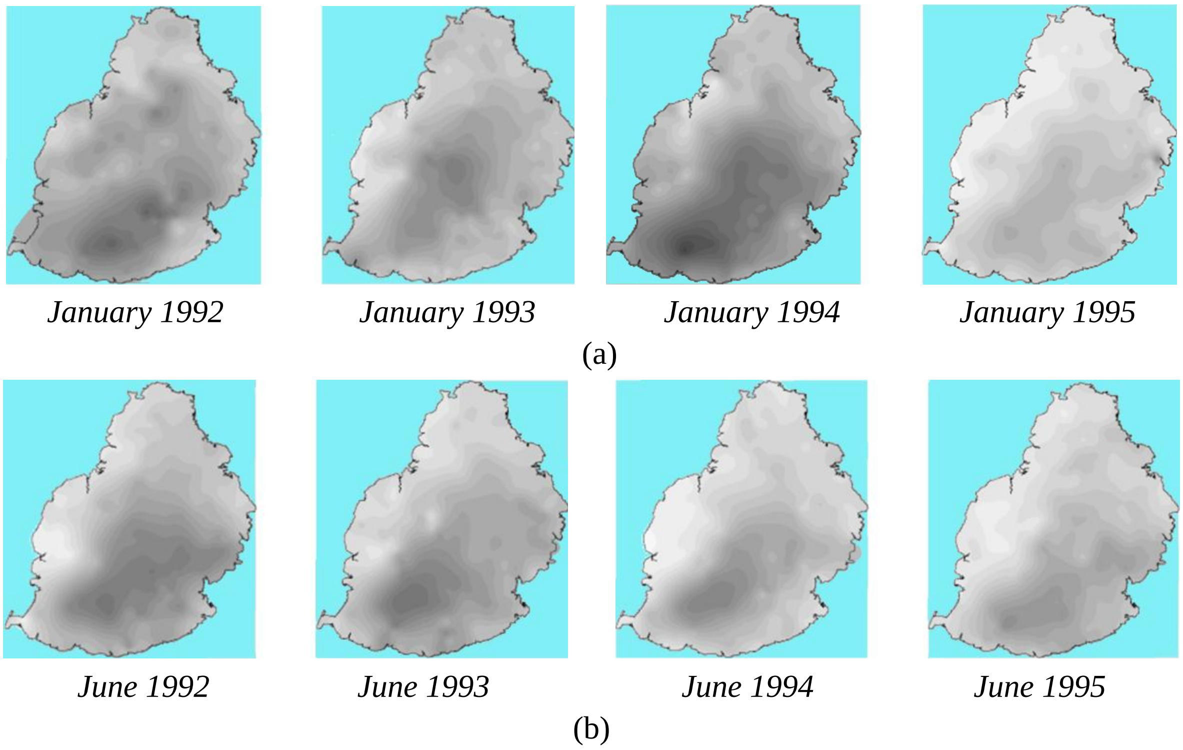


Figure 12. Contour plots for 1992 to 1995: January and (b) June

5.2 Method 2

Figure 13 focuses on the five principal components for the month of January only for illustration purposes. The first principal component clearly shows the dominance of the effect of altitude on rainfall. The other principal components revealed characteristics of the wind regime which are most common during the years. Component 2 showed the effect of easterlies and sea breeze on the west coast while component 3 that on the east coast. The fourth component demonstrated the effect of perturbation of easterlies in the north and on the south western part of the island. Usually thunderstorms result due to the perturbations and this causes considerable rainfall. The fifth component, which is the last one that has been retained, shows the effect of the expansion of the trades which is common by the end of June. Hence, for method 2, we can conclude that the application of PCA to long term monthly data effectively reveals the dominance of the rainfall dependence on the orography coupled with the effects of the directional impact of the windfields over Mauritius.

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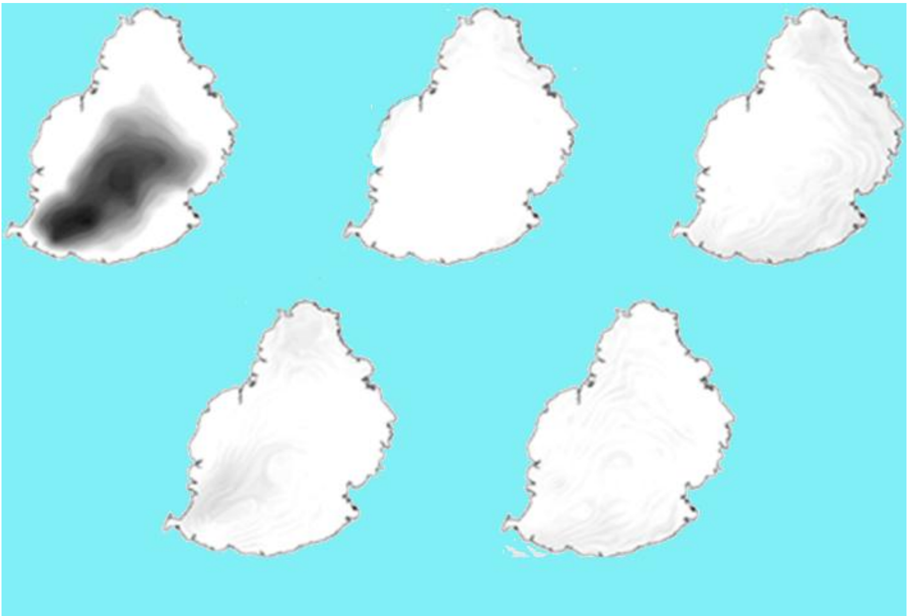

Figure 13. Principal components for the month of January

(with PC1 (96.3%), PC2 (2.0%), PC3 (0.52%), PC4 (0.18%) and PC5 (0.09%))

5.3 Method 3

Method 3 demonstrated which climate systems were most active in particular years as shown in Figure 14. In this way, in 1992, the ITCZ was found to be particularly active. Its effect combined with the effect of cyclone can be observed in the second principal component which shows considerable rainfall throughout the island. The effect of the ITCZ on the west coast is observed in the third principal component. The fourth component reveals the fact that the easterlies were weak during the year while the fifth one shows the effect of perturbation of the easterlies in the north.

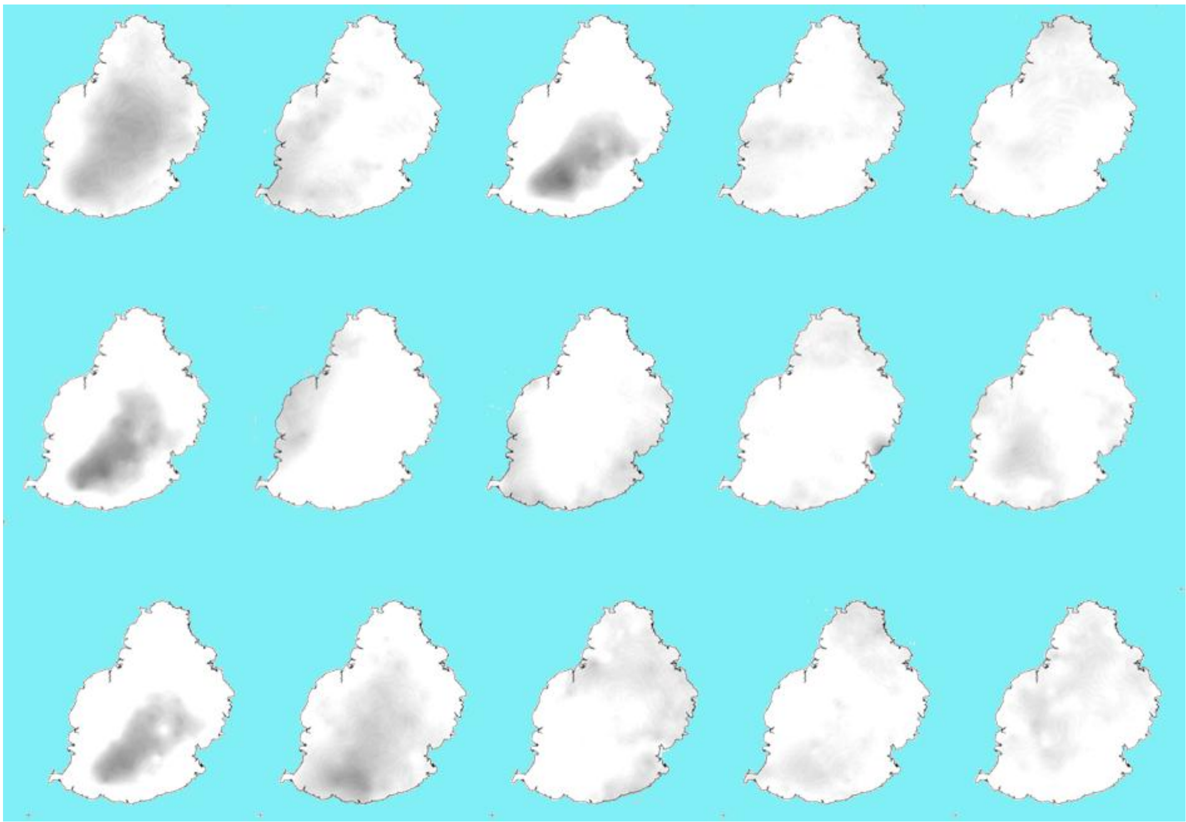

Figure 14. Principal components for years 1992-1994 (from top to bottom)

1992 with PC1 (96.68%), PC2 (1.9%), PC3 (0.36%), PC4 (0.29%) and PC5 (0.21%)

1993 with PC1 (95.83%), PC2 (1.99%), PC3 (0.87%), PC4 (0.44%) and PC5 (0.25%)

1994 with PC1 (97.06%), PC2 (1.21%), PC3 (0.64%), PC4 (0.33%) and PC5 (0.22%)

The year 1993 was one where cyclones were not very active. The components obtained reveal mainly the effect of the easterlies, westerlies and the sea breeze. For the year 1994 the second component shows the effect of cyclone on rainfall; Mauritius was visited by cyclone Hollanda in February of that year. The third component shows the effect of the 1994 easterlies. The results obtained for 1994 are quite similar to that of 1993 except that the third component reveals the expansion of the easterlies southwards which occur by the end of June.

6. Conclusions

The paper focused in investigating PCA as a classification method. Three different methods of applying PCA to rainfall images were investigated. PCA effectively decomposed the impact of the different rainfall bearing climate systems into components so that the spatial extent of their effects were localized. The effect of altitude on rainfall was found to be the most dominant effect according to all the three methods used. The ITCZ and cyclones were seen as the climate systems bringing most rainfall to the island. Cold fronts, anticyclones and perturbation of easterlies were also identified as having specific rainfall patterns associated with them. We therefore, conclude that the application of PCA to rainfall images has turned out to be a very fruitful and promising technique. From the results obtained we may conclude that the three methods used have been useful in:

- Identifying the major climate systems affecting rainfall in Mauritius.
- Identifying the period during the year in which the climate systems are most active
- Identifying the years for which the influence of the climate systems were greater.
- Showing the spatial extent to which the climate systems bring rainfall and the intensity of rainfall brought.
- Providing images useful for estimating the amount of rainfall over different regions and thus identifying the dry and wet regions.
- Understanding the effect of the active different rain-bearing wind regimes over the island.

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