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FUZZY AUTOCATALYTIC SET FOR ANALYSIS OF CLIMATE PATTERNS AND THEIR REGIONAL VARIABILITY

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ABSTRACT

Over the past few decades, climate change and global warming have become serious global issues. In Malaysia particularly, the trends of climate patterns, especially rainfall and temperature have shown extreme changes, which causes floods and heat waves. The extreme climate events have caused economic losses and harmful health effects. Thus, there is a crucial need in analyzing and understanding the climate patterns for proper climate action. This study introduces a dynamic fuzzy graph algorithm, to analyze the rainfall and temperature patterns across 14 different states in Malaysia, from 2010 - 2022. The fuzzy graph is a sophisticated mathematical method that could handle complexities and uncertainties arise from the unpredictable nature of climatic events. The data is modeled in the form of dynamic fuzzy graph and further analyzed using the algorithm developed in MATLAB software. As a result, clusters of patterns are observed in the fuzzy graph coordinated plot, which illustrate the severity of the climate and weather changes of the region and states. Kelantan, Pahang and Sabah show high severity of rainfall distributions, meanwhile, Perak, Negeri Sembilan, Kelantan, Kedah and Sarawak are in the high-severity zone for temperature analysis. The results are compared with a statistical method, namely kernel principal component analysis (kPCA) for verification. The dynamic fuzzy graph algorithm offers an alternative for analysis involving complex and large climate datasets. The dynamics and relations of climate patterns across different regions are able to be identified, which is crucial for effective climate actions.

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1. INTRODUCTION

In recent decades, the increasing threat of climate change and global warming have become a serious global issue. According to Abbas et al. [1], climate change refers to the shifting of climate patterns and trends for a certain period of time. Climate patterns comprise the trends and changes in temperature, rainfall, pressure and humidity. Over the past few years, the trends of climate or weather patterns, particularly temperature and rainfall have shown extreme changes and caused extreme climate events such as drought, heat waves, storms, and floods. Numerous factors within the climate systems contribute to the change in climate patterns. According to Turrentine [2], human activities are the major cause for the changes in climate pattern, in which 48% of the carbon dioxide ($CO2$) in the atmosphere originates from human activities. The increase of $CO2$ is driven by the advancement of technology and the Industrial Revolution (IR), particularly in developed and developing countries, due to their high energy production and well-established industrial sectors [3].

In addition, the temperature and precipitation patterns may differ in the areas surrounded by mountains and forests. Moreover, the regions at subduction zones have greater risk of facing volcanic eruptions [4] [5]. Changes in climate patterns and extreme weather events could disrupt the economies and business, cause damage to infrastructure, and increase health risk factors and spread of diseases [1]. According to Daniele [6], the extreme floods disaster in Malaysia in December 2021 had caused financial losses of 6.1 billion ringgit (US$1.3 billion) and caused infrastructure and agricultural damage. Additionally, according to Mazlan et al. [7], the extreme rainfall and floods, particularly in Terengganu, Malaysia, had become severe over the past 40 years, and resulted in the displacement of people and economic loss of almost RM46.4 million in 2022. Meanwhile, extreme and rising temperatures could cause heat waves which lead to heat-related illness such as heat stroke that can cause death [8]. Thus, the issues of changes in climate patterns and extreme weather events are alarming, particularly in Malaysia whereby heavy rainfalls and floods have resulted in severe financial loss and infrastructure damage. Moreover, several reports on rise in temperature and heat stroke cases have been reported over the past few years. By the 2090s, Malaysia is expected to face a rise of 3.11 degrees Celsius above pre-industrial levels, surpassing the 1.5 degrees Celsius set in the Paris Agreement [9]. Therefore, understanding climate patterns is crucial for proper climate action and mitigation strategies.

Numerous researchers have studied the climate patterns in Malaysia using diverse methods. Tan et al. [10] used Mann-Kendall test to investigate the trend of extreme temperature in Malaysia. As a result, the trend in major cities in the northern and western parts of Peninsular Malaysia showed higher intensities of temperature due to the accelerated urbanization. Munawar et al. [11] utilized the cubic spline method and a multivariate regression model to investigate the land surface temperature in Borneo. Their results showed that Sarawak has a significant increase in temperature compared to Sabah. Muhammad et al. [12] applied Sen's slope trend test for trend and pattern analysis of heat waves in Malaysia. Their findings showed that the northern region experiences more heat waves, and the southwest region is also becoming prone to severe heat waves due to rising global temperature. Furthermore, several researchers also studied the trend and rainfall patterns in Malaysia. Mazelan and Suhaila [13] employed functional data analysis to investigate the variations and patterns of rainfall in Peninsular Malaysia. Both their findings showed that eastern regions in Malaysia have high rainfall intensity, especially during the northeast monsoon season. Faizal and Ismail [14] and Miniandi et al. [15] utilized Mann-Kendall test to investigate the rainfall trend in Malaysia's east coast region and Kuala Lumpur, respectively. Results by Faizal and Ismail [14] showed a significantly increasing trend at few areas in Pahang and Terengganu, meanwhile Miniandi et al. [15] revealed that urbanization had increased Kuala Lumpur's trends of extreme rainfall. Subramanian et al. [16] studied the rainfall and surface temperature patterns in Malaysia using Support Vector Regression (SVR), Random Forest Regression (RFR) and Linear Regression (LR). Their results showed Malaysia is having significant increase in temperatures and unpredictability of rainfall, which impact agricultural activities. Othman et al. [17] also analyzed the impact of climate change, rainfall and temperature shifts, particularly on tourism sector in Malaysia. They used autoregressive distributed lag (ARDL) technique to examine the impact and relationship between the climate variables. Their results showed that climate shifts have a long-term impact on tourism receipts. These researchers utilized the statistical analysis of regression and Mann-Kendall test to study the factors, trends and impact of climate change and variability. However, their analyses only provide numerical results and summaries of the significant trend, and lack of visualization of the pattern and classifications. Data visualization and classification analysis are crucial in providing a more insightful and clear classification of severity of the weather changes at specific locations.

Comprehensive analysis of climate patterns requires reliable and robust analytical tools to handle the uncertainties and analyze their complex dataset. The complexities and uncertainties within climate data arise from the unpredictable nature of climatic events such as rainfall's unpredictable behavior, which is influenced by extreme events and localized phenomena [18]. Temperature and rainfall are highly uncertain because of their sensitivity to external forcing and measurement limitations [19]. Addressing these uncertainties is crucial for accurate climate modeling. Therefore, a mathematical method that is able to interpret and provide thorough analysis on the dynamics and patterns of the climate system is required, particularly of temperature and rainfall. Existing literature notably lacking in addressing the climate patterns of all states in Malaysia, and most of the researchers applied statistical methods but no studies incorporating fuzzy set theory were discovered. Hence this research serves to bridge the gap in knowledge through comprehensive analysis by delving into unexplored areas of climate variability within Malaysian context, using a fuzzy graph algorithm. The fuzzy graph algorithm also able to handle uncertainties arise, by introducing computations of fuzzy values conversion. According to Honna [20], fuzzy set theory demonstrates an effective modelling compared to crisp method. Additionally, fuzzy coordinated plot is also introduced to display clusters of the dataset, for clear classification of the samples according to their characteristics. The dynamic fuzzy graph, namely fuzzy autocatalytic set algorithm for climate variability, is developed to analyze the pattern of temperature and rainfall in 14 states in Malaysia. The fuzzy autocatalytic set was first introduced by Ahmad et al. [21] to model a waste incineration system in the form of fuzzy graph plot. Their paper was able to identify the most significant depleted vertices and variables from the waste incineration system. However, their results were computed manually, without proper algorithm for coordinated vertices plot using mathematical software. In this paper, the fuzzy autocatalytic set method is modified, and an algorithm is developed for climate variability analysis, in particular for classification analysis of temperature and rainfall patterns in Malaysia. The results are then compared with kernel principal component analysis (k-PCA) for validation. The principal component analysis (PCA) is an established statistical analysis that has been used in numerous visualization analysis. The k-PCA is an extension of PCA that captures and allows nonlinear relationships in data and thus is appropriate for validating the fuzzy graph results.

2. RESEARCH METHODS

2.1 Study Areas and Data Collection

Malaysia is a country located in Southeast Asia. The country consists of Peninsular Malaysia and Northern Borneo or East Malaysia [22]. Malaysia comprises 14 states which are Johor, Kedah, Kelantan, Malacca, Negeri Sembilan, Pahang, Penang, Perak, Perlis, Selangor, Terengganu, Sabah, Sarawak and Federal Territory (Kuala Lumpur, Putrajaya and Labuan). The map of Malaysia is shown in Fig. 1.

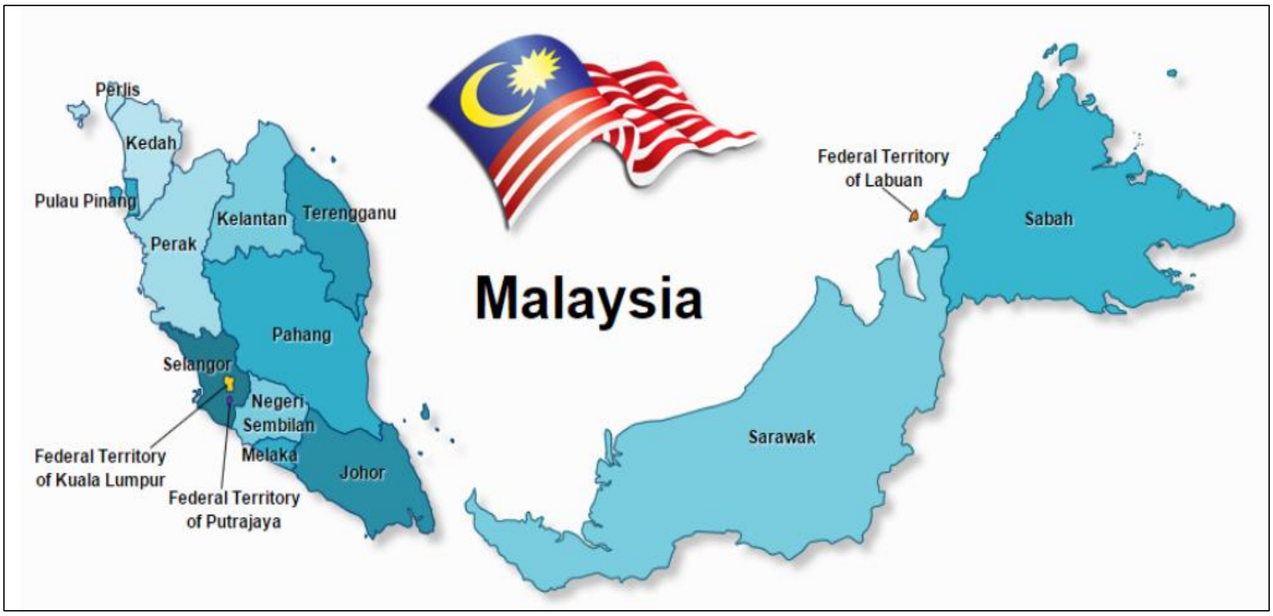

Figure 1. The Map of Malaysia [23]

Malaysia has an equatorial climate, and experiences warm and humid weather throughout the year [24]. According to the Malaysian Meteorological Department [25] , the average daily temperature in Malaysia is ranging from 21 - 32 degree Celsius. Meanwhile, rainfall distribution varies according to monsoon seasons. Southwest monsoon occurs in May to September; meanwhile northern monsoon happens in October to March [26]. During the southwest monsoon, most areas in Malaysia experience warm weather and lesser rainfall, while rainstorms and heavy rainfall occur in most areas and cause major flood events. In particular, the daily temperatures and rainfall patterns in recent years have shifted over time due to climate change [26]. Deforestation, urbanization, industrialization as well as the natural phenomena of El-Niño are among the key factors affecting the changes in climate patterns in Malaysia, thus increasing the vulnerability to floods, droughts and heat waves. Given its exposure to climate risks and commitment for climate action, there is a need for climate research in Malaysia to address the climate challenges. Therefore, this research focuses on analyzing the temperature and rainfall patterns in 14 states (13 states and 1 federal territory of Kuala Lumpur) in Malaysia from the year of 2010 - 2022. The daily temperature and rainfall distribution data are obtained from the Department of Statistics Malaysia. The data collection period is in accordance with the alarming climate change rate by the World Meteorological Organization [27].

2.2 Fuzzy Graph Method

The fuzzy graph method is a merge of fuzzy set theory and graph theory concepts. Fuzzy set theory was introduced by Zadeh [28] to characterize the uncertainty in real-world problems, especially complex and big datasets, in the form of fuzzy numbers.

Definition 1. [28] *Fuzzy set, A in X, where X is a space of objects or points* $x \in X$*, is characterized by membership function* $f_A(x)$*, that assigned each point with real number [0,1].*

The membership values are range from 0 to 1, which characterizes the strength and significance of the elements in a system. The graph theory concept is a representation of systems in the form of vertices and edges. It was first introduced by Leonhard Euler in 1735, to solve the Konigsberg bridge problem [29]. In 2010, Ahmad et al. [21] introduced fuzzy autocatalytic set (FACS), to model a waste incineration system in the form of fuzzy dynamic graph. The FACS method is a combination of fuzzy graph and autocatalytic set (ACS) concepts. Autocatalytic set (ACS) was initially introduced by Jain and Krishna [30], to model the dynamic and catalysis of each element. Ahmad et al.[21] then introduced the membership value of (0, 1], which indicates the existence of incoming link for autocatalytic behavior, and the value must not be zero.

Definition 2. [21] *Fuzzy graph,* $G = (\sigma, \mu)$*, where* $\sigma: S \to [0,1]$ *and* $\mu: S \times S \to [0,1]$*, and for all* $x, y \in S$*, there exist* $\mu(x, y) \leq \sigma(x) \times \sigma(x)$*, where S is a set of objects.*

Definition 3. [30] *Autocatalytic set (ACS) is a subgraph where every vertex has at least one inward edge from other vertex in similar subgraph.*

Definition 4. [21] *Fuzzy autocatalytic set (FACS) is a subgraph where the nodes have at least one inward edge with characteristic value of* $\mu(e_i) \in (0,1]$.

The FACS method is crucial for interpretation and identification of the depleted sequence of chemicals during the incineration process. Since then, the ACS and FACS methods have been applied in numerous researches involving the modeling of dynamic systems and irregular datasets, such as electroencephalography (EEG) signal during seizure [31] and pressurized water reactor system [32]. The graph theory technique, in combination with fuzzy set theory, has been proven to be useful in modeling the complex system and handling the uncertainties. However, with the current advancement of technology and vast amounts of data, a more sophisticated algorithm with the aid of software is required, in assisting the big data analytics of complex processes and systems thoroughly. Hence, in this paper, the FACS method is modified and an algorithm for dynamic fuzzy graph is constructed, particularly in modeling and analyzing the vast climate dataset, for pattern and classification analyses. This research aims to bridge the gap between the complex dynamics of climate data through big data driven analysis using fuzzy graph techniques. The fuzzy graph algorithm is established and seeks to capture the inherent fuzziness and complex dynamics of climate variability, providing a more comprehensive understanding and analysis for effective decision making and climate adaptation strategies.

The fuzzy graph algorithm adapts the concept of fuzzy autocatalytic set, in combination with the Laplacian matrices and Conjugate gradient method, to model and analyze the complex and vast temperature and rainfall data in a form of fuzzy graph and its matrix, efficiently using MATLAB software. A conversion to dynamic fuzzy value is introduced in the algorithm, to assign the fuzzy value at each vertex. The algorithm is called dynamic fuzzy graph algorithm and depicted as follows:

Algorithm 1. Dynamic Fuzzy Graph Algorithm

Input: Temperature and rainfall data (Dataset in .xlsx format).
Output: Coordinated plot in Euclidean space.

1: Select the dataset as input of the system.
2: Convert the values in the dataset to dynamic fuzzy values, $\mu(v_i)$ for every vertices, v_i for $i = 1,2,3, \dots, n$:

$$\mu(v_i) = \begin{cases} 0, & \text{if } d_i < 0 \\ 1, & \text{if } \max(d_i) \; for \; i \in N \\ \dfrac{d_i}{\max(d_i)}, & \text{others} \end{cases}$$

where d_i is the data for $i = 1,2,3, \dots, n$. Other possible interferences, impurities and negative values are assigned as 0, since fuzzy membership values are restricted from 0 to 1.

3: Construct a square matrix whereby the entries are the fuzzy values obtained from (2)
4: Compute the transition and Laplacian matrices to determine the *x* and *y*-coordinates. The *x*-coordinates are obtained from the Fiedler vector of Laplacian, while the *y*-coordinates are obtained from the solution of $Ly = b$ using conjugate gradient method, where b is balance vector $b = (b_1, \dots, b_n)$ such that $b_i = \sum_{j=1}^{n} \mu_{ij} - \sum_{j=1}^{n} \mu_{ji}$:
4.1: Initialize $x_0 = b$
4.2: Compute $r_0 = b - A\, x_0$, where A is the fuzzy matrices.
4.3: Set $p_0 = r_0$
4.4: For k=0,1,2,…
4.4.1: Compute $\alpha_k = \frac{r_k^T r_k}{p_k^T A\, p_k}$
4.4.2: Update $x_{\{k+1\}} = x_k + \alpha_k p_k$
4.4.3: Compute $r_{\{k+1\}} = r_k - \alpha_k A\, p_k$
4.4.4: Compute $\beta_{\{k+1\}} = \frac{r_{\{k+1\}}^T r_{\{k+1\}}}{r_k^T r_k}$
4.4.5: Update $p_{\{k+1\}} = r_{\{k+1\}} + \beta_{\{k+1\}p_k}$. The results are assigned as *y*-coordinates.

5: Plot the x and y-coordinates in Euclidean space for data visualization analysis.
6: Repeat step 1 until 5 for each system

A novel feature in the graph model, namely impurities, is introduced as hollow vertex to complete the dynamic and catalytic relations in the graph, considering possibilities of interferences or noise that may affect the data that has been measured. The dynamic fuzzy graph algorithm is then performed on the fuzzy graph model using MATLAB software version 2023a (Mathworks, Natick, MA). The algorithm then converts the data into fuzzy values, ranging from 0 to 1. The constructed fuzzy values are then arranged in a form matrix and further computed using a conjugate gradient method, to obtain coordinates. The coordinated vertices of the fuzzy graph are obtained and plotted in Euclidean space, for pattern and classification analyses of the systems. The results and performance of the technique are compared with a statistical method called kernel principal component analysis (kPCA), to verify its reliability and efficiency. The results of the fuzzy graph method are displayed in the form of coordinated plot, while kPCA displayed the results in the form of kPCA plot.

2.3 Kernel Principal Component Analysis

The kernel principal component analysis (kPCA) is an extension of the classic principal component analysis (PCA) method, that allows for the capture on nonlinear relationships in data.

Definition 5. [33] *Principal component analysis (PCA) transforms original data into new dimensions whereby the new variables are arranged as linear combinations of the original variables.*

Definition 6. [33] *Kernel principal component analysis (kPCA) introduces nonlinearity by mapping the original input space to higher dimensional space, B using a nonlinear map* $\omega: A^n \to B$, *where A is real number set and n is the input feature dimension.*

The kPCA incorporates kernel functions to map the original dataset into a higher – dimensional feature space [33]. According to Zhang et al. [34], the kPCA method identifies the leading eigenvectors and their associated eigenvalues within the feature space, which is crucial to determine the dominant patterns in the dataset. This enables the capture of nonlinear patterns that are often missed by PCA, which assumes a linear relationship between variables. The patterns could reveal the presence of clusters that are embedded within complex data structure [35]. Several researchers have applied kPCA for data analysis, to observe clusters and patterns across different datasets. However, only limited studies have focused on climate analysis. Tripathy et al. [36] and Shaw et al [33] applied kPCA to discriminate black tea samples and ethanol concentrations respectively. Their results are able to show that kernel approach is reliable for clustering. Islam et al. [37] utilized kPCA to classify Density of States (DOS) of transition metal sulfide. Their results are able to group materials based on their crystal structures. Moreover, significant deviations are observed for specific compounds such as Nb_2CuS_4, and VCu_3S_4. The study is able to prove that kPCA outperforming PCA and stochastic techniques such as t-SNE or UMAP, since it does not require pre-labeling. Hence, in this study, the kPCA method is performed on the dataset of temperature and rainfall in Malaysia, using R 4.5.1 software. The results in the kPCA plot are then compared with the results of the dynamic fuzzy graph for verification purposes.

3. RESULTS AND DISCUSSION

The 14 states of Malaysia are modeled in a form of dynamic fuzzy graph (see Fig. 2). The vertices $V = \{v_1, v_2, v_3, \dots, v_{14}\}$ represent the states whereby v_1 is Johor, v_2 is Kedah, v_3 is Kelantan, v_4 is Malacca, v_5 is Pahang, v_6 is Perak, v_7 is Perlis, v_8 is Penang, v_9 is Sabah, v_{10} is Sarawak, v_{11} is Kuala Lumpur, v_{12} is Selangor, v_{13} is Terengganu, and v_{14} is Negeri Sembilan. Meanwhile the edges $E = \{e_1, e_2, e_3, \dots, e_{14}\}$ represent the network and route between the states and the impurities represent the noise and irregularities of the data.

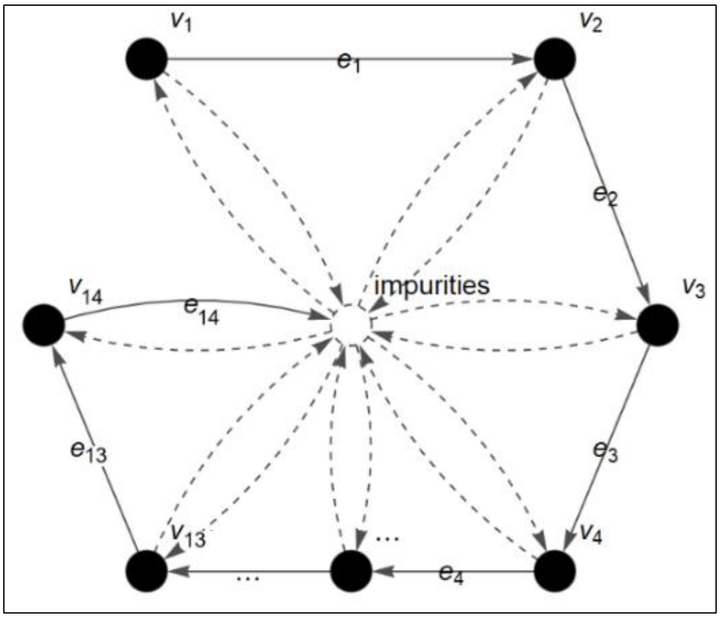

Figure 2. A Dynamic Fuzzy Graph Model of 14 States in Malaysia

The graph then is transformed into a matrix form where the temperature and rainfall data are each converted into fuzzy values and described as the entries of the matrix. The conversion to matrix form and further analysis of the data are performed using the dynamic fuzzy graph algorithm in MATLAB software. The fuzzy matrices of temperature data for each state in Malaysia generated from the algorithm are as follows, and 0 is added as entries to complete the square matrix:

$$\text{Johor: } \begin{pmatrix} 0.9686 & 0.9634 & 0.9634 & 0.9791 \\ 0.9721 & 0.9791 & 1.0000 & 0.9791 \\ 0.9738 & 0.9895 & 0.9878 & 0.9773 \\ 0.9791 & 0 & 0 & 0 \end{pmatrix}$$

$$\text{Kedah:}\begin{pmatrix}1.0000 & 0.9776 & 0.9759 & 0.9793\\ 0.9811 & 0.9897 & 1.0000 & 0.9707\\ 0.9862 & 0.9948 & 0.9862 & 0.9725\\ 0.9690 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Kelantan:}\begin{pmatrix}0.8536 & 0.9665 & 0.9718 & 0.9735\\ 0.9718 & 0.9877 & 1.0000 & 0.9735\\ 0.9806 & 0.9947 & 0.9912 & 0.9788\\ 0.9718 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Malacca:}\begin{pmatrix}0.9792 & 0.9653 & 0.9636 & 0.9757\\ 0.9775 & 0.9861 & 1.0000 & 0.9237\\ 0.9705 & 0.9879 & 0.9757 & 0.9671\\ 0.9671 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Pahang:}\begin{pmatrix}0.9912 & 0.9701 & 0.9701 & 0.9824\\ 0.9859 & 0.9912 & 1.0000 & 0.9824\\ 0.9842 & 0.9912 & 0.9930 & 0.9824\\ 0.9806 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Perak:}\begin{pmatrix}0.9726 & 0.9590 & 0.9709 & 0.9709\\ 0.9744 & 0.9778 & 1.0000 & 0.9709\\ 0.9658 & 0.9863 & 0.9795 & 0.9692\\ 0.9778 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Perlis:}\begin{pmatrix}0.9829 & 0.9624 & 0.9675 & 0.9709\\ 0.9812 & 0.9846 & 1.0000 & 0.9863\\ 0.9897 & 0.9846 & 0.9829 & 0.9726\\ 0.9744 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Penang:}\begin{pmatrix}0.9845 & 0.9656 & 0.9691 & 0.9828\\ 0.9845 & 0.9674 & 0.9777 & 0.9777\\ 0.9845 & 1.0000 & 0.9897 & 0.9811\\ 0.9914 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Sabah:}\begin{pmatrix}0.9776 & 0.9707 & 0.9741 & 0.9741\\ 0.9759 & 0.9897 & 1.0000 & 0.9724\\ 0.9879 & 0.9879 & 0.9741 & 0.9638\\ 0.9603 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Sarawak:}\begin{pmatrix}0.9753 & 0.9717 & 0.9876 & 0.9876\\ 0.9876 & 0.9876 & 0.9982 & 0.9912\\ 0.9912 & 1.0000 & 0.9894 & 0.9823\\ 0.9788 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Kuala Lumpur:}\begin{pmatrix}0.9757 & 0.9671 & 0.9723 & 0.9827\\ 0.9861 & 0.9896 & 0.9913 & 0.9601\\ 0.9879 & 1.0000 & 0.9931 & 0.9792\\ 0.9792 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Selangor:}\begin{pmatrix}0.9680 & 0.9747 & 0.9764 & 0.9731\\ 0.9781 & 0.9865 & 1.0000 & 0.9781\\ 0.9798 & 0.9933 & 0.9899 & 0.9832\\ 0.9804 & 0 & 0 & 0\end{pmatrix}$$

$$\text{Terengganu: }\begin{pmatrix} 0.9859 & 0.9736 & 0.9824 & 0.9789 \\ 0.9842 & 0.9912 & 1.0000 & 0.9842 \\ 0.9877 & 0.9982 & 0.9930 & 0.9824 \\ 0.9806 & 0 & 0 & 0 \end{pmatrix}$$

$$\text{Negeri Sembilan: }\begin{pmatrix} 0.9808 & 0.9686 & 0.9861 & 0.9774 \\ 0.9791 & 0.9895 & 1.0000 & 0.9739 \\ 0.9721 & 0.9634 & 0.9721 & 0.9617 \\ 0.9599 & 0 & 0 & 0 \end{pmatrix}$$

The matrices of temperature dataset of each state are then further computed to find their eigenvalue and Fiedler vector to obtain x-coordinates, while the y-coordinates are obtained using conjugate gradient method. The rainfall dataset follows the same processing steps in the algorithm. The coordinated vertices for each temperature and rainfall dataset are plotted in Euclidean space. The results are shown in Figs. 3 and 4.

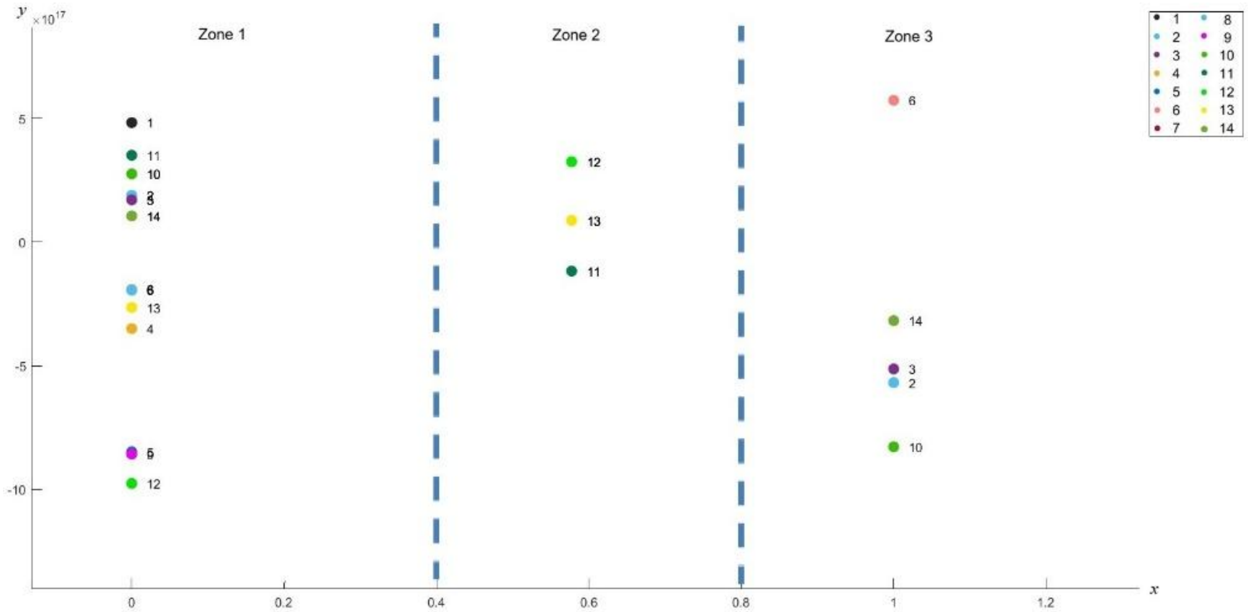

Figure 3. Coordinated Plot of Dynamic Fuzzy Graph for Temperature Dataset

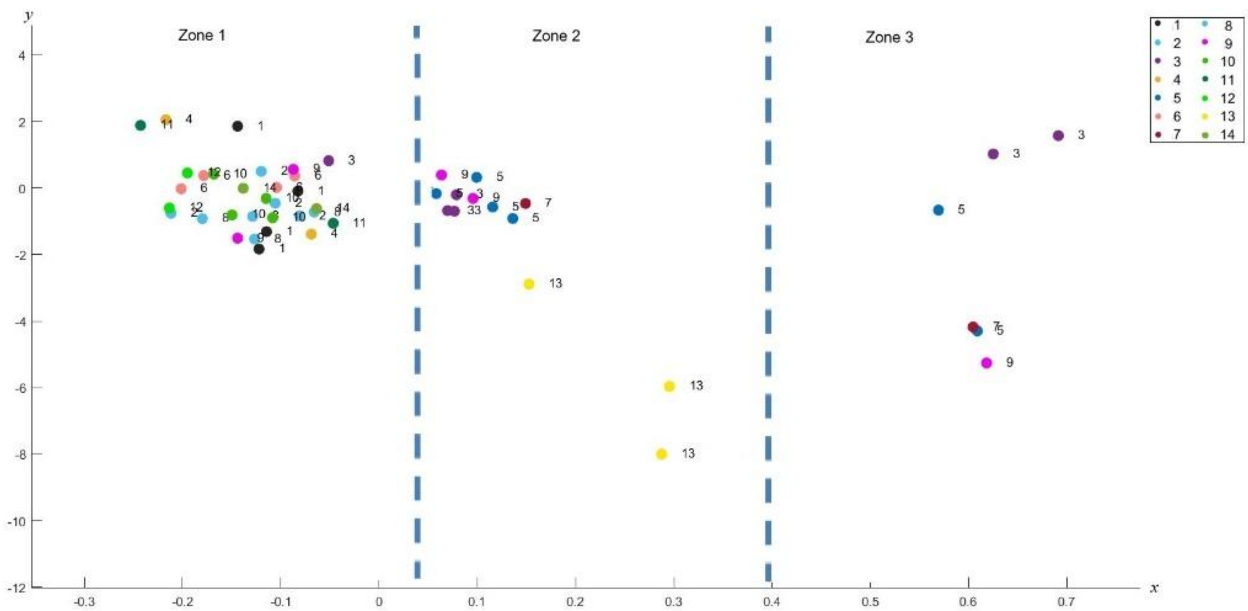

Figure 4. Coordinated Plot of Dynamic Fuzzy Graph for Rainfall Dataset

The analysis provides clusters of the states according to their severity of their changes in climate patterns. The Euclidean graph is divided into three zones, whereby the area on the left side represents the low-severity zone (Zone 1), the middle area represents the moderate-severity zone (Zone 2), while the right-side area is the high-severity zone (Zone 3).

The results in Fig. 3 shows that v_6 (Perak), v_{14} (Negeri Sembilan), v_3 (Kelantan), v_2 (Kedah) and v_{10} (Sarawak) are the states that positioned in the high-severity zone for analysis involving temperature dataset. Meanwhile, v_{11} (Kuala Lumpur), v_{12} (Selangor) and v_{13} (Terengganu) are positioned in the moderate-severity zone. Other states are positioned in the low-severity zone. This result signifies that Perak, Negeri Sembilan, Kelantan, Kedah and Sarawak are highly exposed to rising global temperature and heat waves, meanwhile, Kuala Lumpur, Selangor and Terengganu are becoming vulnerable to high temperatures and may be at risk of severe heat waves if no proper climate action is executed. According to The Straits Times [38], Perak and Kedah recorded the highest number of cases for heat stroke due to ongoing heat waves and phenomena of El-Niño in March 2024, followed by other states including Negeri Sembilan, Kelantan, Kuala Lumpur, Selangor, Terengganu and Sarawak. In July 2024, the second surge of heat wave was reported at few states in Malaysia [39]. Kelantan, Perak, Sabah and Sarawak were issued with level 1 warning of heat waves, with Sarawak being the state with the most locations with high temperature between 35 to 37 degrees Celsius for three consecutive days. In the previous year, level 1 warning of heat waves were also issued in Kedah, Negeri Sembilan and Kelantan, with highest temperature of 38.4 degree Celsius is recorded in Negeri Sembilan on 22 April 2023 [40], [41]. Thus, the results of dynamic fuzzy graph analysis on the temperature dataset from 2010 to 2022 concur to the reported rising temperature and heat wave events in the states of Malaysia, during 2023 and 2024 [38], [39], [40], [41].

The results in Fig. 4 show that coordinated vertices of v_3 (Kelantan), v_5 (Pahang) and v_9 (Sabah) are positioned in the high-severity zone for analysis involving rainfall dataset. Meanwhile, v_{13} (Terengganu) is positioned in the moderate-severity zone. Other states are positioned in the low-severity zone. This result signifies that Kelantan, Pahang, and Sabah are prone to experiencing severe change in rainfall intensities and frequencies, which lead to extreme climate events such as floods. Malaysia is expected to face 20% to 40% increase in rainfall frequency during monsoon season in 2024, particularly in Kelantan, Pahang, Sabah, and Terengganu [42], [43]. The continuous and heavy rainfall may increase the risk of flooding. Additionally, Kelantan, Pahang and Terengganu have been continuously experiencing heavy rainfall during northeast monsoon, and severe floods are continuing to occur every year [44]. The worst flood incidence was in 2021 where RM6.1 billion in losses suffered by Malaysia and RM622.4 million in losses in 2022, which is mainly contributed from floods in Kelantan and Terengganu [44] In 2023 to 2024, several flood incidences recorded in Kelantan, Pahang, Sabah and Terengganu [45], and Kelantan particularly, recorded the worst flooding in decade during November 2024 [43]. Thus, the results of dynamic fuzzy graph analysis on the rainfall dataset from 2010 to 2022 also concur to the rainfall events in the states of Malaysia, during 2023 and 2024 [42], [43], [44], [45].

Additionally, to quantitatively validate the results, a centroid-based separation analysis was performed. The coordinates were first aggregated and normalized, and then each coordinate was assigned to one of fourteen clusters. The centroid of each cluster was computed as the means of the coordinates of the member of the clusters. The separation between the clusters was measured using Euclidean distance, q_{ij} between centroids such that $q_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$, where i and j are different clusters. The distance signifies degrees of separation among the systems, with small inter-cluster distance indicates extremely close and identical positions of clusters' members. For the coordinated fuzzy graph of temperature dataset, the separation between zone 1 with zone 2 and zone 3 are 0.0336 and 0.0328 respectively, which indicates clear separation between zone 1 to the other zones. While the separation between zone 2 and zone 3 is smaller, which is 0.0008, indicating close position between the two zones. Thus, the results are consistent with the clustering observed in Fig. 3. Meanwhile, the minimum inter-cluster distance is on the order of 10^{-7} for rainfall clustering, indicating that high degree of similarity among certain clusters and systems, especially in zones 1 and 2, as they are mostly overlapped and positioned very close to each other. Overall, the analysis confirms that the clustering is able to capture distinct clusters and similarities between the systems.

The results are also concurred with the results of kPCA as shown in Figs. 5 and 6.

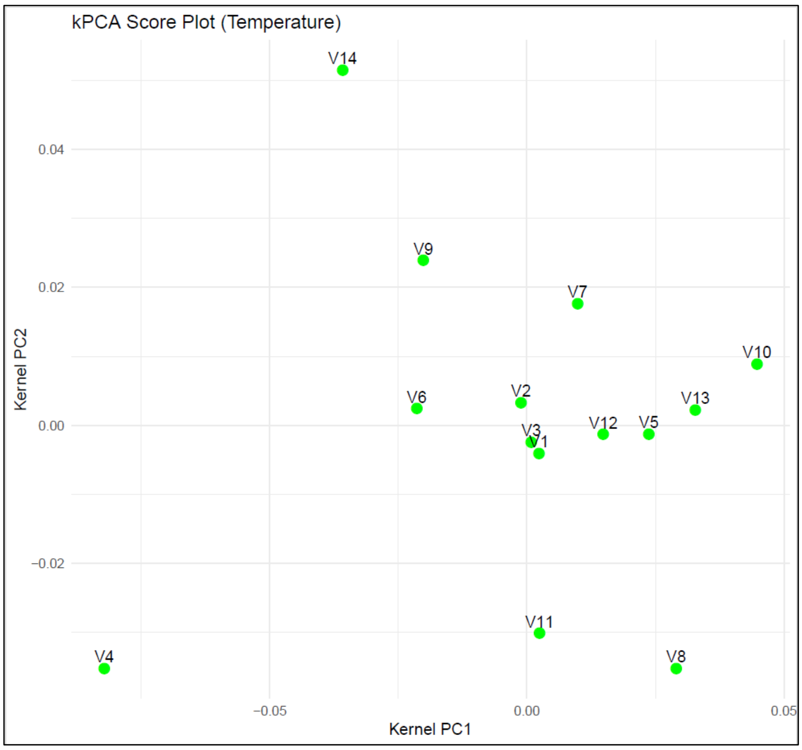

Figure 5. kPCA Plot of Temperature Analysis

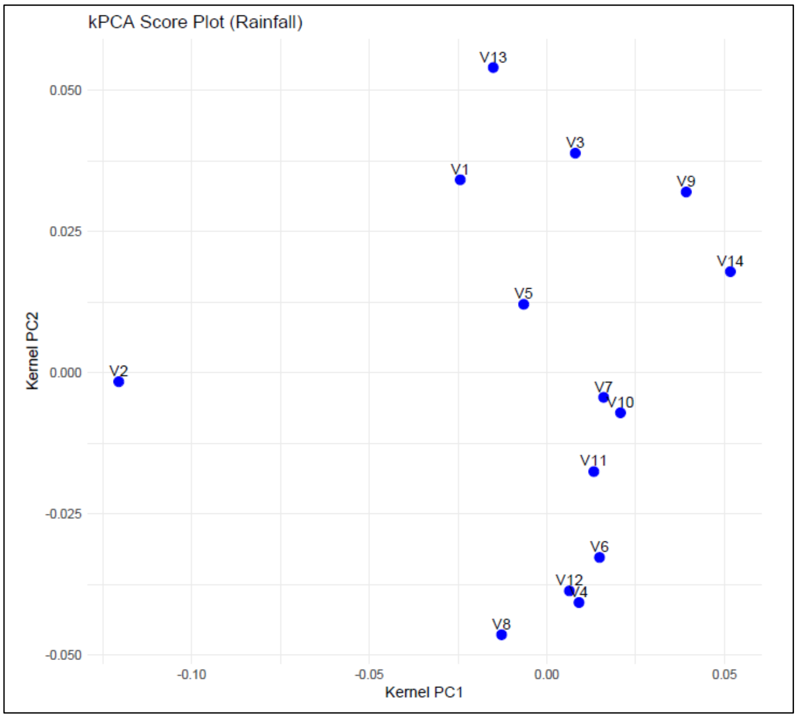

Figure 6. kPCA Plot of Rainfall Analysis

The kPCA plot in Fig. 5 shows that v_{14} (Negeri Sembilan), v_9 (Sabah), v_7 (Perlis), v_6 (Perak), v_2 (Kedah), and v_{10} (Sarawak) are clustered in the upper area, for analysis involving temperature dataset. This result signifies that the states have similar characteristics or experience similar circumstances. Meanwhile, the kPCA plot in Fig. 6 shows that v_{13} (Terengganu), v_3 (Kelantan), v_1 (Johor) and v_9 (Sabah) are clustered in the upper area, for analysis involving rainfall dataset. The results of kPCA concur to the results of the dynamic fuzzy graph analysis, whereby Negeri Sembilan, Perak, Kedah and Sarawak particularly, have been experiencing severe rise in temperature, caused by the natural phenomena of El-Niño and also due to global warming. Meanwhile, Kelantan, Sabah and Terengganu are at risk of extreme floods, due to heavy rainfall during the northeast monsoon, and Kelantan in particular, has been experiencing the most severe flood that caused economic loss, ever since 2021.

4. CONCLUSION

The dynamic fuzzy graph algorithm able to model and analyze the pattern of temperature and rainfall in Malaysia. The states in Malaysia are able to be clustered and classified according to their severity of temperature changes and rainfall frequencies. Thus, the method is more efficient than the available statistical methods that mainly determine the climate trend numerically and are unable to classify the severity zone clearly. The dynamic pattern and data visualization analyses from the algorithm are significant for understanding and interpreting the complex climate system, so that proper mitigation measures and climate action plans can be implemented. The analysis using dynamic fuzzy graph algorithm concurs with the kPCA results and recent climate events reported in 2023 and 2024. For analysis involving temperature, the paper revealed that Negeri Sembilan, Perak and Kedah are experiencing extreme rise in temperature. For analysis involving rainfall, the dynamic fuzzy graph revealed that Kelantan, Sabah and Terengganu are experiencing severe rainfall intensities and frequencies. For several years, Kelantan has been experiencing the worst flood incident due to heavy rainfall during the northeast monsoon, which contributed to major economic losses. Therefore, proper mitigation measures should be implemented, particularly in the most severe areas and moderate severity areas to alleviate the impact of floods. The classifications of the states according to their severity level are crucial for predicting future climate trends and facilitating effective decision-making and adaptation strategies in climate research, especially at the most significant and severely identified states. The clusters obtained from the coordinated plot simplify the complex climate data by grouping the states with similar trends and characteristics, making the information more actionable. Policymakers can use this clarity to create focused interventions plans, such as infrastructure upgrades and emergency planning. These targeted actions could improve policy effectiveness and climate resilience outcomes. Thus, the algorithm is beneficial in providing an effective tool for big data analytics, particularly in climate research. While this study provides an algorithm that captures large and complex data, the methodology relies on square matrix structure, in which the amount of data is preferably in perfect-square size. If it is not possible, zero values can be added to complete the matrix, with slight impact on accuracy.

Author Contributions

Nurfarhana Hassan: Conceptualization, Methodology, Formal Analysis, Writing-Original Draft. Zarith Sofia Jasmi: Draft Preparation, Writing-Review and Editing, Validation. Zamali Tarmudi: Supervision. Thaer Thaher: Validation, Writing-Review and Editing. Mujahid Abdullahi: Validation. All authors discussed the results and contributed to the final manuscript.

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Declarations

The authors declare no competing interest.

Declaration of Generative AI and AI-assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript, including for writing, editing, data analysis, or the creation of tables and figures.

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