

## Overview of Air Quality and Climate Variations in Peninsular Malaysia (2003–2022)

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KEYWORDS	ABSTRACT
Air quality Climate trend Temporal analysis Spatial distribution Peninsular Malaysia	In this paper, the investigation of long-term variations in climate and air quality across Peninsular Malaysia from 2003 to 2022 was conducted to understand regional atmospheric changes over time. The main objective of this study is to identify overall trends and spatial patterns in key environmental parameters, including temperature, relative humidity (RH), Particulate Matter (PM <sub>10</sub> ), Carbon Monoxide (CO), Ozone (O <sub>3</sub> ), and Nitrogen Dioxide (NO <sub>2</sub> ). To achieve this, time series and heatmap analyses were applied using 20 years of data obtained from monitoring stations across Peninsular Malaysia. From the analyses, it was observed that temperature and relative humidity show increasing trends, while air pollutant concentrations, particularly PM <sub>10</sub> exhibit gradual declines in most regions. The findings provide a general overview of the long-term air quality and climate condition in Malaysia and can serve as a reference for future climate and environmental management studies.

### 1. INTRODUCTION

Understanding long-term changes in climate and air quality is essential for evaluating environmental conditions and strengthening air quality management. Over the past two decades, rapid urbanization and industrial growth have intensified anthropogenic emissions, contributing to shifts in both local and regional air quality patterns [1,2]. Moreover, climate variability plays a significant role in influencing pollutant dispersion [3].

Previous studies have primarily focused on short-term air quality assessments or isolated pollution events such as transboundary haze episodes [4,5]. However, limited attention has been given to the long-term evolution of meteorological factors and key air pollutants, which is critical for identifying persistent trends and understanding the influence of climate variability.

This study aims to analyze and visualize the long-term trends of key climate and air quality parameters which is temperature, relative humidity (RH), carbon monoxide (CO), and ozone (O<sub>3</sub>) from 2003 to 2022 across Peninsular Malaysia. Through time series and heatmap analyses, this paper provides a general understanding of how these atmospheric variables have evolved over the past two decades.

### 2. EXPERIMENTAL PROCEDURE

The data used in this study was from 20 air quality monitoring stations across Peninsular Malaysia, representing different area classifications, including urban, sub-urban, rural, and industrial area. The dataset spans a 20-year period (2003–2022), includes climate variables such as temperature (T) and relative humidity (RH), along with air pollutant parameters (Particulate Matter (PM<sub>10</sub>), Carbon Monoxide (CO), Ozone (O<sub>3</sub>), and Nitrogen Dioxide (NO<sub>2</sub>)). The daily data were obtained from the Department of Environment Malaysia. Figure 1 illustrates the geographical locations of each monitoring station.

Two main analytical methods were employed in this study to identify long-term variations in climate and air quality parameters. Time series analysis was used to visualize the overall trends and annual fluctuations of each variable from 2003 to 2022. This approach enabled the identification of gradual upward or downward trends in the observed parameters over the study period. In addition, heatmap visualization was applied to detect the spatial patterns and pollutant concentrations across different monitoring stations by representing data intensity with color gradients.



Figure 1. Locations of 20 continuous air quality monitoring stations across Peninsular Malaysia.

3. RESULTS AND DISCUSSION

Over the past two decades (2003–2022), temperature and relative humidity (RH) in Peninsular Malaysia have shown a gradual increasing trend (Fig. 2). Fig 3(a) further reinforces these findings by showing a gradual and widespread increase in temperature across almost all monitoring stations, with the trend becoming more pronounced after 2018. This situation was consistent with the global climate change which driven by the accumulation of greenhouse gases in the atmosphere leading a warming pattern observed worldwide [6]. The RH trend shows a notable color shift at almost all monitoring stations post-2017 as shown in Fig. 3(b), signifying a general increase in humidity levels. This spatial pattern reinforces that the increase is not only regional but also broadly distributed across most locations.

The trend of PM<sub>10</sub> concentrations shows an overall decline particularly after 2017, as seen in both Fig. 2 and Fig. 3(c). Earlier peaks in 2015 and 2019 correspond to major transboundary haze events linked to forest fires in Indonesia [5,4]. Following 2019, PM<sub>10</sub> levels decreased steadily, a direct outcome from the strengthened air quality regulations under the Environmental Quality (Clean Air) Regulations 2014 and the National Clean Air Action Plan (2010–2020). The COVID-19 lockdowns in 2020–2021 further contributed to temporary improvements in air quality [4,6].

Meanwhile, Fig 2. shows a long-term increasing trend in CO with minor short-term fluctuations. This upward trajectory is strongly associated with intensified urbanization, particularly in areas where traffic density and commuting durations have significantly increased [1]. As CO is primarily emitted from incomplete combustion processes, the trend likely reflects changing fuel

consumption patterns and rising energy demand in both transportation and industrial sectors.

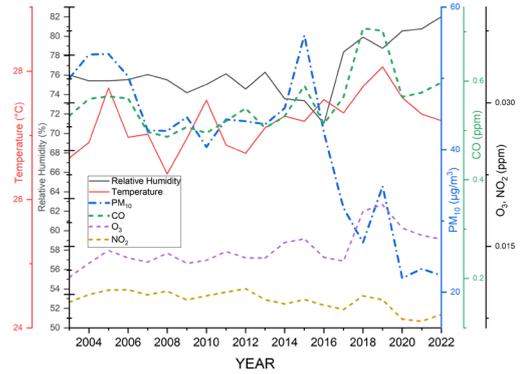
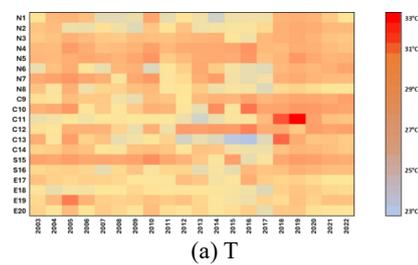
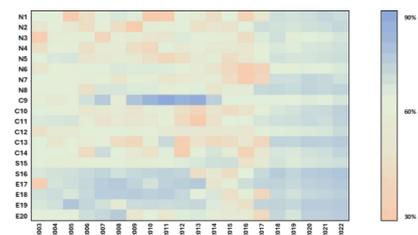


Figure 2. Annual mean of temperature, relative humidity, and air pollutant concentrations (PM<sub>10</sub>, CO, O<sub>3</sub>, NO<sub>2</sub>) from 20 monitoring stations in Peninsular Malaysia (2003–2022).

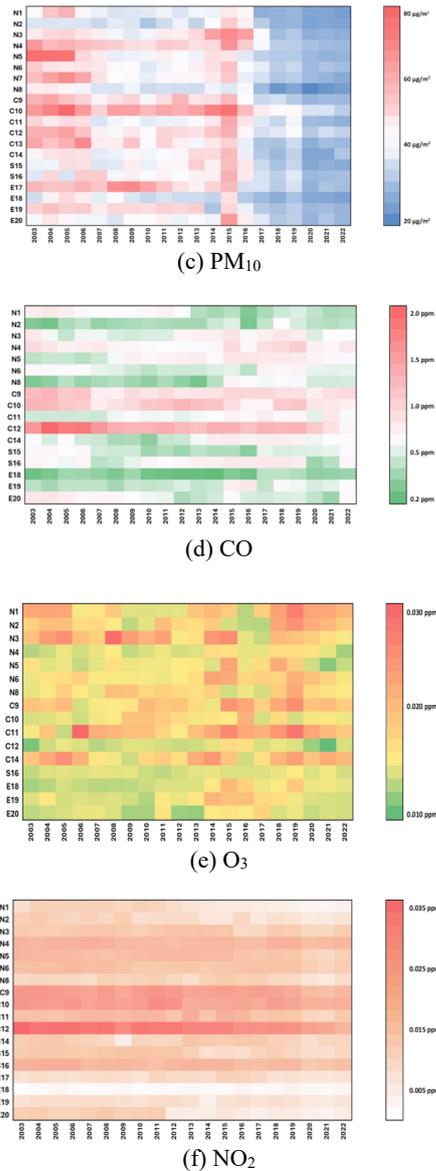
Ozone (O<sub>3</sub>) exhibits a noticeable increasing trend, particularly in the later years of the study period with elevated concentrations becoming more pronounced after 2014. This trend aligns with the consistent rise in ambient temperature, as shown in both Fig. 2 and Fig. 3(e) which directly enhanced photochemical activity and accelerated ground-level ozone formation [7]. Despite high RH generally suppressing ozone formation, the co-occurring rise in temperature and availability of photochemical precursors appears to offset this effect, sustaining or even enhancing O<sub>3</sub> levels [8]. Alongside rising O<sub>3</sub> levels, NO<sub>2</sub> shows gradual declining trend over the 20-year period. This observed rise in O<sub>3</sub> is closely tied to changes in NO<sub>2</sub> levels. Since NO<sub>2</sub> plays a central role in O<sub>3</sub> formation through photochemical reactions, a gradual decline in NO<sub>2</sub> can lead to less ozone destruction, resulting in higher ozone concentrations in the atmosphere [8].



(a) T



(b) RH



**Figure 3.** Spatial distribution (heatmap) of temperature (T), relative humidity (RH), and air pollutants (CO, O<sub>3</sub>, PM<sub>10</sub>, and NO<sub>2</sub>).

#### 4. CONCLUSION

This study highlights the long-term interactions between climate variables and air quality in Peninsular Malaysia from 2003 to 2022. The analysis revealed a gradual increase in temperature and RH, accompanied by a general decline in CO and PM<sub>10</sub> concentrations. In contrast, O<sub>3</sub> and NO<sub>2</sub> displayed more variable patterns, reflecting their strong dependence on meteorological conditions and local emission sources.

These results highlight the need for more targeted mitigation strategies supported by continuous air quality monitoring and predictive modeling approaches. Incorporating predictive models can enhance the ability to forecast pollution episodes and guide early intervention

measures. Integrating these modeling tools with existing air quality management frameworks is essential to sustain environmental progress in the long term.

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