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WIND SPEED PATTERNS FOR RAIN ENHANCEMENT POTENTIAL AREAS DURING MONSOON SEASONS

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ABSTRACT

Rain enhancement, or cloud seeding, is a weather modification method designed to stimulate precipitation in areas affected by water scarcity. The effectiveness of cloud seeding operations (CSOs) is often constrained by complex climatological factors, particularly wind speed and direction, which determine the dispersion of seeding agents. This study investigates spatial wind speed patterns in Peninsular Malaysia during monsoon seasons using a geospatial approach. Wind speeds at the operational seeding height of 2 km were extrapolated using the logarithmic wind profile, while kriging interpolation was applied to map and classify wind speed variations. Validation of the interpolated results demonstrated strong accuracy, with coefficients of determination (R^2) of 0.9624, 0.9677, and 0.925 for January 19, 2020; May 4, 2023; and July 29, 2024, respectively. Findings indicate that wind speeds below 10 m/s are suitable for CSOs, with observed values in seeded areas ranging between 1.6 m/s and 6.7 m/s. Seasonal mapping of wind speed patterns provides critical insight for identifying potential rain enhancement zones and optimizing operational planning. This research highlights how geospatial analysis supports decision-making by enabling agencies such as MET Malaysia to prioritize suitable areas, select favourable seeding times, and improve the overall efficiency and effectiveness of cloud seeding operations.

1. Introduction

Rain enhancement or cloud seeding is a weather modification that stimulates precipitation by dispersing hygroscopic particles, such as salt or silver iodide, that act as ice nuclei (IN) or cloud condensation nuclei (CCN) into potential clouds. These particles attract water vapour, forming larger droplets that coalesce and eventually fall as rain or snow, or reduce hail or fog (Al Homoud et al., 2024; Mehdizadeh et al., 2024). Proper observation of wind patterns is essential to ensure that seeding agents are delivered accurately to target clouds, thereby optimizing precipitation enhancement efforts. Pourmohammadi et al. (2021) and Sadeghi et al. (2024)

pointed out that rain enhancement is closely linked to Sustainable Development Goal (SDG) 6 as it helps increase precipitation and improve water availability in areas affected by water scarcity. This weather modification technology is used to address water shortages by enhancing rainfall, which is crucial for drinking water, agriculture, and industry. Yeh (2025) also stated that this operation is linked to SDG 13 as it can be used to mitigate the impacts of climate change by addressing drought conditions and enhancing water resources. This operation can help manage the effects of climate change on water availability and agricultural productivity. Besides increasing precipitation, rain enhancement can support ecosystems and biodiversity, which are fundamental components of SDG 15. Enhanced rainfall improves soil moisture, supports vegetation growth, and contributes to the overall health of terrestrial ecosystems (Lee et al., 2024).

Mehdizadeh et al. (2024) highlighted that the success of cloud seeding operations (CSOs) depends on several factors, including cloud type, meteorological conditions, and the dispersion of seeding agents, which is heavily influenced by wind speed and direction. Studies by Yuan et al. (2021), Abshaev et al. (2022), and Jung et al. (2022) show that wind is a significant meteorological parameter in determining seeding effectiveness. Wind speed varies significantly across space and time, influencing the consistency and predictability of CSOs. High wind speeds may carry seeding materials away from target clouds, reducing efficiency (Ćurić et al., 2009), while very low speeds can cause accumulation in one location. Selecting an appropriate location and height for seeding by analysing wind speed patterns is therefore essential. According to Wang et al. (2024), factors such as wind patterns, thermodynamics, and terrain characteristics affect seeding agent concentration and height. Jung et al. (2022) reported that optimal wind speed at seeding height is around 6.9 m/s, while Chae et al. (2025) identified 1.5 km elevation as ideal due to high relative humidity and abundant cloud water.

Understanding wind speed patterns is a key component in improving CSO efficiency. Atmospheric pressure variations drive global wind patterns, and global warming is altering these pressure systems, which in turn affect wind dynamics (Stammer et al., 2008). Rehman et al. (2022) highlighted that wind speed varies significantly with geographical features. Coastal areas tend to have higher wind speeds compared to inland regions. According to Aris et al. (2024), wind variability is influenced by orographic winds, sea and land breezes, and other local factors. Yang et al. (2022) reported that land and sea breeze circulation significantly influence wind flow in Malaysia, especially during days with clear skies. Malaysia's equatorial location and monsoonal climate contribute to complex wind speed patterns, with relatively low average speeds due to high temperatures, humidity, and atmospheric stability (Zakaria et al., 2020; Zheng et al., 2023). Over 20 years, Peninsular Malaysia has experienced fluctuations in wind speed, influenced by broader climatic changes as reported by Zheng et al. (2023). Wind speeds vary daily, monthly, and seasonally, with stronger winds typically recorded during the Northeast Monsoon and weaker winds during the Southwest Monsoon (Saberi et al., 2019; Saberi et al., 2020). Uti et al. (2018) also found that the inter-monsoon periods in April and October result in more variable and less predictable wind patterns.

Despite the importance of wind in CSOs, limited spatial analysis exists in Malaysia on wind

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speed variability at different altitudes and seasons, especially around the seeding height of 2 km. This gap hinders the accurate delivery of seeding agents to target cloud formations. To address this challenge, wind modeling and spatial interpolation techniques are tools for improving wind analysis. For example, Support Vector Machines (SVMs) have shown high prediction accuracy in short-term wind speed forecasting (Tian et al., 2020). Moreover, Geographic Information System (GIS) interpolation methods are fundamental to accurately estimating wind speed across spatial domains. Techniques such as Kriging (Chen et al., 2024; Wang et al., 2024), Inverse Distance Weighted (IDW) (Barrena-González et al., 2022; Guidoum, 2024), spline interpolation (Karim et al., 2018), and natural neighbour interpolation (Widodo et al., 2024) each have unique strengths and are suited for different spatial applications. Many researchers, such as Wang et al. (2020), Lee (2022), and Chen et al. (2024), have specifically applied Kriging interpolation to estimate the spatial distribution of wind speed. Kisuule et al. (2023) confirmed that Kriging is widely used as an effective approach for interpolating meteorological parameters, including precipitation, temperature, relative humidity, and wind speed. Therefore, this study aims to determine spatial wind speed patterns in Peninsular Malaysia during monsoon seasons using GIS interpolation. The objectives were to estimate wind speeds at 2 km seeding height using a logarithmic wind profile and to classify wind speed patterns based on kriging interpolation.

2. Methodology

Three main phases were carried out to achieve the study's aims and objectives. The first phase involved data acquisition of daily mean surface wind speeds from 70 ground-based meteorological stations. The second phase used the Logarithmic Wind Profile to estimate wind speeds at a 2 km height based on ground-based wind speeds. Finally, the wind speed was interpolated and classified using Kriging interpolation in ArcGIS to produce maps of wind speed spatial patterns (Refer to Figure 1). Kriging methods, including ordinary, universal, and anisotropic Kriging, have been shown to provide more accurate wind speed predictions compared to traditional interpolation methods. Irfan et al. (2021) stated that kriging improved the prediction accuracy of wind speeds in various studies, with correlation coefficients as high as 99.8 percent for ordinary and universal Kriging. Wang et al. (2020) also highlighted that Kriging is effective for short-term wind speed forecasting, showing high accuracy over brief periods. This method is also effective in handling spatial variability and heterogeneity. It can integrate geographical variables and spatial structures, making it suitable for complex terrains and varied landscapes (Wang et al., 2020).

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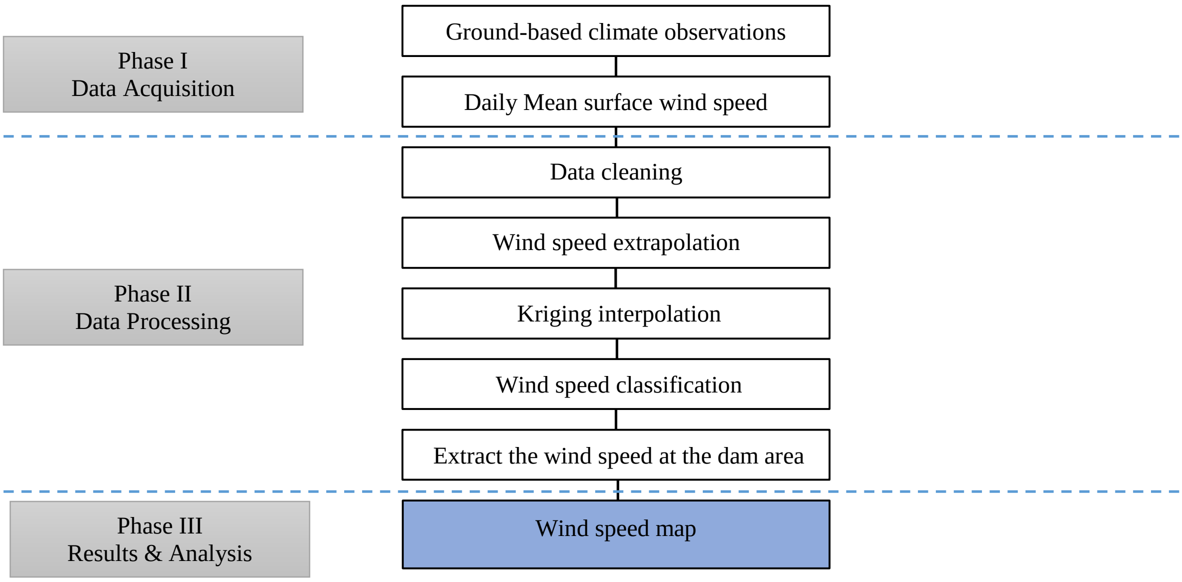

Figure 1. Research Methodology Workflow.

2.1 Study Area

The study area was located in Peninsular Malaysia. Figure 2 illustrates the study area with the distribution of ground-based wind monitoring stations operated by MET Malaysia across Peninsular Malaysia. These stations collect real-time data on weather parameters, including wind speed and direction, and are important for weather forecasting and atmospheric research. According to Vincent et al. (2022) and Alzian et al. (2025), wind patterns in Malaysia are influenced by the Southwest, Northeast, and inter-monsoon. Elias et al. (2024) highlighted that Malaysia experiences low mean annual wind speeds, averaging 1.8 m/s to 2 m/s. Although it experiences low wind speeds, some areas experience higher wind speeds during certain monsoon phases. Azhar et al. (2023) identified Mersing in Johor as one of the windiest areas of Peninsular Malaysia, particularly during the Northeast monsoon season from November to March.

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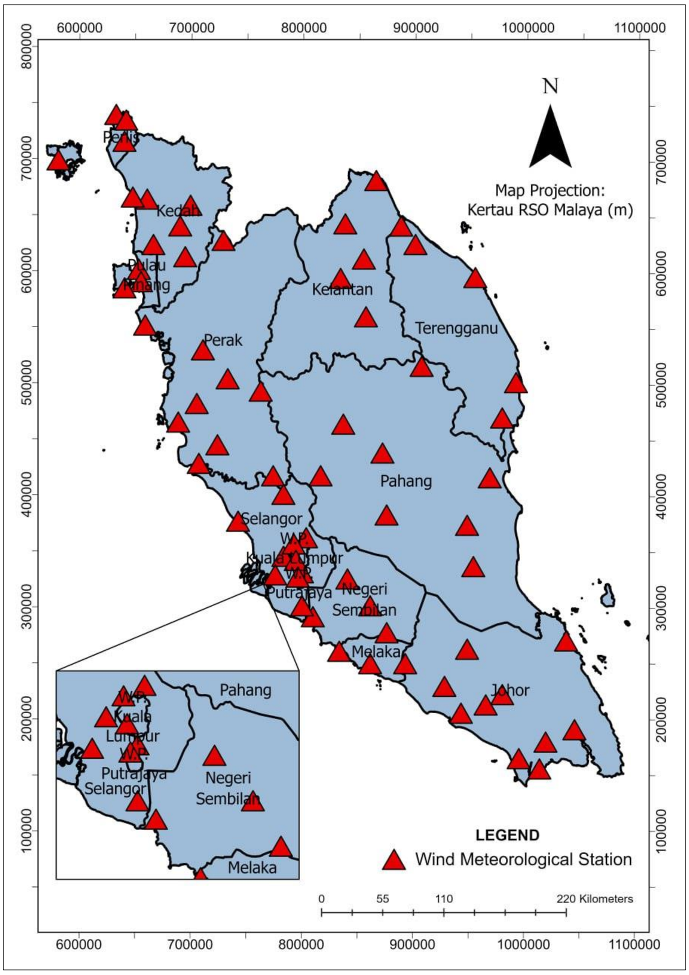

Figure 2. Study Area

2.2 Estimation of Wind Speeds using Logarithmic Wind Profile

In this study, estimation of wind speeds from ground-level or surface wind speed data is essential to assess wind conditions at seeding altitude. Data cleaning was first carried out on daily mean surface wind speeds to ensure the accuracy in the analysis by removing missing values, such as incomplete or absent wind speed records, duplicate entries, and checking format irregularities. A mathematical model based on the logarithmic wind profile was then applied to extrapolate (El Khachine et al., 2025) surface wind speeds and estimate wind speeds at an altitude of approximately 2 km, which represents the ideal seeding height (Chae et al., 2025). In this study, the computation assumes neutral atmospheric stability and uniform terrain. Based on Equation (1), *u(z)* represents the wind speed at a given height *z*, while u_* denotes the friction velocity. The constant κ is the von Kármán constant, valued at 0.4. The variable *z* refers to the vertical height above the ground, and z_0 indicates the surface roughness length (Lopez-Villalobos et al., 2022).

$$u(z)=\frac{u_*}{\kappa}\ln\frac{z}{z_0} \tag{1}$$

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2.3 Spatial patterns of wind speed using Kriging Interpolation

Kriging interpolation was applied in this study to estimate spatial wind speed patterns based on estimates of wind speeds at 2 km across the study area. Chen et al. (2024) and Wang et al. (2024) described spatial interpolation as a method that uses data from nearby meteorological observation stations within the region to estimate values at non-observed locations. Chen et al. (2024) highlighted that kriging estimates the value of a location by calculating a weighted average of nearby known values. This geostatistical interpolation method generates an estimated surface from scattered points with z-values. It examines the spatial patterns within the data to gain insight into the underlying phenomenon before selecting the most appropriate estimation technique for producing the final output (Rao et al., 2023). The kriging in Equation 2 is explained as $\hat{Z}(x_0)$ represents the estimated wind speed at the unknown location x_0. The variable *n* denotes the total number of known observation points. Each λ_i is an unknown weight assigned to the observed wind speed $Z(x_i)$ at location x_i.

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (2)$$

The interpolated wind speed was then extracted specifically at the dam area to classify wind speed classes within the area of interest. A wind speed map was produced to represent the results of spatial interpolation and wind speed classification.

3. Results and Discussion

3.1 Wind Speed Estimation

The wind speed data at 2 km altitude were categorized into five levels, as listed in Table 1. On January 19, 2020, very low wind speeds (<1.5 m/s) were mostly recorded in Pahang. Meanwhile, the high to very high wind speeds exceeding (>3.5 m/s) were concentrated at ten stations, mainly in Johor, Pulau Pinang, and Terengganu.

Based on the wind speed estimation on May 04, 2023, Pahang again had the most very low wind speed stations (<1.5 m/s), with six out of the 31 stations in this category. Johor recorded the most in the low category (1.5 to 2.5 m/s). Nine stations were identified in the moderate wind speed category (2.5 to 4.0 m/s), and Terengganu stood out with two stations. Penang and Kelantan had the most stations with high wind speeds, ranging from 4.0 to 5.5 m/s. Only one station recorded very high wind speeds (> 7.0 m/s), which was found in Kedah.

By July 29, 2024, most stations across Peninsular Malaysia experienced very low wind speeds, with 28 stations recording values below 1.5 m/s. Meanwhile, 20 stations reported low wind speeds between 1.5 and 2.5 m/s, with Kedah recording four stations, while Johor was in the moderate range. Finally, very high wind speeds (> 5.0 m/s) were recorded at eight stations, mainly in Penang, where Prai, Butterworth, and Bayan Lepas recorded the strongest winds.

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Table 1. Wind Speed Estimation.

No	Date	Category (m/s)	Wind Speed 2 km (m/s)	State	Station
1.	January19, 2020	Very Low (< 1.5)	0.1	Pahang	JAKOA Kuala Lipis
2.			0.7		Felda Bukit Tajau
3.			0.8		Batu Embun
4.			0.9		Pusat Pertanian Gali Raub
5.			1.2		Felda Chini 2
6.			1.2		Temerloh
7.		Low (1.5 – 2.5)	1.6	Perak	Lubok Merbau
			2.0		MARDI Hilir Perak
8.			1.6		Pusat Pertanian Titi Gantung
9.			2.0		MARDI Hilir Perak
10.		Moderate (2.5 – 3.5)	2.6	Perak	Ipoh
11.			3.5		Hospital Teluk Intan
12.			3.5		Sitiawan
13.		High (3.5 – 5.0)	3.6	Johor	Majlis Daerah Labis
14.			4.2		Senai
15.			4.8		Kluang
16.		Very High (> 5.0)	7.0	Penang	Prai
17.			7.7		Bayan Lepas
18.			6.8		Butterworth
19.			5.1	Terengganu	Gong Kedak
20.			7.5		Kuala Terengganu
21.			7.7		Kerteh
1.	04 May, 2023	Very Low (< 1.5)	0.7	Pahang	Muadzam Shah
2.			1.2		Batu Embun
3.			0.4		JAKOA Kuala Lipis
4.			1.3		Temerloh
5.			1.2		Felda Chini 2
6.			1.2		Pusat Pertanian Gali Raub
7.		Low (1.5 – 2.9)	2.0	Johor	Senai
8.			2.0		Pusat Pertanian Ayer Hitam
9.			2.2		Hospital Tangkak
10.			2.3		MARDI Alor Bukit Pontian
11.			2.8		Nusajaya
12.		Moderate (3.0 – 4.9)	3.4	Terengganu	Gong Kedak
13.			4.8		Kuala Terengganu
14.		High (5.0 – 6.9)	5.1	Penang	Prai
15.			5.7		Butterworth
16.			5.2	Kelantan	Chemara Res. Tanah Merah
17.			5.5		Kota Bharu
18.		Very High (≥ 7.0)	8.1	Kedah	Pusat Pertanian Charok Padang

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1.	July 29, 2024	Very Low (< 1.5)	1.0	Pahang	Felda Bukit Tajau
2.			1.0		Cameron Highlands
3.			1.1		Pusat Pertanian Gali Raub
4.			1.2		Temerloh
5.			1.3		Felda Chini 2
6.			1.4		Muadzam Shah
7.			1.4		Batu Embun
8.		Low (1.5–2.5)	1.6	Kedah	Pusat Pertanian Gajah Mati
9.			1.6		Mardi Bukit Raya
10.			2.2		Kuala Kangkong
11.			2.3		Hospital Sungai Petani
12.		Moderate (2.5–3.5)	2.8	Johor	Nusajaya
13.			3.0		Senai
14.			3.1		Batu Pahat
15.			3.2		MARDI Alor Bukit Pontian
16.		High (3.5–5.0)	3.6	Kedah	Pulau Langkawi
17.			4.6		Alor Setar
18.		Very High (> 5.0)	5.5	Penang	Prai
19.			5.9		Butterworth
20.			8.3		Bayan Lepas

3.2 Validation of Kriging Interpolation with Wind Speed at 2 km

The coefficient of determination or R^2 values for all three dates indicate a strong linear relationship between the Kriging interpolated wind speeds and the wind speed at 2 km, as shown in Figures 3, 4, and 5. On January 19, 2020, the R^2 was 0.9624, showing that the interpolation represented 96.24 percent of the variation in observed wind speed. On May 4, 2023, the R^2 reached 0.9677, the highest among the three, indicating the strongest relationship and most accurate interpolation. On July 29, 2024, the R^2 was slightly lower at 0.9388, but still reflected a strong correlation and reliable prediction performance. These high R^2 values indicate that Kriging provided consistently accurate spatial wind speed estimations across the selected dates.

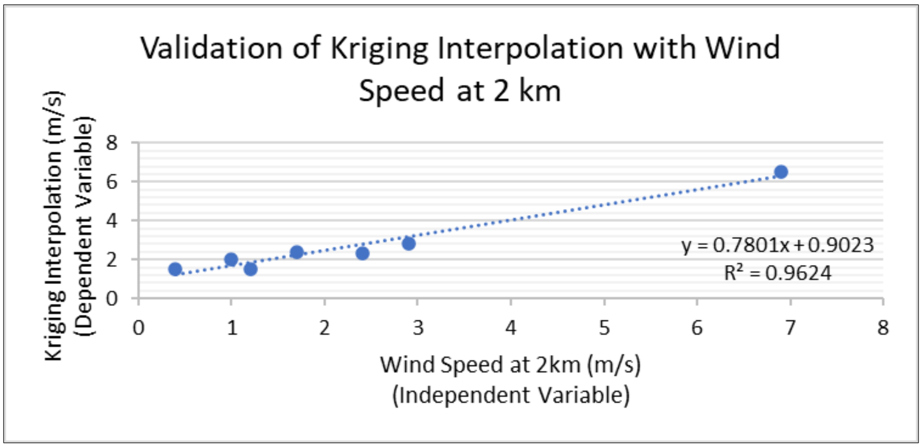

Figure 3. Validation of Kriging Interpolation with Wind Speed at 2km on January 19, 2020

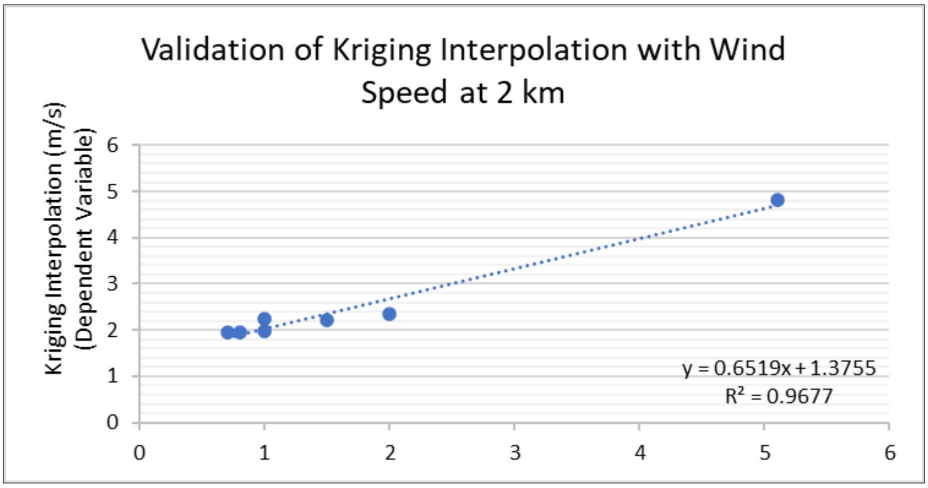

Figure 4. Validation of Kriging Interpolation with Wind Speed at 2km on May 4, 2023

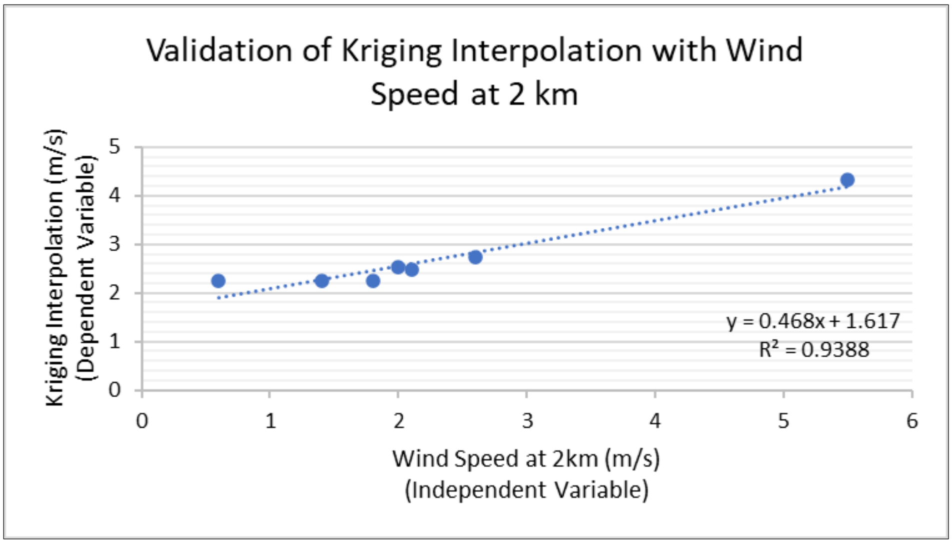

Figure 5. Validation of Kriging Interpolation with Wind Speed at 2km on July 29, 2024

3.3 Maps of Speed Spatial Patterns

Figure 6 illustrates the spatial patterns of wind speed across the study area at the 2 km cloud seeding height. The recorded wind speeds were divided into five categories. In Figure 6(a), lower wind speeds, ranging from 0.7 m/s to 10.2 m/s, are shown in brown and were predominantly observed in the central and southern regions. In contrast, higher wind speeds, indicated in blue, were concentrated along the northern coastal areas, particularly Kelantan, Terengganu, and Pulau Pinang, due to their direct exposure to strong monsoon winds from the sea. During this period, Peninsular Malaysia was under the influence of the Northeast Monsoon (November–March), with winds originating from the northeast and crossing the South China Sea (Mahmud et al., 2025). On the west coast, the Titiwangsa Range acted as a natural barrier, reducing wind strength before it reached those areas (Tee et al., 2024).

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Figure 6(b) shows the wind speed patterns at the seeding height of 2 km on May 4, 2023. Wind speeds ranged from 1.2 m/s to 3.4 m/s. Moderate to low wind speeds were generally observed across the central, southern, and eastern coastal regions, including Kelantan, Terengganu, and Pahang. In contrast, higher wind speeds, indicated in blue, were concentrated in the northwest, particularly in Kedah, Pulau Pinang, and northern Perak. According to the Malaysian Meteorological Department (MET Malaysia), early May falls within the inter-monsoon period, as the Southwest Monsoon typically begins later, around May 17. During this transitional phase, wind conditions are usually light and variable due to the shift between the Northeast and Southwest monsoons. This pattern is consistent with findings by Tiang et al. (2012), who reported that Penang tends to experience higher wind speeds due to its geographical location.

The map in Figure 6(c) displays wind speed patterns at the seeding height on July 29, 2024, with values ranging from 1.4 m/s to 5.3 m/s. Higher wind speeds, shown in blue, were observed in several coastal and southern regions, particularly in Johor, as well as parts of the northwestern areas such as Pulau Pinang and Kedah. In contrast, wind speeds gradually decreased inland across Pahang, Negeri Sembilan, Selangor, and Perak. This pattern is influenced by the Titiwangsa Range, which acts as a natural barrier that weakens wind flow from the west as it moves eastward (Tee et al., 2024). This finding is related to Daryabor et al. (2014), where the Southwest Monsoon typically begins in late May or early June and lasts until late August, characterized by generally light and variable winds over the South China Sea, occasionally disrupted by changes in flow patterns.

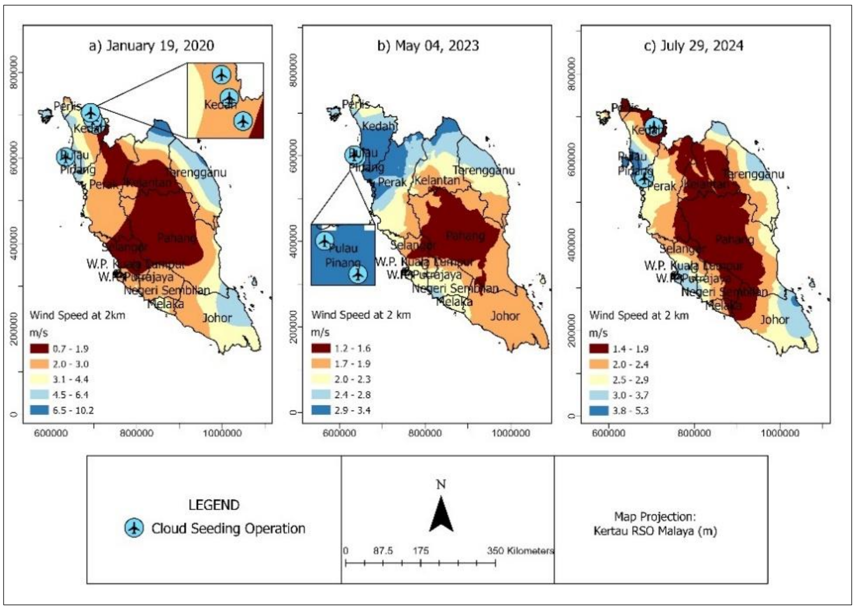

Figure 6. Wind Speed Patterns in Malaysia on (a) January 19, 2020, (b) May 04, 2023, (c) July 29, 2024

The wind speed values at selected dam areas in Peninsular Malaysia on three different dates, each corresponding to a monsoon season, were tabulated in Table 2. These dams were selected based on previous CSOs conducted by MET Malaysia. Based on the results, the suitable wind

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speed range for CSOs falls between 1.6 m/s to 6.7 m/s. On January 19, 2020, during the Northeast Monsoon, wind speeds across the dam in Kedah ranged from 2.1 m/s at Muda Dam, 2.5 m/s at Pedu Dam, and 2.6 m/s at Ahning Dam. The highest wind speed was recorded at Teluk Bahang Dam in Penang, reaching 6.7 m/s. During the inter-monsoon period on May 4, 2023, wind speeds in Penang remained relatively consistent. Air Itam Dam recorded a speed of 3.3 m/s, while Teluk Bahang Dam showed a similar range of 3.3 m/s. On July 29, 2024, within the Southwest Monsoon, wind speeds ranged from 1.6 m/s at Muda Dam to 3.1m/s at Bukit Merah Dam in Perak. Teluk Bahang Dam recorded 3.3 m/s, maintaining comparatively higher wind speeds than other regions.

Table 2. Wind Speed Patterns in Rain Enhancement Potential Areas.

No	Date	Latitude (N)	Longitude (E)	State	Dams	Wind Speed (m/s)
1.	January 19, 2020	6.1307	100.8579	Kedah	Muda	2.1
2.		6.2572	100.7841		Pedu	2.5
3.		6.3813	100.7420		Ahning	2.6
4.		5.4432	100.2142	Penang	Teluk Bahang	6.7
5.	May 04, 2023	5.3957	100.2615	Penang	Air Itam	3.3
6.		5.4432	100.2142		Teluk Bahang	3.3
7.	July 29, 2024	6.1154	100.8566	Kedah	Muda	1.6
8.		5.0334	100.6517	Perak	Bukit Merah	3.1

4. Discussion

The analysis has shown that wind speed patterns across different monsoon phases are a significant meteorological parameter in determining rain enhancement potential areas. Malik (2020) reported that the absence of low-level clouds and strong 40 km/h winds at altitudes of 5,000 to 10,000 feet is unfavourable for conducting CSOs. As mentioned by Li et al. (2023), wind speeds during the Southwest Monsoon are generally below 7 m/s and can reach up to 15 m/s during the Northeast Monsoon. Therefore, it is crucial to carefully select rain enhancement potential areas during the Northeast Monsoon, as stronger winds during this period may cause rain clouds to form outside the intended target areas. According to Sekaran (2024), the CSOs conducted in February 2024 over Bukit Merah in Perak and Air Itam and Teluk Bahang dams in Penang did not result in rainfall over the targeted areas. However, light rain occurs in nearby locations, such as Taiping and Kerian, due to strong winds at approximately 1,524 meters (5,000 feet) that may have carried seeded clouds away from the intended areas. This situation supports the findings of this study that wind speed patterns at seeding height can significantly affect the spread of seeding materials and the location of rainfall occurrence.

5. Conclusion

In conclusion, this study highlights that wind spatial patterns at seeding height vary significantly across different monsoon seasons in Peninsular Malaysia and are essential in determining the effectiveness of CSOs. By applying the logarithmic wind profile and kriging interpolation, wind speed classification maps were successfully produced. Overall, this study has proven that geospatial techniques enable better estimation of wind speeds in the area, thus allowing the identification of potential rainfall enhancement areas for future CSO. Future studies should include additional meteorological parameters, the use of integrated GIS and satellite remote sensing images like ERA5 satellite images to model long-term wind speed patterns at seeding height with high-resolution wind data across multiple atmospheric levels, including altitudes relevant to cloud seeding.

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