

Characterizing the Meteorological Signature of Frost Events in the Dieng Highlands

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Abstract – Frost in the Dieng Highlands is a localized agrometeorological hazard that appears during selected tropical highland nights, yet its recurring near-surface meteorological structure remains insufficiently documented using high-temporal-resolution observations. This study characterizes the meteorological signature of Dieng frost events using quality-controlled 10-minute Automatic Weather Station (AWS) observations from 2021 to 2025. Observations were arranged into nocturnal windows from 19:00 to 06:50 Western Indonesian Time and classified into frost and non-frost nights using 50 documented event dates. Temporal distribution, median nocturnal composite profiles, Mann-Whitney U tests, Cliff's delta, and Spearman correlation were applied to temperature, humidity, dew-point depression, wind speed, rainfall signal, cooling rate, and pressure. Among 1,819 analyzed nights, 50 were classified as frost nights, corresponding to 2.75% of the observation period. The events were concentrated in the dry-season months, especially July, followed by August and June. Frost nights showed a persistent nocturnal thermal pathway, with median night-mean and minimum temperatures of 6.11 °C and 2.65 °C. They were also calmer, had stronger negative cooling rates, and lower rainfall signals, whereas dew-point depression and relative humidity did not differ significantly between classes. These results indicate that Dieng frost is best understood as a combined cold, calm, humid, radiatively efficient, and seasonally dry nocturnal signature rather than as a low-temperature condition alone.

Keywords: Dieng Highlands; frost occurrence; meteorological signature; nocturnal cooling; radiation frost.

1. Introduction

The Dieng Highlands are characterized by a tropical mountain environment where elevation, terrain configuration, and open agricultural surfaces interact to produce distinct near-surface weather conditions. Although frost is commonly associated with temperate and subtropical regions, the same physical process can occur in tropical highlands when nocturnal radiative cooling becomes sufficiently strong to cool exposed surfaces and the adjacent near-surface air layer. In Dieng, this phenomenon is locally known as embun upas and has become an agrometeorological hazard because ice deposition or frozen dew on crop surfaces can injure plant tissues and reduce agricultural productivity, particularly in open-field vegetable farming systems [1- 3].

Frost formation is closely related to the physical processes occurring within the nocturnal near-surface layer. After sunset, the land surface loses energy through longwave radiation, while heat supply from the air above and the soil below may be insufficient to compensate for this loss. Under calm and radiatively efficient conditions, this process produces a shallow cold layer close to the ground. Weak wind can reduce turbulent mixing with warmer air aloft, while local terrain may support cold-air pooling in lower or sheltered parts of the highland landscape. These processes are consistent with the general understanding of radiation frost, near-ground microclimate, and stable nocturnal boundary-layer development over complex terrain [4 - 8].

The occurrence of frost is therefore not controlled by air temperature alone. It has a complex relationship with several meteorological parameters, including minimum temperature, relative humidity, dew-point temperature, wind speed, rainfall, and the intensity of nocturnal cooling. A low minimum

temperature may indicate a cold background state, but visible frost may not occur if wind-induced mixing, rainfall, cloud-related disturbance, or unsuitable surface conditions interrupt the cooling process. Conversely, frost-forming nights often reflect the simultaneous development of cold air, weak wind, sufficient moisture, and efficient radiative cooling.

Previous studies on frost in the Dieng region have provided important foundations for understanding its spatial risk, predictive potential, and meteorological background. Pradana et al. [9] showed that frost hazard in Dieng is influenced by local terrain characteristics and agricultural exposure. Aini and Faqih [10] examined the use of subseasonal-to-seasonal temperature information for anticipating frost-risk periods. Numerical modelling studies have also indicated that Dieng frost is associated with low temperature, weak surface wind, and near-saturated atmospheric conditions, although local-scale discrepancies between model outputs and observations remain important [11, 12]. In a broader climate context, Nugraheni et al. [13] placed Dieng frost within the variability of surface temperature and cold extremes over the Dieng Plateau.

The practical relevance of Dieng frost has also been emphasized by institutional and applied studies. BMKG [14] reported that frost and minimum-temperature observations in the Dieng area have been supported by Automatic Weather Station instrumentation and that frost mainly appears during the dry season when particular highland weather conditions are met. Jufri et al. [15] developed a real-time frost monitoring system for Dieng agriculture, highlighting the importance of temperature, humidity, dew point, and wind information for operational monitoring. Fatiatun et al. [16] discussed crop damage and farmer mitigation practices related to embun upas, while the FAO initiative on frost early warning in Dieng further shows the need for timely meteorological information to support agricultural risk reduction [17].

Despite these advances, the recurring near-surface meteorological structure of frost-forming nights in the Dieng Highlands remains insufficiently characterized using continuous high-temporal-resolution observations. Many existing studies have focused on hazard mapping, model simulation, prediction, monitoring systems, or agricultural impacts. Fewer studies have explicitly examined how temperature, humidity, dew-point depression, wind, rainfall, and cooling rate evolve together during documented frost-event nights and how these conditions differ from non-frost nights. This gap is important because frost occurrence in Dieng is rare but recurrent, suggesting that it requires a specific alignment of meteorological conditions within the local dry-season highland environment. Similar reasoning has been used in other frost-prone agricultural regions, where minimum temperature must be interpreted together with location, season, and exposure [18].

In this study, the term meteorological signature is used to describe a coherent and repeatable set of near-surface atmospheric signals associated with frost occurrence. The signature does not refer to a single index, operational threshold, or isolated causal variable. Instead, it represents the combined behaviour of thermal, moisture, wind, rainfall, and cooling-related parameters during the nocturnal period. This study aims to characterize the meteorological signature of frost events in the Dieng Highlands using quality-controlled 10-minute Automatic Weather Station observations from 2021 to 2025.

2. Material and Method

2.1. Study area and meteorological observations

The study used quality-controlled 10-minute weather observations from an Automatic Weather Station (AWS) in the Dieng Highlands during the 2021–2025 period. The AWS is located at 7°12'18" S and 109°54'27" E, at an elevation of approximately 2,050 m above mean sea level. The available variables included rainfall record (rr), wind speed, wind direction, average air temperature, minimum air temperature, relative humidity, air pressure, and dew-point temperature. Cooling rate and dew-point depression were subsequently derived from the available observations. All observations were recorded in Western Indonesian Time (WIB, UTC+7). Detailed instrument metadata, including sensor manufacturer, model, measurement accuracy, and installation height, were not available in the archived dataset. The use of automatic surface observations is consistent with the role of surface observing systems in documenting near-surface meteorological variability [19].

2.2. Frost-event inventory and documentary classification

Frost-event dates were compiled through a documentary review of reported frost occurrences in the Dieng Highlands during 2021–2025. The event dates were identified from publicly accessible documentary sources, including official institutional reports, national and regional online media reports, retrospective or multi-day reports, and dated visual documentation published through social media. These documentary sources were used to identify reported dates of frost occurrence, whereas the AWS observations were used separately to characterize the meteorological conditions associated with those dates. The final inventory consisted of 50 documented frost-event dates.

For each event date, the supporting source and type of documentary evidence were recorded. To provide a more concise representation of the inventory, the supporting evidence was grouped according to the form and temporal specificity of the available information. Official institutional reports, explicitly dated online reports, and dated visual documentation were grouped as explicit/official or dated-visual evidence. Reports that retrospectively identified previous frost occurrences or described frost occurring over several specified dates were grouped as retrospective or multi-day evidence. Forecast-based reports and sources providing indirect information on frost occurrence were classified as lower-confidence documentary evidence. The annual distribution of these evidence groups is summarized in Table 1.

Table 1. Annual distribution of documentary evidence categories supporting frost-event dates in the Dieng Highlands during 2021–2025.

Year	Explicit/official or dated-visual evidence	Retrospective or multi-day evidence	Lower-confidence evidence	Total
2021	5	2	0	7
2022	2	3	2	7
2023	7	6	0	13
2024	5	8	0	13
2025	6	3	1	10
Total	25	22	3	50

As shown in Table 1, 47 of the 50 documented frost-event dates were supported by either explicit/official or dated-visual evidence or by retrospective and multi-day reports referring to specified event dates. Only three dates were retained from lower-confidence documentary evidence. The classification was used to describe the provenance and relative documentary strength of the event inventory and was not used to assign different statistical weights to individual events. Therefore, all retained dates were treated equally in the subsequent frost/non-frost classification.

The AWS observations were not independently used to determine whether frost occurred. A nocturnal period was labelled as a documented frost-event night when its assigned morning date matched a date in the documentary inventory. All remaining complete nocturnal periods were classified as non-frost nights. Because continuous field-based visual observations were unavailable for every night and the supporting documentary evidence varied in strength, the inventory should not be interpreted as a uniformly field-verified frost record. Therefore, the analysis represents a meteorological comparison between documented frost-event nights and the remaining observational record rather than a complete physical frost-detection assessment.

2.3. Nocturnal-window construction and data completeness

The 10-minute observations were reorganized into nocturnal windows extending from 19:00 WIB to 06:50 WIB on the following morning. This interval was selected because radiation frost is associated with surface heat loss after sunset and generally reaches its most favourable conditions shortly before sunrise. Each nocturnal window contained 72 expected observations. The date assigned to each nocturnal window corresponded to the following morning. For example, observations recorded from 19:00 WIB on 5 July 2021 to 06:50 WIB on 6 July 2021 were assigned to the night date of 6 July 2021. No interpolation or statistical imputation was applied to missing observations. Only nocturnal windows containing all 72 expected 10-minute observations were retained, while windows with one or more missing records were excluded. Following quality control and completeness screening, 1,819 nocturnal periods were included in the analysis, consisting of 50 documented frost-event nights and 1,769 non-frost nights.

2.4. Meteorological indicators

Nightly meteorological indicators were calculated to represent the thermal, moisture, wind, rainfall, and pressure conditions associated with frost occurrence. The indicators included night-mean air temperature, minimum air temperature, mean and maximum relative humidity, minimum dew-point depression, mean wind speed, night-time rainfall signal, minimum cooling rate, and mean atmospheric pressure. Dew-point depression was calculated as the difference between air temperature and dew-point temperature, as expressed in Equation (1).

$$D_{Td} = T - T_d \quad (1)$$

Where D_{Td} is the dew-point depression, T is the air temperature, and T_d is the dew-point temperature. A smaller dew-point depression indicates that the near-surface air is closer to saturation, consistent with the use of dew point as an indicator of near-saturation conditions [20].

The cooling rate was calculated from consecutive 10 minutes average air-temperature observations using Equation (2).

$$CR_t = \frac{T_t - T_{t-1}}{10/60} \quad (2)$$

where CR_t is the cooling rate in $^{\circ}\text{C h}^{-1}$, T_t is the air temperature at the current observation time, and T_{t-1} is the air temperature recorded 10 minutes earlier. Negative values indicate decreasing air temperature, while more negative values represent more rapid cooling. The minimum cooling rate within each nocturnal window was used to represent the strongest cooling phase of the night.

The rainfall variable was treated cautiously because inspection of the AWS record indicated that the rr field behaved as a stepwise accumulated or retained rainfall value rather than as an independent 10-minute rainfall amount. Therefore, the individual rr values were not summed across the nocturnal window. Instead, a conservative night-time rainfall signal was calculated using Equation (3).

$$RR_{\text{signal}} = RR_{\text{max}} - RR_{\text{min}} \quad (3)$$

where RR_{max} and RR_{min} are the maximum and minimum rr values within a nocturnal window. This indicator was interpreted as a rainfall signal rather than as a fully validated accumulated rainfall total.

2.5. Statistical analysis

The analysis compared frost-event and non-frost nights using temporal distributions, median nocturnal composite profiles, the Mann–Whitney U test, Cliff’s delta, and Spearman rank correlation. The Mann–Whitney U test was used because normality was not assumed and the frost/non-frost classes were highly imbalanced [21, 22]. Statistical significance was assessed at $p < 0.05$. Cliff’s delta was used to quantify the magnitude and direction of distributional separation between frost-event and non-frost nights [23]. Negative values indicate that a meteorological variable generally had lower values during frost-event nights, whereas positive values indicate that it generally had higher values during frost-event nights. Spearman rank correlation was used to assess the monotonic association between each nightly meteorological variable and the binary frost label [24]. Frost-event nights were coded as 1, while non-frost nights were coded as 0. Because frost events represented only a small proportion of the analysed record, Spearman’s rho was interpreted as a supplementary measure of association, while Cliff’s delta was used as the principal measure of practical separation between the two classes.

3. Results and Discussion

3.1. Temporal concentration of frost events

The analysis covered 1,819 complete nocturnal periods from 2021 to 2025, as summarized in Table 2. Of these, 50 nights were classified as documented frost-event nights, representing 2.75% of the analysed record. Frost events were documented in every study year, with 7 events in both 2021 and 2022, 13 events in both 2023 and 2024, and 10 events in 2025. The annual proportion ranged from 1.92% in 2022 to 3.56% in 2023, indicating that frost was a relatively rare but recurrent feature of the observational period.

The temporal distribution of the documented events is presented in Figure 1. The monthly frequency shows a pronounced concentration during the middle of the dry season. July accounted for 26 of the 50

documented frost events, followed by August with 11 events and June with 6 events. Smaller numbers occurred in May and December, while isolated events were documented in January, March, and April. The accompanying date-level distribution further shows that the June–August concentration occurred repeatedly across different study years rather than being restricted to a single year. These results indicate a clear seasonal concentration of documented frost occurrence during the dry-season months, although occasional events were also recorded outside the main seasonal period.

Table 2. Data coverage and frost occurrence by year based on the 50-date event inventory.

Year	Nights	Frost	Non-frost	Frost (%)
2021	358	7	351	1.96
2022	365	7	358	1.92
2023	365	13	352	3.56
2024	366	13	353	3.55
2025	365	10	355	2.74
Total	1,819	50	1,769	2.75



Figure 1. Temporal distribution of documented frost events in the Dieng Highlands during 2021–2025, showing monthly frequency and individual event dates by year.

3.2. Nocturnal thermal pathway

The clearest meteorological signature appears in the nocturnal thermal pathway. Figure 2 shows that frost nights were already colder than non-frost nights in the early evening and remained colder throughout the nocturnal window. Median night-mean temperature was 6.11 °C on frost nights, compared with 13.47 °C on non-frost nights. Median minimum temperature was 2.65 °C on frost nights and 11.36 °C on non-frost nights. Both variables differed significantly between classes ($p < 0.001$), with large negative Cliff's delta values. This shows that the thermal separation is not only statistically significant but also meteorologically substantial.

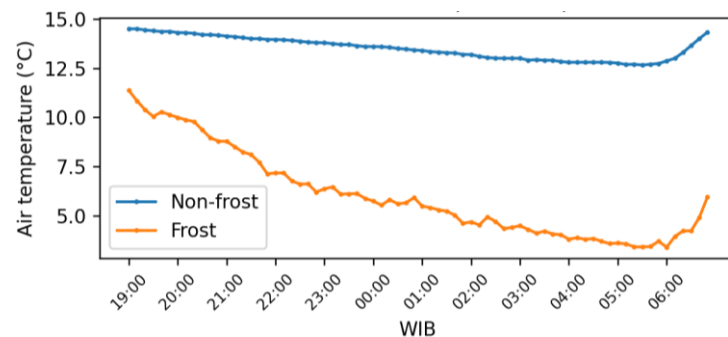


Figure 2. Median nocturnal air-temperature profile for frost and non-frost nights.

This behaviour is consistent with radiation frost. Under calm and radiatively efficient conditions, exposed surfaces lose longwave radiation faster than heat can be replenished from the air above or from the ground below. The result is gradual but persistent cooling of the near-surface layer. In mountain and basin-like terrain, cold-air pooling and weak turbulent exchange can further strengthen local temperature

contrasts [7, 8]. The Dieng frost signal therefore appears as a sustained night-time cooling pathway rather than as a short-lived temperature fluctuation.

3.3. Moisture, wind, rainfall signal, and cooling rate

Moisture variables showed a more nuanced pattern. Relative humidity was high on both frost and non-frost nights, with nearly identical median mean relative humidity values. Thus, relative humidity alone did not separate frost from non-frost nights. Minimum dew-point depression did not differ significantly between frost and non-frost nights, with medians of 0.05 °C and 0.06 °C respectively ($p = 0.318$). This result reinforces that moisture alone is not a discriminating factor. Rather, it indicates that the Dieng near-surface environment is consistently humid regardless of frost occurrence, and the decisive contrast arises when this humid background coincides with stronger cooling and weaker turbulent mixing.

Wind speed provided a clearer separation between the two groups. Frost-event nights had a median mean wind speed of 0.33 ms^{-1} , compared with 1.17 ms^{-1} on non-frost nights. Weak wind helps maintain a shallow stable layer near the surface by reducing turbulent mixing with warmer air above. In the Dieng setting, these calm conditions support the retention of cold air near exposed surfaces and are consistent with frost-pocket formation in complex terrain. The contrasting median nocturnal wind-speed profiles of frost-event and non-frost nights are illustrated in Figure 3.

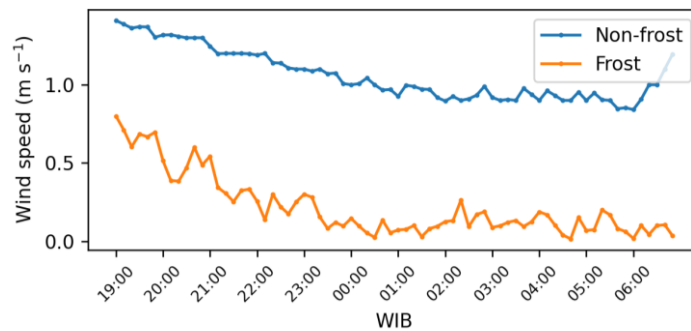


Figure 3. Median nocturnal wind-speed profiles for frost and non-frost nights.

The statistical contrasts between frost-event and non-frost nights are summarized in Table 3. The night-time rainfall signal was lower on frost-event nights, with a median within-window rr range of 0.00 mm compared with 0.20 mm on non-frost nights. Although this separation was weaker than the temperature and cooling-rate signals, it is physically consistent with radiation frost, because rainy or disturbed nights generally inhibit sustained surface heat loss. The minimum cooling rate also differed strongly, with frost-event nights showing a more negative median value of -5.77 °C h^{-1} , compared with -4.08 °C h^{-1} on non-frost nights. This reinforces the interpretation that frost is associated with more persistent nocturnal heat loss.

Table 3. Statistical contrast between frost and non-frost nights based on the 50-date event inventory.

Variable	Frost med.	Non-frost med.	p	Delta	rho
Night-mean air temperature (°C)	6.11	13.47	<0.001	-0.91	-0.26
Minimum air temperature (°C)	2.65	11.36	<0.001	-0.93	-0.26
Mean wind speed (ms^{-1})	0.33	1.17	<0.001	-0.59	-0.17
Night-time rainfall signal (mm)	0.00	0.20	<0.001	-0.30	-0.09
Minimum cooling rate (°C h^{-1})	-5.77	-4.08	<0.001	-0.53	-0.15
Minimum dew-point depression (°C)	0.05	0.06	0.318	-0.08	-0.02
Mean relative humidity (%)	96.99	96.99	0.504	0.06	0.02

As illustrated in Figure 4, the numerically modest Spearman correlation coefficients should not be interpreted as evidence of negligible practical separation between frost-event and non-frost nights. The binary frost label was highly imbalanced, with only 50 frost-event nights compared with 1,769 non-frost nights, which likely attenuated the magnitude of the rank-based correlation coefficients. In contrast, Cliff's delta directly quantified the distributional separation between the two groups. Therefore, the large negative

Cliff's delta values for night-mean and minimum air temperature indicate substantial practical differences despite the comparatively modest Spearman's rho values.

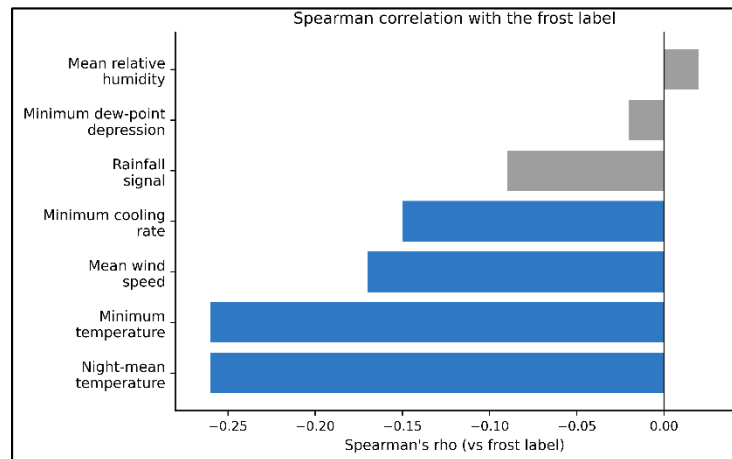


Figure 4. Spearman correlation between nightly meteorological variables and the frost label.

3.4. Synthesis of the meteorological signature

The results support the use of meteorological signature as a diagnostic framework. The signature is not a new index or a single operational threshold. It is a recurring combination of near-surface conditions that distinguishes documented frost-event nights from the larger population of non-frost nights. Based on the 50-date inventory, the Dieng frost signature consists of five main elements: a cold nocturnal thermal background, persistent radiative cooling, calm boundary-layer conditions, a lower rainfall or disturbance signal, and seasonal concentration during the dry-season months. The principal elements of the Dieng frost meteorological signature are summarized in Table 4.

Table 4. Summary of the meteorological signature of documented frost events in the Dieng Highlands.

Signature	Observed evidence	Meteorological meaning
Cold background	Lower night-mean and minimum temperatures	Near-surface air is already colder from the early evening.
Persistent cooling	More negative minimum cooling rate	Longwave heat loss continues through the nocturnal period.
Calm layer	Lower mean wind speed	Reduced turbulent mixing allows cold air to remain near the surface.
Low disturbance signal	Lower rainfall signal	The night is more consistent with sustained radiative heat loss.
Seasonal timing	Peak in July and clustered in June-August	Dry-season background favours frost-forming conditions.

Two interpretation limits are important. First, the available AWS data do not include direct observations of cloud cover, longwave radiation, leaf-surface temperature, soil temperature, or surface wetness. Therefore, the available observations do not provide direct evidence of clear-sky radiative forcing, and the results are more appropriately interpreted as being consistent with radiatively efficient nocturnal conditions. Second, because the *rr* field behaved as a stepwise accumulated or retained value, it was treated conservatively as a night-time rainfall signal rather than as a fully validated accumulated rainfall total. Consequently, the rainfall-related results should be interpreted as an indicator of lower nocturnal rainfall or disturbance rather than as a precise measure of rainfall accumulation.

Overall, the meteorological signature of Dieng frost is best interpreted as a coupled nocturnal state rather than an isolated temperature anomaly. Low temperature provides the thermal background, weak wind helps preserve a shallow stable layer, moisture availability remains common across the highland environment, and the lower rainfall signal permits more sustained cooling. This combination supports the operational direction suggested by monitoring and early-warning studies in Dieng: frost-risk information

should combine temperature, humidity or dew point, wind, rainfall condition, and seasonal timing rather than rely on a single temperature threshold [15], [17].

4. Conclusion

Dieng frost is a rare but recurrent dry-season phenomenon that depends on the alignment of several near-surface meteorological conditions. The strongest signature is thermal. Frost nights are markedly colder, with a persistent cooling pathway toward early morning, weaker wind, stronger cooling, and a lower rainfall signal. Dew-point depression and relative humidity do not differ significantly between classes. Overall, Dieng frost is best understood as a cold, calm, radiatively efficient, and seasonally dry nocturnal pattern rather than a low-temperature condition alone. Future work should incorporate direct observations of frost timing, surface wetness, and cloud cover to strengthen early-warning applications for agricultural risk reduction.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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