NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Bulletin of Geography. Physical Geography Series, No. 27 (2024): 57–69
http://doi.org/10.12775/bgeo-2024-0010

Geomorphological control on the scarce-tropical frost events in the Dieng Volcanic Complex, Indonesia

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Abstract. In recent decades, frosts have been reported in several volcanic landscapes in the tropical Indonesian archipelago. However, this unique and rare phenomenon is still poorly understood and not covered in the literature. In this paper, we evaluate the influence of various geomorphological aspects on frost formation in the Dieng Volcanic Complex (DVC). There are several significant findings in this study. First, frost occurs in the dry season in various basins with land cover of natural shrubs and grasses. Second, several basin structures exist in the DVC, but not all allow frost formation. Frost formation results from a combination of factors that include air temperature with morphology and land cover type. Lastly, not all aspects of geomorphology affect the appearance of frost; they are limited to morphology/structure and land cover material. In summary, this paper provides new insight into the influence that the geomorphological conditions of volcanic complexes have on climatic control over the formation of frost.

Key words:
Frost,
outwash,
geomorphology,
volcanic complex,
Indonesia

Introduction

Frost, also known as hoarfrost, is a rare and unique phenomenon in Indonesia. The Indonesian archipelago, located in the tropics, has a climate characterised by high average air temperatures throughout the year and no winter. Concerning this climatic situation, frost is an interesting weather phenomenon to study. The formation of ice crystals due to dew freezing on the land's surface at certain times is often a surprise to the public, gaining much attention and even temporarily attracting tourism. In Indonesia, frost forms in high mountain areas with low air temperatures. In terms of their genesis, the mountainous regions of Indonesia consist of structural and volcanic landforms. Interestingly, many frosts have occurred in volcanic areas with large calderas, such as Papandayan, Dieng, Tengger, Iyang and Ijen (Van Steenis 2010). Recently, as reported in the mass media and reported through social media, frost was also found on the stratovolcano slopes of Java Island, such as Semeru, Lawu and Merbabu. Frost in the tropical mountains of tropical Southeast and South Asia at more than 1500 m a.s.l. is an exciting phenomenon that has long received attention (Kalma et al. 1992).

Tropical frosts, such as those that occur in Indonesia, differ from frosts that form in four-season regions in terms of how they are created and the impacts they have. Unlike frosts in the four seasons that form seasonally when there is no vegetation growth, frosts in the tropics form for just a few hours each day and are immediately followed by land warming (Kasprzak et al. 2022). This is especially true for tropical plants that cannot withstand frost (Van Steenis 2010). In many regions of Indonesia, especially Java Island, frost damage to crops has been reported. The problem is that studies on tropical frost are still lacking. As a unique and rare phenomenon, this topic is still poorly understood and not covered in detail in the literature. Moreover, there is also a lack of discussion on the influence of geomorphological factors as climate controls in determining frost formation in a location.

Dieng Volcanic Complex (DVC) is a volcanic complex located in the centre of Java Island, Indonesia. The region has received the most attention concerning frost, since this phenomenon usually occurs at the peak of the dry season in late July to early August. Reports from the Indonesian Meteorological, Climatological and Geophysics Agency in 2021 show that frost in DVC occurs in May and July (Harmoko 2021). Meanwhile, Aini dan Faqih (2021) explained that frost can form from July to September in DVC. The formation of frost in DVC is a unique meteorological phenomenon on the one hand, but on the other hand, it also has a significant negative impact on the agriculture cultivated in this region (Pradana et al. 2018a, b). The morphology of DVC as volcanic complexes is also a specific type of volcanic landform compared to stratovolcanoes and calderas, two other types of volcanic landforms that also contain frost (Zaennudin 2010; Harijoko et al. 2016; Ashari and Purwantara 2022). DVC is a group of many volcanic morphologies in the form of small- to medium-sized stratocones growing in a former ancient caldera with a small area. This morphology differs from other volcanic formations in Indonesia, such as stratovolcano and caldera, which are single and large volcanic morphological units.

Studies on the genesis and mechanism of frost formation in DVC, especially frost concerning geomorphological characteristics, are important issues that need further evaluation. The studies on frost that have been conducted in DVC so far have focused on frost as a meteorological event (Aini and Faqih 2021; Harmoko 2021) and its impact on agriculture (Pradana et al. 2018a, b). Meanwhile, studies that take a frost perspective concerning landscape characteristics, as exemplified by Lindkvist et al. (2000) and Saavedra and Takahashi (2017), have not yet been found in DVC and other regions in Indonesia. Studies of frosts and their relationship with volcanic landscapes conducted around the globe are still relatively lacking. The lack of literature items on frost and its relationship with geomorphologic factors is a scientific gap that this study aims to address. This study aims to analyse the phenomenon of frost, especially related to geomorphological control, which, in this case, is the topographic factor.

In this paper, we evaluate the influence of various geomorphologic aspects of DVC on frost formation. The objectives of this paper are to analyse as follows: (1) the characteristics of the meteorological and land environment in DVC at the time of the frost event, (2) the spatial distribution of frost by landform in DVC, (3) the influence of various geomorphologic aspects on frost phenomena in DVC. This research intends to explain that various aspects of geomorphology, including landform, material, process, structure, stage and environment, affect the occurrence of frost and its spatial distribution. This paper attempts to provide alternative information about the influence of geomorphological aspects on the formation and distribution of frost as a unique meteorological phenomenon in the tropics.

Method

Data collection and analysis

This study uses a geomorphological approach to analyse the problem, which focuses on characterising landforms and landform systems and stems from geographical spatial science (Hugget 2017). This study examines the various environmental processes that occur in landforms – one of the two problems of geomorphology as described by Urban (2013). Related to the geomorphological scale used, this study implements absolute space with geomorphological feature order V and VI, which is a coverage area of 10 km^2 or more detailed up to 10 m^2, volcanic structure analysis unit, and local climate influenced by the pattern of relief (Millar 2013). In analysing the problem, the study is also supported by various geography themes, namely location, place, human–environment interaction, movement and region.

This study uses primary and secondary data. Primary data were obtained through field observations, namely geomorphological data, including morphography and morphometry of landforms; geological data, including rock lithology; weather data, including air temperature and air humidity; and land condition data, including land use, soil temperature and soil moisture. Secondary data from various sources also support primary data related to these variables. These secondary data are complementary to the primary data. Secondary data collected in this study include documents published in maps and statistical data, literature studies, and satellite imagery published through Google Earth. The relationship between the types of data collected, the data collection methods used, and the instruments and secondary data sources is shown in Table 1. The air temperature measurements taken are not free from several uncertainties of devices, including instrument limitation and self-heating. To overcome this situation, we used several thermometers simultaneously during the measurement and recorded the values indicated by many thermometers.

The data analysis used in this study is a descriptive-spatial analysis with a geomorphological approach supported by GIS analysis. Descriptive analysis was conducted by considering the spatial variation of frost phenomena in various morphological units of DVC and evaluating the causal relationships between different geomorphological variables with frost events. This analysis also considers spatial and temporal scales in geomorphology as described by Millar (2013), and geomorphic frame of system analysis as defined by Urban (2013). The spatial scale used is geomorphological features order V. Thus, this study analyses the causal relationship between the influences that stratocone cone structures, inter-stratocone valleys, or more detailed landforms such as craters and stratocone slopes have on frost formation. In addition to the spatial scale, this study implements a temporal scale based on geomorphic

Table 1. Types of data, method of data collection, and instruments/data sources

No.	Data	Collection method	Instrument/data sources
1	Air temperature	Observation	GPS, thermometer, air quality tester JLDG JD-3002, Particle Counter HTI HT 9600
2	Relative humidity	Observation	GPS, thermo-hygrometer, air quality tester JLDG JD-3002, Particle Counter HTI HT 9600
3	Soil temperature	Observation	Glass thermometer
4	Soil humidity	Observation	Soil test kit, Soil pH-moisture meter
5	Morphography of landform	Observation	GPS, digital camera, Drone DJI Phantom
6	Morphometry of landform	Observation	GPS, Abney level, geological compass, levelling staff 5 meter
		Remote sensing image interpretation	Digital Elevation Model from Shuttle Radar Topography Mission, Google Earth engine
7	Geomorphological process	Observation	GPS, digital camera, Drone DJI Phantom, observation guide
8	Rock type	Observation	Geological compass, geological hammer, geological loupe
		Documentation	Geological Map of Dieng Volcanic Complex provided by Sukhyar et al. (1986) and Luthfian (2014)
		Literature study	Harijoko et al (2016)
9	Land use	Documentation	Indonesian Topographical Map (RBI Map / Peta Rupabumi Indonesia) Sheet 1408-441 and 1408-442
		Observation	GPS, digital camera, Drone DJI Phantom, observation guide

time. In this study, analysis at sampled time is used, which means analysis is limited to the time of a particular event.

Furthermore, GIS analysis was used to determine the spatial variation of frost occurrence in DVC. GIS analysis was performed with an average nearest neighbour to determine the distribution pattern of frost events in the study area. In this case, we identify location points representing the area of frost occurrence. Then, these points are analysed for their distribution patterns. This analysis was used to strengthen spatial variation in the previous stage descriptively.

Study area

This study was conducted in the DVC area, Central Java, Indonesia. As a volcanic complex, DVC is one of Indonesia's most volcanically complex areas (Verstappen 2013; Harijoko et al. 2016; Ashari and Purwantara 2022). The DVC is located in the central part of Java Island, which is physiographically in the northern zone of the area (Zaennudin 2010). Referring to the classic theory on the physiography of Java Island written by Pannekoek (1949), the position of the DVC in the northern zone is an anomaly because volcanic areas on Java Island are generally located in the centre of the island. DVC is located at coordinates 9192467 MU to 9211006 MU and 368616 MT to 391618 MT in the Universal Transverse Mercator (UTM) coordinate system zone 49S. The area of DVC is 249 km^2, which administratively includes four districts in Central Java Province, Indonesia (Fig. 1).

Verstappen (2013) explains that DVC is a collection of small- to medium-sized volcanic features that developed within the caldera of an old volcano. The steep rim of the caldera is visible in the north. Towards the south of the steep wall of the caldera there is recent Holocene volcanic activity, where young, active volcanoes produced a variety of morphologies, including eruption craters, tuff ring craters, scoria cones, small stratovolcanoes, and lava flows. Eruptions in DVC vary between effusive in the east, explosive in the centre and phreatic in the west. Harijoko et al. (2016) give a slightly different

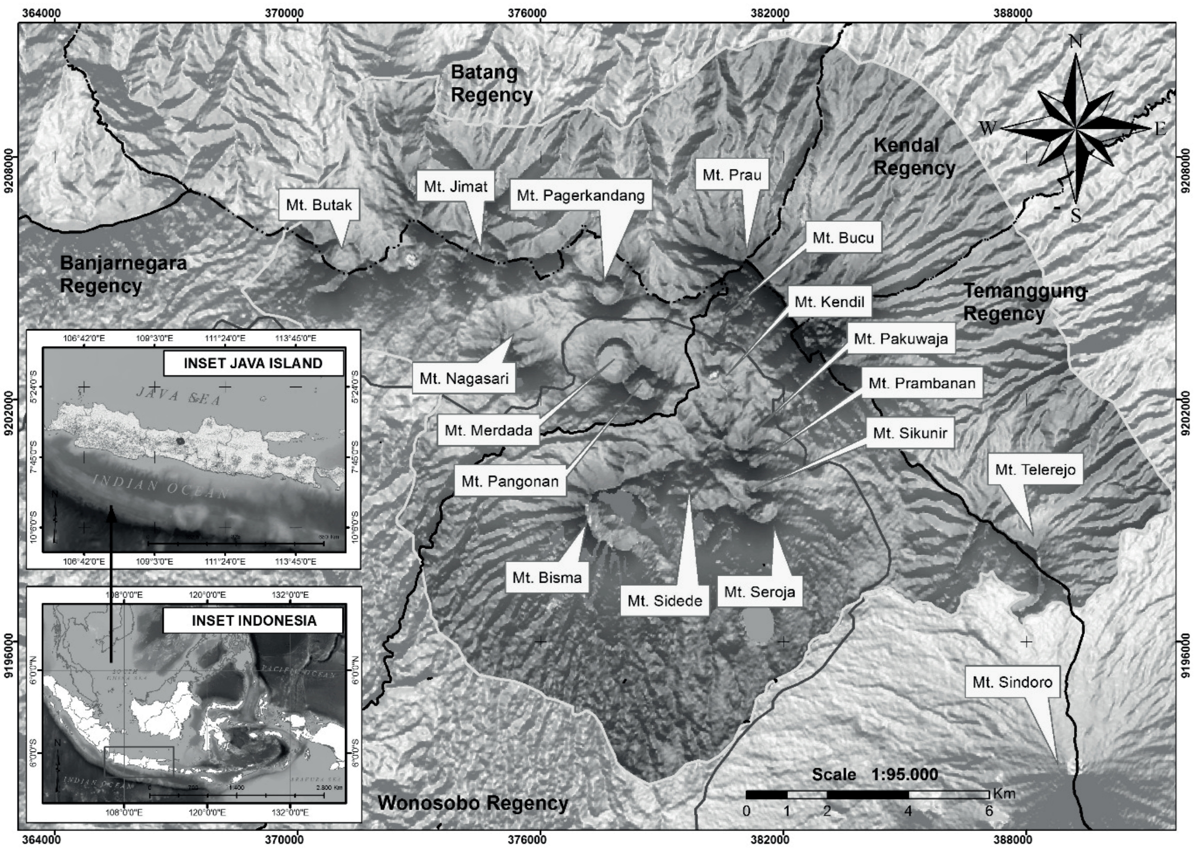

Fig. 1. Map of the Dieng Volcanic Complex

view of the arcuate structure of Mount Prahu, where the caldera slope is not purely formed by caldera-forming eruptions alone but also due to volcano-tectonic collapse caused by eruptions. The arcuate structure of Mount Prahu, which frames the caldera, is a prominent morphology and the main feature of DVC. The caldera floor of DVC itself is widely known in Indonesia as the Dieng Plateau, although volcanism rather than structural processes genetically form it.

As a volcanic complex, DVC is located next to two large stratovolcanoes, Sundoro (3,153 m a.s.l.) and Sumbing (3,371 m a.s.l.), which Lavigne et al. (2008) referred to as twin stratovolcanoes. In addition, four other volcanic units neighbour DVC, namely Rogojembangan, Jimat, Kendang and Telerejo. Within DVC itself, there are 12 volcanic units, namely Prahu, Nagasari, Sidede, Bisma, Pagerkandang, Bucu, Pangonan-Merdada, Kendil, Pakuwaja, Sikunir, Prambanan and Seroja (Fig. 1). These volcanic units grew and developed in three stages: pre-collapse episode, second episode and youngest episode. The first generation of pre-collapse episodes includes Prahu, Telerejo, Sidede, Bisma, Nagasari and Jimat. All these stratovolcanoes consist of pyroclastic rock deposits and lava flows and are located at the edge of DVC.

Furthermore, during the second episode, several stratocones emerged that underwent explosive eruptions and covered the depression with their volcanic products, namely Pangonan, Merdada, Pagerkandang, Bucu and Seroja. These stratocones consist mainly of pyroclastic and lava fallout deposits. With explosive activity, the volcanoes in this second episode are believed to be the primary source of the Dieng tephra that covers the Dieng and Batur depressions. Finally, in the youngest episode, several volcanoes appear in the south-eastern part of DVC, namely Pakuwaja, Sikunir, Prambanan and Kendil (Harijoko et al. 2010, 2016). Recent DVC activity is phreatic explosive eruptions, some of which have been recorded since the 18th century in geothermal areas such as the Pakuwaja Stratocone and several craters, namely Sileri, Sikidang and Candradimuka (Luthfian 2014).

DVC is one of the volcanic morphologies in Indonesia that experiences frost events at the peak of the dry season. According to Kalma et al. (1992), the frost formed at DVC is genetically categorised as radiation frost. Unlike advective frost, which occurs due to a large-scale cold air influx, radiation frost happens at night. It results from intense longwave radiation cooling in calm, clear, dry atmospheric conditions. Two field observations and measurements of frost occurrence were conducted in DVC on July 30, 2023 and August 20, 2023. The observation results show that frost does not occur in all areas of DVC but is limited to specific locations where frost is possible. From this, it can be seen that frost is influenced by weather factors in the DVC area and a combination of influences between various weather elements with geomorphological conditions and land cover.

In general, frost occurs when the DVC region in central Java experiences the peak of the dry season. The dry season in Indonesia is influenced by the movement of the monsoon from Australia, which is cold and dry. The Indonesian Meteorological, Climatological and Geophysical Agency (2019) explained that, from June to August, the cold monsoon from Australia moves actively and causes the peak dry season in Indonesian regions south of the equator, including Java Island. The insistence of dry and cold airflow from Australia causes relatively colder air conditions, especially at night. Cold air can be felt more significantly in highland or mountainous areas.

Moreover, the Indonesian Meteorological, Climatological and Geophysical Agency (Setiawan and Ripaldi 2023), in its August 2023 weather report, explains that the DVC region has experienced below-normal rainfall since July 2023. The region also experienced very long days without rain of up to 60 days, which is expected to continue until September 2023. These meteorological conditions in DVC at the peak of the dry season, characterised by low rainfall and low temperatures, play a role in triggering frost. Various previous studies conducted by Harmoko (2021) and Aini and Faqih (2021) also show that the potential for frost is enormous at the peak of the dry season around the middle of the year.

The climate in DVC, as in other monsoonal regions of Indonesia, is characterised by a peak in rainfall at the turn of the year. This period is known as the rainy season. Meanwhile, minimal rain occurs in the middle of the year, when the Indonesian monsoonal region experiences the dry season. The average rainfall in the last ten years shows that the peak rainfall occurs in February, while the minimum rainfall occurs in August. The average annual air temperature based on data from

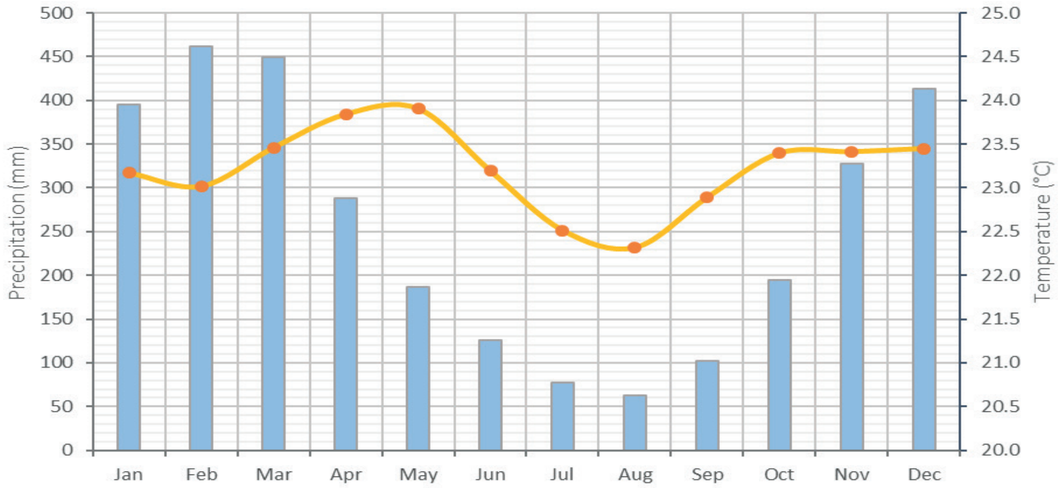

Fig. 2. Climatogram of the Dieng Volcanic Complex (2014-2023)

2014–23 shows that the highest air temperature occurs in May, which is likely related to the Sun's position in the southern hemisphere. The minimum air temperature occurs in August during the peak of the dry season. These cold and dry conditions cause frost to occur at DVC (see Fig. 2).

Result

Meteorological and land characteristics of DVC during frost events

In this section, we describe the characteristics of the physical environment in DVC at the time of the frost event. The physical environment characteristics include the meteorological and terrain conditions where the frost was found. Interestingly, frost does not occur in the entire DVC area but is limited to certain areas. This study observed the Dieng Basin, Kepakisan Basin, stratocone slopes bordering the Dieng and Kepakisan Basins, the Terus Crater Basin and Merdada Caldera. It turned out that frost did not occur in all areas observed. Frost did not occur on the slopes of the stratocone nor the Merdada Caldera and Kepakisan Basin. In two observations conducted on July 30, 2023 and August 20, 2023, frost was only found to occur in the Dieng Basin and Terus Crater Basin. Dieng Basin is surrounded by various stratocone units: Prahu, Bucu, Kendil, Pangonan, Merdada, Pagerkandang and Pakuwaja. The Dieng Basin is characterised by its highland morphology and is, therefore, better known to the public as the Dieng Plateau. Meanwhile, Terus Crater Basin is one of the craters in DVC located adjacent to Telaga Warna Crater Lake and Telaga Pengilon, both famous tourist attractions in the region.

Weather conditions in DVC at the time of frost in the two observations indicated low air temperature, very high relative humidity, weak wind movement, and no rain with a relatively clean atmosphere without cloud cover. The air temperature in the Dieng area generally ranges from 5°C to 8°C. The average air temperature that is not lower than zero is a factor that determines that frost does not occur throughout the DVC area. The relative humidity of the air in the region is very high (95–99%). Meanwhile, the average wind was only about 3–5 km/h. Weak winds cause the air to stand still, which in turn can play a role in causing frost. There are variations in these weather elements between different places in DVC. Compared to other sites in DVC, the Dieng Basin area and Crater Lake continue to have weather conditions allowing frost formation.

The Dieng Basin is one of the most frost-prone locations during the dry season year after year. The near-surface air temperature in this area can drop below zero degrees Celsius. Measurements on July 30, 2023 and August 20, 2023 show air temperature variations between –1°C and –2°C in different sectors of the basin. Sub-zero temperatures were observed in the early morning before sunrise, persisted around sunrise, and gradually increased with the morning sun. Similar conditions were observed at Terus Crater Basin, where the air temperature reached −1°C) at the time of measurement. This very low temperature was not found in all measurement locations. At the same time, the air temperature on the stratocone slopes, Merdada Caldera and Kepakisan Basin showed 5°C to 6°C. This indicates the presence of weather conditions in a minimal area, affecting the variation of frost occurrence throughout the study area. Low air temperatures below zero degrees Celsius are very important in the event of frost. Kalma et al. (1992) explain that frost occurs when the air temperature near the Earth's surface drops below zero degrees Celsius. Meanwhile, Moulton and Oliver (2005) explain that the presence of frost indicates that the surface where the frost forms is 0°C or colder.

Low air temperature is associated with high relative humidity. The relative humidity where frost is found when the temperature is below zero degrees Celsius varies between 90% and 99%. Meanwhile, the relative humidity ranged from 90% to 94% in other locations where frost was not found. This condition shows that relative humidity is not the primary determinant of frost occurrence, although saturated humidity affects frost occurrence, as explained by Moulton and Oliver (2005). The relative humidity of the air mass does not differ between locations where frost is found and those where frost is not found. Soil temperature and humidity also do not affect frost. Although the air temperature is below zero degrees Celsius when frost occurs, the soil temperature at that time is relatively warmer. Soil temperatures at the locations where frost was found ranged from 3°C to 10°C. The highest temperature was found near Balekambang Lake. According to information from Kalma et al. (1992), wet soil is warmer than dry soil.

Meanwhile, soil temperatures in locations where no frost occurred ranged from 7°C to 12°C. Soil moisture varied from 10% to 80% depending on the land cover type but also did not determine the occurrence of frost. It can be concluded that the soil in the study area did not freeze and did not determine the event of frost. The occurrence of frost is solely due to calm, cold air with certain types of land cover that quickly experience cooling.

Spatial distribution of frost by landform in DVC

In this section, we describe the spatial distribution of frost based on landforms in DVC. Measurements and observations were made at several locations in DVC, including the inter-stratocone basin, stratocone slope and crater basin. These various landform units were selected as measurement samples based on consideration of the variety of landforms present in DVC. Two basins, namely Dieng Basin and Kepakisan Basin, were chosen as locations that represent the morphology of the inter-stratocone basin; the stratocone slope is represented by Pangonan Volcano, while Merdada Caldera and Terus Crater Basin represent the crater basin morphology. In each landform unit with varied land use, more detailed observations are made to represent each land use. Land use variations in the study area include settlements, agricultural land and shrubs. Settlements are placed in the inter-volcanic basin and are places of population concentration with high building density. Agricultural land is also found in the inter-volcanic basin, filling areas not occupied as settlements. In addition, it is found on the stratocone slope. In the inter-volcanic basin and stratocone slope, agricultural land is planted with vegetable crops, especially potatoes. Meanwhile, shrubs grow naturally and wild on land not used for settlements and agriculture, namely in the crater basin.

The results of field observations show that among the various landforms, frost is only found on the landforms of the basin between stratocone and crater basin. The inter-stratocone basin is characterised by a broad basin morphology and flat to gentle slopes, and it is surrounded by stratocones with relatively steep slopes. Crater basins are smaller than inter-stratocone basins and can be located within the stratocone as the eruptive centre of the volcano or at the edge of the stratocone, indicating a possible side eruption. Interestingly, not all inter-stratocone and crater basins examined in the observations showed the presence of frost. Among the two inter-stratocone basins, frost was found in the Dieng Basin but not in the Kepakisan Basin. Similarly, in the crater basin landform, frost was found in the Terus Crater Basin but not in the Merdada Caldera Crater Basin. Meanwhile, no frost was found on the stratocone slopes.

These findings suggest that frosts form in particular environments, which allow for the fulfilment of various meteorological requirements for frost formation. It can also be said that frost formation is not associated with specific landforms within DVC but with specific morphological conditions. According to Van Steenis' explanation (2010), frosts in the Java Mountains form under the control of several physical requirements, including low temperatures in the mountains, still air for the accumulation of frozen air, a dry and clean atmosphere, heat conducted from the substratum, and the topography of the basin where cold, still air accumulates. The low air temperature and transparent atmosphere in the dry season in DVC are determinants of early frost formation, as discussed in the previous section. However, the findings of this study that frost does not occur everywhere and on all landforms within DVC prove that topographic factors determine frost formation.

Interestingly, frost that occurs on the landforms of the basin between stratocone and crater basins does not form evenly over the entire landform terrain. On small landforms such as the Terus Crater Basin, frost can form relatively evenly throughout the area because the land cover tends to be homogeneous, dominated by shrubs. However, frost is not found evenly on landforms of large sizes, such as the Dieng Basin. Among the various forms of land use in the Dieng Basin, namely settlements, shrubs, open agricultural land and agricultural land with crops, it turns out that frost only occurs in areas with shrub land cover. This condition shows that, in addition to topographic factors, other factors also determine the existence of frost, namely heat transmission from the substratum and radiation from objects on the surface. Thus, the spatial distribution of frost in DVC is not evenly distributed but in specific locations with topography and land cover suitable for frost formation.

Since frost is only formed on the topography of the basin with shrub land cover, the spatial distribution pattern of frost in DVC certainly follows the distribution pattern of the land cover. GIS analysis with the average nearest neighbour method shows that the existence of frost in the Dieng Basin has a clustered pattern with a z-score of −6.36. The clustered pattern cannot be separated from the distribution of shrub land cover, which tends to cluster while the dominant land use is

Fig. 3. Frost formed in DVC. (A) ice crystals on dry twigs in Dieng Basin, (B) Dieng Basin soccer field grass completely frosted, (C) frost found on grass around Setyaki Temple, Dieng Basin, (D) frost on shrubs in Terus Crater Basin. Photos A and B were taken on July 30, 2023 at 06:38 and 05:05, respectively. Photos C and D were taken on August 20, 2023 at 06:28 and 06:42, respectively.

agricultural land. Meanwhile, the frost distribution pattern in Terus Crater Basin is dispersed, with a z-score of 7.38. This condition is the opposite of the Dieng Basin, where the distribution of shrubs is more expansive, and only a few areas are used as agricultural land. In this study, we only found frost on grass and shrubland. Farmland with vegetable crops did not experience frost, as previous studies by Pradana, Mardiana et al. (2018) and Aini and Faqih (2021) have reported. In previous studies, it has been reported that frost on these farms causes damage to vegetable crops. The air temperature factor seems to influence the occurrence of frost, where the critical temperature of frost in agricultural fields ranges from −5°C to −7°C (Pradana et al. 2018). Our findings in our two observations in 2023 show minimum temperatures only ranging from −1°C to −2°C (see Fig. 3).

Influence of the geomorphic aspect on frost phenomena in DVC

In this study, we found that the phenomenon of frost in volcanic areas such as DVC is due not only to meteorological conditions but also to geomorphological factors on the Earth's surface, which play a crucial role. Geomorphological factors include aspects of structure, process and stage, referring to William Morris Davis, or morphology, material and process, according to Lester King (Oldroyd 2013; Pramono and Ashari 2014; Huggett 2017). Meanwhile, Berta (2005) explains that there are five topoclimatic variables, where the relief aspect related to the direct radiation of the Sun on a surface area needs attention in the context of frost occurrence.

Morphological factors play a vital role in determining the occurrence of frost. Steenis (2010) explains that the morphology of basins in the mountains, especially former craters covered by sediment, are pockets of frost that become the location of frost formation. This basin morphology is a place to store a layer of frozen air that is still. The heavy, cold air will descend to the surface and come into contact with objects that also cool due to their radiation at night. As a result, frost forms at the morphological base of the basin. Morphological aspects consist of morphometry and morphography. The Dieng Basin and Terus Crater Basin have morphometry conducive to being frost pockets with slopes at the base of the basin ranging from 0 to 3% and slopes at the basin's edge ranging from 15 to 70%. These morphometric conditions allow the cold air layer to accumulate near the surface with a height of only about three metres above the land surface (Fig. 4).

In addition to morphometry, morphographic aspects also play an essential role concerning frost. This is evidenced by the absence of frost in the Kepakisan Basin despite having a gentle slope at the base of the basin and a steep slope at the edge of the basin. The broad morphographic nature of the Kepakisan Basin, with two open gaps, allows for air circulation. Kalma et al. (1992) referred to this morphography as "cold air drainage". Moving air is not effective enough to cool the air to freezing. Not all basins in DVC can be categorised as frost pockets, as Van Steenis (2010) described. Only basins that fulfil the morphography of a basin without many open gaps with gentle bottom morphometry and steep slopes, which Kalma et al. (1992) referred to as "cold air puddles", can become frost pockets. Frost pockets are not associated with a particular type of landform. If they meet the morphographic and morphometric criteria, various landforms will become frost pockets, and vice versa; if they do not meet them, they will not.

The second factor is land cover material. Frost forms not on just any and all land covers but specifically on bush grass vegetation types. Referring to Steenis (2010), frost occurs due to the cooling of objects on the Earth's surface that cannot be balanced by the heat conducted from the substratum. Moulton and Oliver (2005) explain that surfaces already cooled by outward radiation are very suitable for frost accumulation. In agreement with these theories, the findings of this study also show that frost occurs on shrubgrass vegetation that cools quickly. Dry and withered grass and dead twigs also quickly become a medium for frost formation because little heat is conducted from the substratum. Various types of substratum have warmer temperatures than air temperatures. Measurements in the study area never obtained substratum temperatures lower than zero. In other words, there is no permafrost layer on the soil in the study area.

Land surface temperatures in the Dieng Basin with lacustrine sedimentary materials vary between 3°C and 10°C. The coldest surface temperatures were

Fig. 4. F Symptoms of near-surface cold air layer (A) Cold air layer with a height of about 3 metres above the surface of Dieng Basin farmland, (B) mist around Balekambang Pond with limited height. Photos A and B were taken on July 30, 2023, at 05:39 and 06:01, respectively.

found in areas planted with potatoes. Meanwhile, areas with shrub grassland cover where frost was present had higher surface temperatures of 4 °C to 10 °C. This shows that the heat transfer factor from the substratum to the surface land cover determines the occurrence of frost. In areas planted with potatoes in excellent and healthy condition, there is no frost even though the surface temperature is low. This is influenced by effective heat transfer. Meanwhile, frost occurs in areas with higher surface temperatures, but the land cover cannot transfer heat effectively. The same condition is also found in the Terus Crater Basin, where the relatively warm surface temperature ranging from 7 °C to 10 °C turns out to be frost because the land cover is in the form of grass shrubs that are not effective enough in transferring heat.

Other geomorphologic aspects, such as geomorphic processes and landform development stages, do not affect frost formation. Geomorphic processes that mainly occur in the DVC area are weathering, erosion and mass movement on stratocone slopes, and sediment deposition in basins. Many of these geomorphic processes occur during the rainy season. Meanwhile, frost is a phenomenon that occurs in the dry season, so geomorphic processes do not much control it. The stage of landform development in the DVC area is also relatively uniform because the various landform units have a relatively uniform age, namely from the Pleistocene.

Discussion

This study's leading and most important finding shows that frost in tropical volcanic complexes such as the Indonesian archipelago cannot be separated from meteorological and geomorphological factors. In this case, the meteorological factor is the very low air temperature near the Earth's surface, below zero degrees Celsius. Interestingly, the occurrence of these low air temperatures is precisely because of the influence of geomorphological factors, where the morphological structure in the form of a basin will allow the formation of frost pockets (Van Steenis 2010) or cold air puddles (Kalma et al. 1992). Not all basin morphologies can develop frost pockets. Basins with open crevices that drain cold air (Kalma et al. 1992) are unfavourable for frost formation. Small basins in the form of crater depressions are critical in frost formation. Meanwhile, no frost is found in the slopes and peaks of the stratocone that express the divergence of curved lines (Kalma et al. 1992). The above theories are validated in this study so that it can be said that frost in volcanic complexes is not much different from that in structural mountains.

In contrast to Kalma et al. (1992) and Van Steenis (2010), the findings of this study obtained different results from the theory proposed by Martinez et al. (2016). Based on their study findings, Martinez et al. (2016) showed that the freezing zone is located at the centre of the basin and forms a cold-air lake. Cold air blocked by natural or artificial barriers will cause the accumulation of frost to increase. Thus, frost is most abundant in the centre of the basin. Our findings obtained different results where frost occurs not always in the basin's centre but at the edges. This is because land cover is more important than morphology.

However, this study also obtained new findings that are pretty interesting. First, the cold air temperature in frost pockets is not only around two metres, as described by Van Steenis (2010), but can reach three metres or slightly higher. Secondly, land cover is the most decisive factor among the various factors that influence frost formation. Instead of frost pocket basins, the existence and distribution of frost in the DVC are more influenced by the type of vegetation covering the land. Evidently, in basins with steep morphometry and morphography more characterised by basins, frost cannot be formed because of land cover in agriculture, both planted and not yet planted. Conversely, basins with smaller morphometry and less deep basin morphography, such as the Terus Crater Basin, have frost due to land cover factors like grass and shrubs (Table 2). Third, this study also found frost on grass and shrub land cover at an air temperature of −1°C to −2°C. Meanwhile, frost that occurs on crops in DVC, as found in previous studies by Aini and Faqih (2021) and Pradana, Mardiana et al. (2018), was not found in this study. This leads to a new conclusion that frost can occur in various vegetation cover types with a greater critical temperature or colder air temperatures (e.g., 5°C to −7°C). However, frost is limited to grass and shrub land cover at smaller critical temperatures or relatively warm temperatures (−1°C to −2°C, as found in this study).

The findings of this study also reinforce the results of Masaki (2021), who explained that different types of land cover with varying conduction rates affect frosts that are not the same among various

Table 2. Basin morphometry in relation to frost occurrence in DVC

	Dieng Basin	Terus Crater Basin	Merdada Crater Basin	Kepakisan Basin
Elevation (m a.s.l.)	2061	2059	2045	1897
Depth (m)	169	40	238	124
Average Slope (%)	22.37	18.87	69.20	30.25
Maximum Slope (%)	43	39	123	60
Area (km^2)	1	0.11	0.47	0.56
Result	Frost	Frost	No Frost	No Frost

types of land cover. As a result, even though the meteorological conditions are the same, the surface heat may differ. As a result, frost may appear and disappear randomly. Slightly differently from the results of Masaki (2021), in this study, we found that frost is not random but tends to cluster in shrub areas.

This study also has similarities and differences compared to previous research. Kotikot et al. (2020) found that frost occurs in dry months that are cloudless and cold. These conditions are similar to those encountered in DVC. Lindkvist et al. (2000) showed that more than 90% of mountain frosts are radiation frosts. Terrain factors also determine the occurrence of frost, which occurs most often in narrow valleys and then in concave and flat locations. Dune and convex areas have minimal radiant frost. Compared to this study, our findings validate the radiation frost type but cannot prove the occurrence of frost in areas of mound and convex morphology. In this study, all the frosts found in DVC only occur in concave areas of tiny depressions.

Conclusion

Frost in tropical mountainous terrain is a unique phenomenon that results from a combination of meteorological, geomorphological conditions and ground cover. Here, we found that the volcanic complex region allows for the forming of various basin morphologies. These basin structures can develop as pockets of cold air where frost can occur. We found that this geomorphologic factor is very decisive for the occurrence of frost. The air temperature at the peak of the dry season in DVC is still a few degrees above zero degrees Celsius. However, due to the influence of geomorphological factors, a body of still air cools down to below zero degrees Celsius due to the influence of radiation. However, the land cover type determines the occurrence of frost because the temperature of various types of cover is not the same. Shrubs and grasses experience frost at temperatures of −1°C to −2°C, which is still relatively close to zero temperature.

For evaluation, this study also has limitations. The observation period in this study is relatively short, so there is less variation in air temperature below zero. Thus, this study has not found a link between air temperature and frost on certain land cover types. Future studies are highly recommended to follow up on this section. Which land cover types experience frost at each air temperature level is a topic that needs further investigation. This will provide more comprehensive information on frost in volcanic areas in the tropics.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: AA; data collection: AA, ME, MW; statistical analysis: AA, ME; result interpretation: AA, ME, MW; manuscript preparation: AA; literature review: AA, MW.

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Received 16 February 2024
Accepted 13 November 2024