Abstract. This study aimed to analyze the spatial and temporal lightning distribution in North Sulawesi. The general meteorological condition of North Sulawesi has also been considered to identify the cause of the lightning occurrence. Lightning activity over North Sulawesi has been investigated using lightning data from Winangun Geophysical Station during 2019-2020. The result shows that in the land area of North Sulawesi, the highest lightning density occurred in the Tomohon regions due to its topographical features. Overall, the flash density over the land area is higher than the sea area due to its high atmospheric instability. The maximum flash density does not occur during the wet periods, but it occurs during September - October – November, which has a high surface temperature over this region. It is also known that shearline and low-pressure areas contribute to the high lightning occurrence in October 2019, while La Nina in the Pacific Ocean influences lightning activity in July 2020

1. Introduction

Tropical areas are known as areas with a high level of heating which can cause a high potential for lightning incidents compared to sub-tropical regions [1]. Over the maritime continent of Indonesia, convective clouds are more dominant than other types of clouds [2]. These convective clouds can grow into thundercloud clouds.

Various studies have been conducted to identify spatial and temporal lightning distribution over various areas. Lightning is primarily located in deep convective areas and occurs less frequently in stratiform areas [3]. Lightning has the same distribution pattern as convective rainfall, indicating that most lightning is associated with such type of rainfall [4]. Lightning is also associated with heavy rainfall events (>50 mm per day) [5]. Most lightning events do not occur during the rainy season but during the transitional season, where this is related to the presence of more active wind movements at the time of changing seasons to help the formation of convective clouds [6]. The knowledge about lightning can be used as a forecast of extreme weather events [7].

The previous study has identified the potential for lightning occurrences in the North Sulawesi region, which detects the frequency of lightning occurrences in several areas. Generally, lightning has the highest potential to occur during transitional season [6]. However, the research did not explain the cause of the lightning occurrence regarding its meteorological conditions. Furthermore, this study aimed
to analyze spatial and temporal lightning distribution in 2019 - 2020 and the influence of synoptic elements on lightning occurrence in North Sulawesi.

2. Methodology

2.1. Study Area
The study area of this research is North Sulawesi Province which is located in 0° - 6° N and 123° - 128° E. This area is mainly surrounded by the sea, such as the Celebes Sea on the west side, the Molucca Sea on the south, and the Pacific Ocean on the northeast side, as shown in Figure 1.

![Figure 1. Research Area.](image)

2.2. Data and Methods
Two years of lightning data (2019-2020) was obtained from the Nextrom lightning sensor of Winangun Geophysical Station, which then was processed by Lightning Data Processing software and mapped with Surfer. This sensor can reach within a radius of up to 480 km [8]. Nevertheless, the best detection efficiency of the lightning detector is less than 55 km from the sensor with 73-75% efficiency [9].

To solve the synoptic conditions during the lightning occurrence, monthly synoptic data during 2019-2020, which was obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset, has been analyzed. It consists of 850 mb wind, surface temperature, and precipitable water [10]. It can be downloaded from https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. Then it processed using the GrADS application to show a spatial data map of surface temperature overlay with 850 mb wind and a map of precipitable water.

This research also used monthly climatological rainfall data from 2000 to 2020, which was obtained from Global Satellite Mapping of Precipitation (GSMaP), to analyze the rainfall type of the North Sulawesi area as well as to map its distribution. This data has 0.1°x0.1° resolution. It can be downloaded from https://sharaku.eorc.jaxa.jp/GSMaP/ in .dat format. The rainfall data were then processed using the GrADS application to map rainfall spatially. The GSMaP data algorithm is recommended for rainfall estimation over the Indonesian Maritime Continent due to its good performance [11].

In addition to synoptic conditions and rainfall data, the seasonal variations during 2019 – 2020, which influence the weather conditions in North Sulawesi, such as El Nino Southern Oscillation (ENSO), tropical cyclones, and Sea Surface Temperature (SST) Anomaly, are also taken into
consideration. The historical data are obtained from climatological summaries on the Bureau of Meteorology (BoM)’s website.

3. Discussion

3.1. General Meteorological Conditions in North Sulawesi
Climatological rainfall data has been analyzed to determine the rainfall type of the North Sulawesi area, as shown in Figure 2. The data was divided into four periods: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). According to the data obtained, North Sulawesi can be categorized as a monsoonal type because it has two rainfall peak periods and one dry period [12]. It is shown that the rainfall mainly occurred during the DJF period. JJA has a high rainfall period as well. Meanwhile, SON is the driest period in that area. This result fits with the previous study, which mentioned that North Sulawesi has a relatively longer wet period than the dry period [6].

Figure 2. Seasonal rainfall data (unit: mm) during (a) December-January-February (b) March-April-May (c) June-July-August (d) September-October-November

The cause of this pattern can be analyzed from synoptic data, which consists of surface temperature, 850 mb wind, and total precipitable water analysis data. Figure 3 displays the overlay of surface temperature data with 850 mb wind data. In terms of wind movements, during the DJF and MAM periods, the wind tends to move from the North to the Northeast, indicating the movement of the Asian monsoon. Meanwhile, during the JJA and SON periods, the wind moved from Southeast to South, indicating the Australian monsoon. This fairly regular movement of the monsoon winds is in line with climatological rainfall conditions, where this type of rainfall is categorized as a monsoonal type. These wind movements have a significant influence on the formation of convective clouds in the North Sulawesi area.
On the other hand, surface temperature data shows that the highest air temperature is in the MAM period (reaching 28.5°C), while the lowest surface temperature is recorded during the DJF period or the rainy season. The relatively high temperatures were also observed in the SON period (28°C). This can also be due to the SON period, which is quite dry, as explained in the rainfall pattern because the wind pattern blowing from Australia brings dry air masses.

![Figure 3](image-url)

**Figure 3.** Seasonal mean surface temperature data (unit:°C) and wind pattern at 850 mb (streamline) during (a) December-January-February, (b) March-April-May, (c) June-July-August, and (d) September-October-November

Figure 4 shows the spatial distribution of the mean seasonal total precipitable water (TPW) over North Sulawesi from 2019-2020. The lowest TPW value happened during the SON period, which was around 46-50 mm. This TPW content increases until it reaches the peak in JJA, which is 52-54 mm in almost every region in North Sulawesi. The TPW value correlates with the rainfall intensity, as shown in Figure 2. The vast sea area around the North Sulawesi area also supports the high TPW in that area. The TPW value indicates possible thunderstorm activity in the vicinity [13].
3.2. Spatial Lightning Distribution
Figure 5 shows the distribution of lightning density over North Sulawesi in 2019 - 2020. There is a difference between lightning that occurred over the sea and land area. In this case, flash density over the land area is higher than over the sea area. This result aligns with the previous studies, which mentioned that land area is more favorable for lightning occurrence because of its higher atmospheric instability [14].

The flash density over regions in North Sulawesi also has been identified, as shown in Table 1. Among several regions in the North Sulawesi area, the highest lightning density was in Tomohon City with a total density of 75,19 strikes/km²/year during 2019 - 2020, contrary to the South Minahasa Regency area, which has the lowest number of strikes (11 strikes/km²/year). Tomohon City area is a highland area in North Sulawesi Province. In this area, there are also several mountains, such as Mount Lokon and Mount Mahawu. The lightning occurrence correlates with topographic factors, where the mountain area has frequent valley-mountain wind, which triggered the formation of convective clouds around that area [15].
Figure 5. Spatial lightning distribution over North Sulawesi during 2019-2020.

Table 1. Flash density over regions in North Sulawesi.

| Region          | Total strikes | Area (km²) | Strikes/km²/year |
|-----------------|---------------|------------|------------------|
| Manado          | 18701         | 157,27     | 59,46            |
| Bitung          | 17881         | 302,89     | 29,52            |
| Tomohon         | 17174         | 114,2      | 75,19            |
| Minahasa North  | 121077        | 1.114,87   | 54,30            |
| Minahasa South  | 48547         | 918,49     | 26,43            |
| Southeast Minahasa | 31016     | 1.049,97   | 11,00            |
|                 |               | 38505      | 27,08            |

3.3. Seasonal and Monthly Lightning Distributions

Figure 6 shows the seasonal lightning density over the North Sulawesi region during 2019-2020. It can be seen that the SON period has the highest density compared to other periods. It also shows the uneven distribution of the JJA season. The highest lightning distribution focused on the Minahasa Regency area with a lightning density frequency of 250 strikes/km². In the SON season, the distribution of lightning density is more evenly distributed, with the highest density value occurring over the coastal area in the North of Manado City with a density value of 120 strikes/km². The lowest density occurs during the MAM season with a maximum density value of 70 strikes/km². The results of this study are different from previous studies in Bandung and Semarang, which have MAM and DJF, respectively, as the season with the most lightning [16]. This can be caused by different geographical conditions between the two
places, where Bandung and Semarang are in the southern latitude, while North Sulawesi is in the northern latitude.

The high lightning occurrence during the SON period was caused by the strong convective activity during that month which was triggered by the high surface temperature in the North Sulawesi region despite being the driest season. Moreover, the formation of convergence and shearline area in northern Indonesia make the convective activity occur more, which is later explained in Figure 7.

Figure 6. Flash density over the North Sulawesi area (unit: unit/km²) during (a) December-January-February, (b) March-April-May, (c) June-July-August, and (d) September-October-November

The more detailed information about temporal lightning distribution in North Sulawesi is shown in Figure 7. The figure represents the fluctuation of monthly lightning occurrence from 2019 to 2020. From
this graph, the number of lightning strikes is more visible, and the factors that affect the occurrence of lightning can be described in more detail.

**Figure 7.** Monthly variation of lightning frequency in North Sulawesi during 2019 – 2020.

The lowest lightning flashes in 2019 occurred in February and March, with 6901 and 4625 strikes. Weak El Nino and the strong Australian monsoon to mid-March prevented convective cloud growth over North Sulawesi. This is also supported by sea surface temperature, which is in cold conditions and some tropical cyclones occurred in the southern part of Indonesia and attract air masses to southern Indonesia. From the end of March until June, the Asian monsoon was active and provided a chance of convective cloud formation, especially in the northern part of Indonesia. The Asian monsoon started to weaken in July, and at the same time, the Australian monsoon started getting strong until October. However, this study found the highest lightning flashes occurred in October 2019 with 339100 strikes. There were shearline and low-pressure areas that occurred over North Sulawesi. This is due to the sun’s movement, which is around the northern part of Indonesia, and brought air masses from the southern part of Indonesia. Another study also found that there was an increase in rainfall in October 2019 [17].

February 2020 is the time when lightning has the lowest lightning flashes, with 3705 strikes. In this month, the Asian monsoon was active, but there were some dry areas in Indonesia. Besides that, some tropical cyclones occurred in the southern part of Indonesia and attracted air masses to southern Indonesia. The highest lightning flashes in 2020 occurred in July (246058 strikes). The increase of La Nina around the Pacific Ocean in July 2020 contributes to its high lightning occurrence. A previous study mentioned that El Nino tends to increase the global lightning frequency, except in the Pacific Ocean which the lightning increases more during the La Nina period [18].

4. Conclusion

Lightning activity in North Sulawesi during 2019-2020 has been analyzed both spatially and temporally. This study was able to discover the overall lightning distributions over North Sulawesi in 2019 - 2020 regarding area and regions, as well as the seasonal and monthly distribution of lightning activity. Aside from the rainfall and synoptic conditions, some seasonal phenomena that happened during 2019 - 2020 have also been considered to elaborate the cause of lightning occurrence.

Lightning occurred more over the land area compared to the sea area due to its higher atmospheric instability. Topographic is a dominant factor behind the difference in lightning density in the land area of North Sulawesi, where the Tomohon region has the highest lightning density due to its highlands area, which triggered the convective clouds.

The amount of rainfall is not the main factor in the occurrence of lightning if divided by season. The SON period has the most lightning occurrences despite being the driest period compared to other
periods. This is due to the high surface temperature during that period. Throughout 2019 - 2020, October 2019 had the most lightning phenomena due to shearline and low-pressure areas in northern Indonesia, which triggered convective activity. Meanwhile, in 2020, July had more lightning occurrences due to the increase of La Nina around the Pacific Ocean. Further research is encouraged to identify the influence of seasonal variability on lightning activity.

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