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Analysis of Atmospheric Conditions During Heavy Rain Using Adiabatic Lapse Rate in Tangerang City

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Abstract. This study aims to understand the rate of temperature decrease in atmospheric conditions and determine the comparison between atmospheric stability and rainfall in Tangerang City using daily rainfall data and upper air data for the period 2019 to 2023. The data was obtained from Soekarno-Hatta Meteorological Station. The results of the analysis showed that the highest rainfall occurred in February 2020, with a total of 23 rainy days. In addition, lapse rate analysis indicates that atmospheric conditions are in a conditionally unstable state for 25 days. However, there is a difference between the number of rainy days and the number of days with unstable conditions, indicating that atmospheric instability does not always lead to precipitation. This study explains that although rain occurs under unstable atmospheric conditions, not all unstable conditions produce rain. Therefore, this study recommends the need for further studies to understand the complex interactions between meteorological factors that influence heavy rainfall phenomena in the region.

Keywords: atmosphere, lapse rate, precipitation

1. Introduction

Heavy rain is an extreme weather phenomenon that often occurs in tropical regions such as Indonesia. Geographically, Indonesia is located at the coordinates of 6° north latitude to 11° south latitude and 95° to 141° east longitude. As an archipelago crossed by the equator, Indonesia has a tropical climate with warm temperatures and high rainfall throughout the year. Because it is traversed by the equator, Indonesia has a surplus of energy due to more sunlight exposure (Muzaki et al., 2021). The large area of the sea and the surplus of heat energy in Indonesia result in high levels of humidity and water vapour, making it easy to form convective clouds that trigger heavy rains (Arrashid et al., 2023).

Global climate change has triggered an increase in the frequency and intensity of heavy rainfall, especially in the tropics. The IPCC (Intergovernmental Panel on Climate Change) report projects that extreme rainfall will increase in the tropics along with high greenhouse gas emissions. This phenomenon is linked to global warming, which strengthens the hydrological cycle, accelerates evaporation and increases the atmosphere's capacity to store water vapour (IPCC, 2021).

In general, Indonesia has a seasonal pattern that is divided into the rainy season (October to March) and the dry season (June to September). Oldeman classifies climate based on monthly rainfall, namely wet months and dry months (Hidayat & Yustiana, 2023). Wet months are defined as months that have monthly rainfall above 200 mm, while dry months are months with monthly rainfall less than 100 mm (Tasiyah et al., 2024).

Tangerang City as part of Banten Province is located between 6°6' to 6°13' South latitude and 106°36' to 106°42' East longitude. It has an area of 164.55 km² and consists of 13 subdistricts and 104 urban villages. In Koppen's climate classification, Tangerang City falls into the Am category, which is a tropical monsoon climate that has two seasons (Universitas STEKOM, 2025). According to (Badan Pusat Statistik Kota Tangerang, 2023), Tangerang City experiences relatively high annual rainfall with an average total of more than 100 mm.

Rainfall is the amount of rainwater that falls on an area in a certain time with a high degree of change, both spatially and temporally, including daily, monthly, seasonal, and annual variations (Solihin et al., 2021). The formation of rain begins with the evaporation of surface water into water vapour in the atmosphere which is influenced by climatological factors such as temperature and air pressure (Agroho et al., 2021). The water vapour in the air then undergoes a condensation process, where the water vapour turns into water droplets that form clouds. Condensation occurs when rising air is adiabatically cooled, so that the relative humidity (RH) increases. Condensation begins at the condensation nucleus when the RH reaches about 78%, although perfectly saturated conditions (100% RH) are reached only later (Kholiviana et al., 2022). This change in relative humidity is influenced by water vapour that increases through evaporation or a decrease in saturated vapour pressure due to cooling. This process produces water droplets that eventually form clouds, including cumulonimbus clouds that have the potential to produce heavy rainfall and extreme weather.

Atmospheric instability is one of the factors in the formation of heavy rain. Atmospheric conditions can be divided into three, namely stable, unstable and neutral (Thistle, 1996). Atmospheric stability is influenced by ambient air and the rate of adiabatic decline (Winardi, 2014). The lapse rate is the decrease in temperature as the height of the atmosphere increases. Lapse rate is defined as a negative vertical temperature gradient, which means the temperature decreases with altitude (Lisnawati et al., 2017). There are three types of temperature lapse rates with height, namely the environmental lapse rate, the dry adiabatic lapse rate, and the saturated adiabatic lapse rate (Almethen & Aldaithan, 2017). Rohman et al., (2024) classified atmospheric stability into three categories based on the relationship between environmental lapse rate (Γ), saturated adiabatic lapse rate (Γ_s), and dry adiabatic lapse rate (Γ_d), consisting of stable ($\Gamma < \Gamma_s < \Gamma_d$), conditionally unstable ($\Gamma_\mathrm{s} < \Gamma < \Gamma_\mathrm{d}$), and absolutely unstable ($\Gamma_\mathrm{s} < \Gamma_\mathrm{d} < \Gamma$). Therefore, this study aims to understand the rate of temperature decrease in atmospheric conditions and determine the comparison between atmospheric stability and rainfall in Tangerang City.

2. Methodology

This research uses quantitative methods based on temporal data and lapse rate analysis. The data used includes daily rainfall data for the period 2019 - 2023 and daily upper air data at 00 and 12 UTC obtained from radiosonde observations by the Meteorology, Climatology and Geophysics Agency (BMKG) for the period February 2020. The data was collected from Soekarno-Hatta Meteorological Station, which has a strategic location to represent atmospheric conditions in the study area.

Data processing in this study was carried out using Microsoft Excel and Minitab software to calculate lapse rate values. The data processing process is divided into several stages, namely calculating the highest monthly rainfall, calculating the lapse rate value, and determining atmospheric conditions based on the lapse rate value.

Lapse rate analysis is used to understand atmospheric stability through three main types of calculations, namely: Environmental Lapse Rate (ELR), Dry Adiabatic Lapse Rate (DALR), and

Saturated Adiabatic Lapse Rate (SALR). ELR describes the change in air temperature as it moves upwards in the atmosphere, which is calculated using the equation (Lisnawati et al., 2017):

$$\Gamma = -\frac{\partial T}{\partial z} \quad (1)$$

∂T is the temperature change (°C) and ∂z is the altitude change (km). DALR refers to the rate of temperature decrease in a dry air parcel travelling vertically in the absence of condensation, calculated using the equation (Curry, 2024):

$$\Gamma_d = \frac{g}{c_p} \quad (2)$$

where g is the acceleration of gravity (9.81 m/s^2) and c_p is the constant pressure specific heat capacity (1005 J/Kg K). SALR is used to analyse air parcels undergoing condensation during the ascension process, using equation (Daidzic, 2019):

$$\Gamma_s = \left(\frac{g}{c_p}\right) \cdot \frac{\left(1+\frac{L_v w_s}{R_d T}\right)}{\left(1+\frac{L_v^2 w_s}{c_p R_v T^2}\right)} \quad (3)$$

where L_v is the latent heat of vaporisation (2.5 x 10^6 J/Kg), w_s is saturated mixing ratio, R_d is the dry air gas constant (287 J/Kh K), R_v is the water vapour gas constant (461,5 J/Kg K), and T is the absolute temperature (K). However, before conducting the SALR analysis, it is necessary to calculate the saturated mixing ratio value using the following equation (Houghton, 1997):

$$w_s = \frac{\varepsilon \cdot e_s}{P - e_s} = \frac{\frac{R_v}{R_d} \cdot e_s}{P - e_s} \quad (4)$$

where e_s is saturated vapour pressure (hPa) and P is air pressure (hPa). The value of e_s can be calculated using the Tetens formula as follows.

$$e_s = 6{,}1078\exp\left(\frac{17{,}27 \times T}{T + 273{,}3}\right) \quad (5)$$

After the lapse rate calculation, the results are analysed to classify atmospheric stability into three categories: stable, conditionally unstable and absolutely unstable. This classification gives an idea of the potential for convective cloud formation that can trigger heavy rain. In addition, data validation is performed by comparing the results of lapse rate analysis with rainy days to ensure the accuracy of atmospheric conditions. The use of this method allows the research to provide in-depth insight into the atmospheric dynamics in Tangerang City.

3. Results and Discussion

Daily rainfall data that has been processed into monthly rainfall data for the period 2019 - 2023 in Tangerang City is presented in Table 1. Based on Table 1, it can be seen that the distribution of rainfall data in Tangerang City shows significant variations from month to month during the period 2019 - 2024. The rainfall pattern tends to fluctuate, with some months experiencing high rainfall peaks, while other months show relatively low values. In addition, there are some prominent outliers (extreme values) in this dataset. These outliers can be more clearly identified through the graph visualisation below, which illustrates the temporal distribution of rainfall.

Overall, the monthly rainfall graph shows a fairly consistent seasonal pattern, with peak rainfall generally occurring at the beginning of the year, between January and March. However, there are variations between years in terms of the timing of peak rainfall. In 2019, the peak rainfall was recorded in March, while in 2022 it occurred earlier, in January. For 2020, 2021 and 2023, the peak rainfall occurred in February. From the overall data, the highest rainfall was recorded in February 2020 with a value reaching 538.7 mm/month. This shows that although the seasonal pattern is clear, the timing of peak rainfall can vary annually.

Table 1. *Monthly rainfall data (mm/month) 2019 – 2023*

Month/ Year	2019	2020	2021	2022	2023
January	271,9	488,7	338,96	372,7	139,3
February	59,9	538,7	469,2	223,6	358
March	364,5	154,3	202,2	98,3	265,1
April	69,5	33,6	150,7	160,2	69,2
May	66,6	99,6	146,8	262,5	19,4
June	31,4	11,4	50,3	107,4	62,6
July	1	19,2	82,4	109,7	28,3
August	0,6	146,5	88,2	68,9	52,6
September	27,2	122,6	56,7	133,8	0
October	31,1	141,8	106,1	113,5	19,8
November	45,6	21,6	37,9	195	182,7
December	319,6	158,4	321,8	109,5	3,6

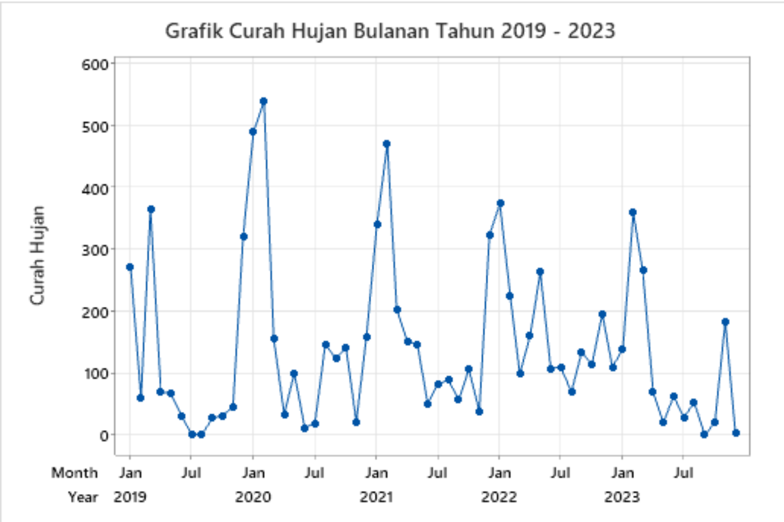

Figure 1. Monthly Rainfall Graph 2019 – 2023

Figure 2 shows that the peak daily rainfall occurred on 24 February with an amount reaching 99.6 mm/day. During the month, rain was recorded for 23 days. This shows that although the total monthly rainfall was high, not every day experienced rain. There were high, low, and even no rainfall at all. This condition illustrates the uneven temporal distribution of rainfall.

The lapse rate analysis used includes dry adiabatic lapse rate, saturated adiabatic lapse rate, and environmental lapse rate. The data used is upper air data from radiosonde observations at Soekarno-Hatta meteorological station at two observation times, namely 00 UTC and 12 UTC. Dry adiabatic lapse rate is used to calculate the rate of vertical decrease in dry air temperature, while saturated adiabatic lapse rate is used to analyse the rate of temperature decrease in saturated air containing water vapour. The environmental lapse rate describes the actual conditions of atmospheric temperature decrease according to observational data. This analysis provides an overview of the vertical dynamics of the atmosphere and the potential for atmospheric stability that affects cloud and rain formation.

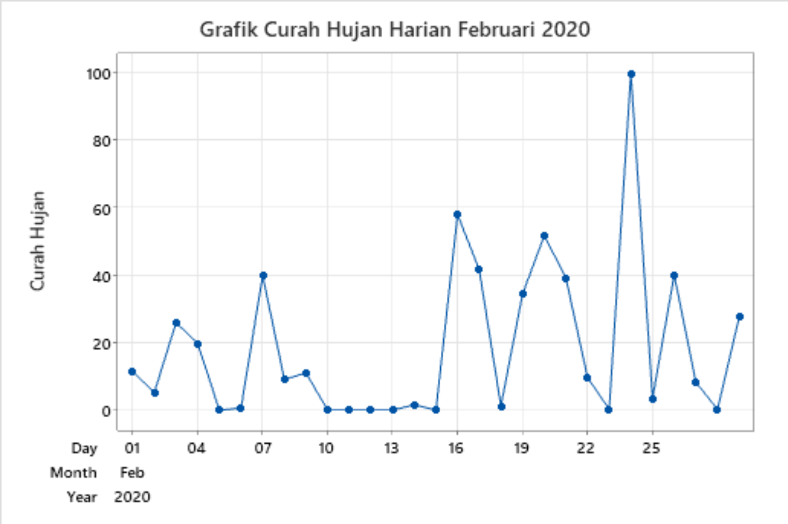

Figure 2. Daily Rainfall Graph February 2020

Dry adiabatic lapse rate has a constant value of 9.8°C/km, which is calculated based on the Earth's gravitational acceleration (9.81 m/s2) and constant pressure specific heat capacity (1005 J/Kg K). Meanwhile, the saturated adiabatic lapse rate has a variable value because it is affected by humidity and temperature conditions. Saturated adiabatic lapse rate can be calculated using several parameters, namely dry adiabatic lapse rate (9.8°C/km), latent heat of vaporisation (2.5 x 106 J/kg), dry air gas constant (287 J/kg K), water vapour gas constant (461 J/kg K), saturated mixture ratio and absolute temperature. The graph showing the saturated adiabatic lapse rate can be seen in Figure 3.

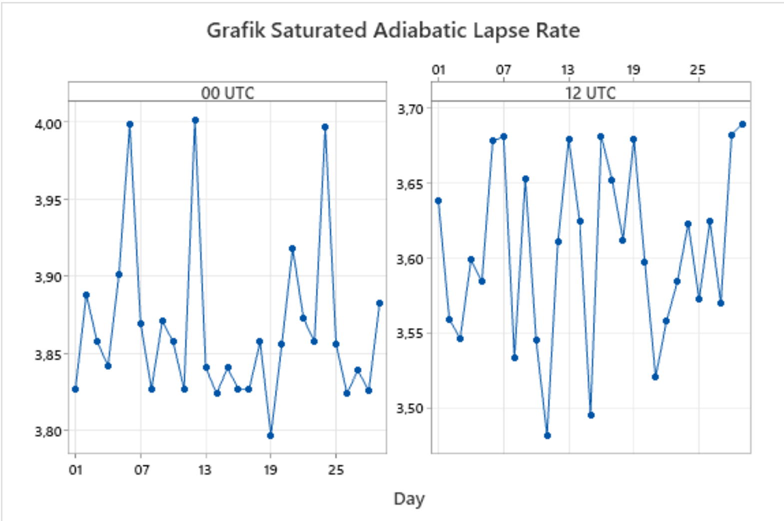

Figure 3. Saturated Adiabatic Lapse Rate Graph

The saturated adiabatic lapse rate is generally smaller than the dry adiabatic lapse rate due to the release of latent heat during the condensation process. When air saturated with water vapour rises, some of the water vapour condenses, releasing latent heat into the surrounding air. This heat reduces the cooling rate of the rising air, so the saturated adiabatic lapse rate is lower than the dry adiabatic lapse rate, which has no latent heat release and remains constant at 9.8 °C/km.

The environmental lapse rate has a variable value and can be calculated based on temperature and altitude data at two different points, namely at the surface and upper layer at an altitude of about 3000 masl. The environmental lapse rate graph can be seen in Figure 4.

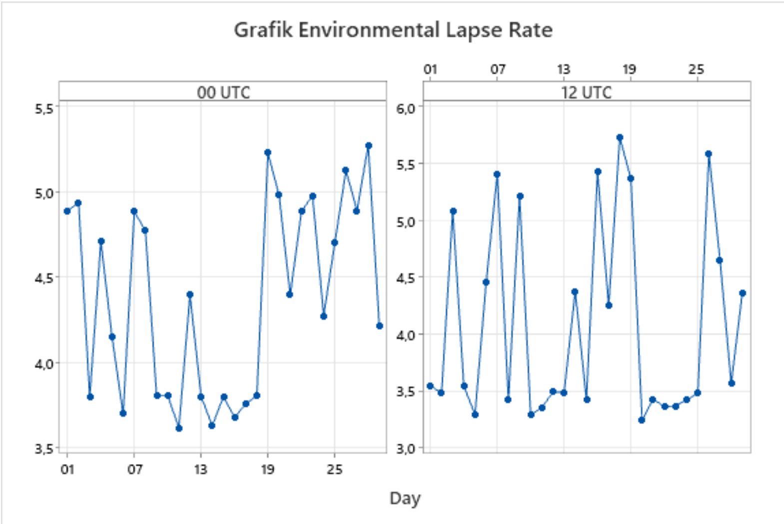

Figure 4. Environmental Lapse Rate Graph

Based on the lapse rate analysis, it is found that the saturated adiabatic lapse rate is always smaller than the dry adiabatic lapse rate. Therefore, Figure 5 only shows the graphs of saturated adiabatic lapse rate (SALR) and environmental lapse rate (ELR) values.

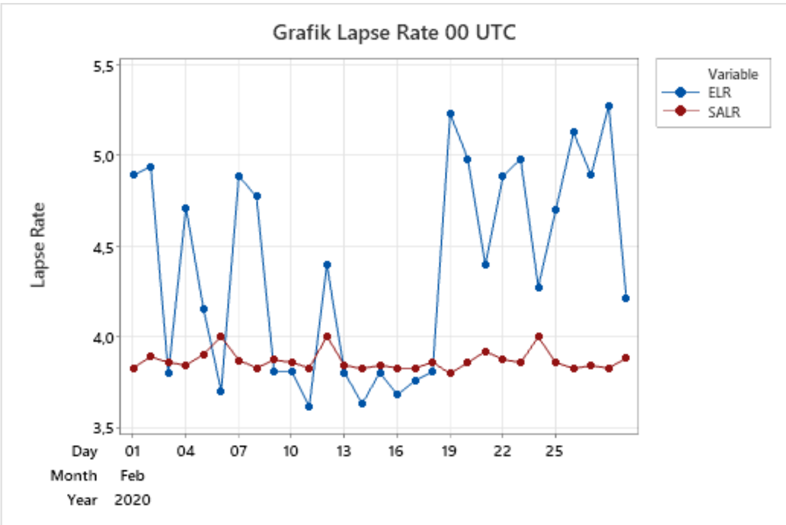

Figure 5. Lapse Rate Graph at 00 UTC

Based on the graph, it can be seen that at 00 UTC for 29 days of observation, the atmospheric conditions that occur are only stable and conditionally unstable. Atmospheric conditions are categorised as stable if the ELR value is smaller than SALR and DALR ($\Gamma < \Gamma_s < \Gamma_d$). Meanwhile, conditionally unstable conditions occur when the ELR value is greater than SALR but still smaller than DALR ($\Gamma_s < \Gamma < \Gamma_d$). In the graph, stable conditions were recorded for 11 days and conditionally unstable for 18 days.

Based on Figure 6, the rate of temperature change at 12 UTC shows that atmospheric conditions also only experience stable and conditionally unstable states. Stable conditions were recorded for 17 days, while conditionally unstable occurred for 12 days. There are differences in atmospheric conditions at 00 UTC and 12 UTC. The difference in atmospheric conditions between 00 UTC and 12 UTC reflects the changing dynamics of the atmosphere as the day progresses. When the two conditions are combined, the total number of days when the atmosphere was in a stable state was 4 days, while conditionally unstable conditions were recorded for 25 days. This shows that during the observation period, the atmosphere was more often in a conditionally unstable state.

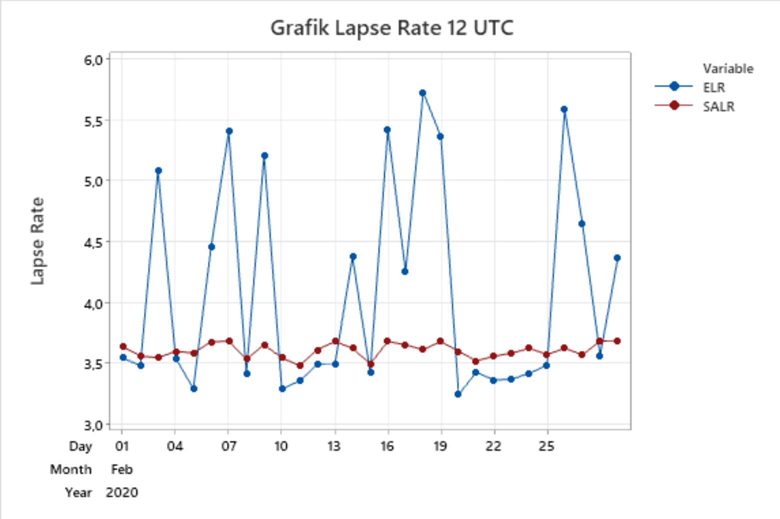

Figure 6. Lapse Rate Graph at 12 UTC

In analysing atmospheric conditions related to heavy rainfall phenomena, it is important to understand that atmospheric instability, whether conditionally unstable or absolutely unstable, is a major factor that can trigger rainfall. When the atmosphere is in an unstable state, it indicates the potential for convection, which often leads to the formation of convective clouds. These clouds have the ability to produce significant rainfall. However, based on the results of the analysis of rainfall and atmospheric conditions, there is a difference between the number of days of rain and the number of days where the atmosphere is unstable.

The number of rainy days was recorded as 23 days, while the number of days with unstable atmospheric conditions reached 25 days. There was a difference on 5 and 12 February 2020, where atmospheric conditions were conditionally unstable but no rain occurred. Unstable atmospheric conditions can indeed increase the chance of rain, but not all unstable situations produce precipitation. This is due to various interacting meteorological factors. Atmospheric conditions are categorised as conditionally unstable when the air only becomes unstable if it reaches a saturation point. In other words, although there is potential for rain to occur under unstable conditions, other factors such as insufficient humidity or lack of convection triggers may hinder the formation of convective clouds and the occurrence of precipitation.

4. Conclusion

Based on rainfall data obtained from Soekarno-Hatta Meteorological Station for five years, the highest rainfall was recorded in February 2020 with a total of 23 rainy days. Lapse rate analysis using upper air data from radiosonde observations at 00 UTC and 12 UTC shows atmospheric conditions experiencing stable and conditionally unstable conditions, with the number of unstable atmospheric days reaching 25 days. These results show that while atmospheric instability can increase the chance of rain, not all unstable conditions result in precipitation. This reflects that other factors such as air humidity also influence rain formation.

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