# Geospatial Artificial Intelligence (GeoAI) and Deep Learning Approaches for Understanding Earth's Atmosphere Phenomena

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**Abstract**:

Based on temperature, Earth's atmosphere consists of five layers: the troposphere, stratosphere, mesosphere, thermosphere, and exosphere; while based on composition, it consists of the homosphere and heterosphere. Based on its composition, Earth's atmosphere transports most of the energy from warmer regions to cooler regions, and winds drive ocean surface currents toward Earth's poles. The movement of energy, temperature, and carbon will affect atmospheric stability. To understand Earth's atmospheric phenomena, research was conducted using a Geospatial Artificial Intelligence (GeoAI) approach and deep learning. This study was conducted to improve the accuracy of atmospheric stability and weather predictions and to support real-time climate change mitigation. To achieve these objectives, Machine Learning (ML) was integrated with Geographic Information Systems (GIS). This research was conducted in the Physics Education Program at the Faculty of Teacher Training and Education, Sultan Ageng Tirtayasa University. In applying the geospatial approach, emission data from industrial zones were used, with the Cilegon industrial zone serving as the case study. Meanwhile, meteorological data were obtained from the Serang Maritime Meteorological Station. The results of atmospheric stability and weather predictions using the GeoAI approach and deep learning indicate that atmospheric stability in Cilegon City in the morning, afternoon, evening, and night varies from A (very unstable) to E (somewhat stable). This indicates that atmospheric conditions in Cilegon range from unstable to somewhat stable, in accordance with Pasquill's atmospheric stability criteria. Using GeoAI and deep learning approaches, students can deterministically predict atmospheric stability.

**Keywords**: Earth's atmosphere, atmospheric stability, weather, geospatial artificial intelligence, deep learning

## INTRODUCTION

The Earth's atmosphere is the layer of air that surrounds the Earth, and together with the Earth, they rotate and revolve around the Sun. The Earth's atmosphere is approximately 500 km, or about 310.7 miles (1 km = 0.6214 miles), thick above sea level. The atmosphere protects living organisms on Earth's surface by helping to maintain stable daytime and nighttime air temperatures and by absorbing radiation, including ultraviolet radiation (Ruhiat et al., 2025). The Earth's atmosphere is generally divided into two categories: by temperature and by composition.

The Earth's atmosphere, classified by temperature, consists of five layers: the troposphere, stratosphere, mesosphere, thermosphere, and exosphere. The troposphere is the lowest layer of the Earth's atmosphere; it contains approximately 75–80% of the total mass of air in the atmosphere and is where all weather phenomena (such as rain, wind, and clouds) occur. Next, the stratosphere extends from 12 to 50 km in altitude and contains the ozone layer, which absorbs ultraviolet (UV) radiation. The mesosphere extends from 50 to 85 km in altitude

and serves as the primary shield against impacts from space debris. Next, the thermosphere extends from approximately 85 to 600 km in altitude, reaching temperatures of thousands of degrees Celsius. Meanwhile, the exosphere is located at an altitude of approximately 500 to 10,000 km and directly borders the vacuum of outer space (Crutzen, 2012). The exosphere is an extremely thin, sparse layer that allows free-moving particles to escape Earth's gravitational pull and be blown into outer space (Taylor, 2003).

Based on its composition, the atmosphere consists of two main layers: the homosphere and the heterosphere. The homosphere is the lower layer with a uniform gas composition; its chemical composition is relatively constant because of continuous air mixing. The gases in the homosphere consist of 78.08% nitrogen, 20.95% oxygen, 0.93% argon, and 0.03% carbon dioxide, while other components include water vapor, neon, helium, and ozone, the amounts of which vary (Zhang & Hu, 2026). Meanwhile, the heterosphere is the upper layer, extending to an altitude of 80 km, and features a varied gas composition. The gas composition in the heterosphere is not uniform but stratified by atomic or molecular weight. Based on its composition, Earth's atmosphere is stratified. It transports most of the energy from hot regions (the equatorial tropics) to regions with low or cold temperatures (the Earth's polar regions), as well as winds that drive ocean surface currents toward the Earth's polar regions. The Earth's atmosphere also serves as a pathway for the movement of carbon between the oceans and land and as a reservoir for other carbon elements. The movement of energy, temperature, and carbon is assumed to influence atmospheric stability.

Atmospheric stability refers to the air's ability to move vertically; this condition is classified into three main types: stable, unstable, and neutral. Atmospheric stability is classified based on a comparison between the Environmental Lapse Rate (ELR) and the Adiabatic Lapse Rate (dry or moist) (Rohman et al., 2025). A Stable condition occurs when the environmental temperature lapse rate is less than the moist adiabatic lapse rate. Under stable conditions, the sky is clear, no vertical cloud formation occurs, and pollutants are likely to remain trapped near the ground. Conversely, unstable conditions occur when the environmental temperature lapse rate exceeds the dry adiabatic lapse rate. Under unstable conditions, there is potential for vertical cloud development (cumulus/cumulonimbus), thunderstorms, and heavy rain. Furthermore, a Neutral state occurs when the rate of environmental temperature decrease lies between the rates of dry and moist adiabatic temperature decrease. In a Neutral state, the weather is generally clear in the morning but can develop heavy convective clouds in the afternoon or evening. Referring to the five atmospheric layers described above, as well as atmospheric stability and its impact on the weather, several learning approaches are used to understand atmospheric phenomena.

Learning approaches for understanding Earth's atmospheric phenomena include: the multidisciplinary or holistic approach, Project-Based Learning (PjBL), discovery learning, and the science literacy framework. The multidisciplinary or holistic approach integrates various scientific disciplines (physics for air circulation, chemistry for greenhouse gases, and geography/biology for their impacts on human ecosystems). The advantages of using a multidisciplinary or holistic approach include a comprehensive understanding of the complex interactions between climate and weather, more accurate disaster forecasting, and the development of more effective solutions for climate change adaptation. On the other hand, the disadvantages include the need for highly complex data, requiring intricate coordination among scientists, and necessitating significant resources and advanced technology (Wilis & Redjeki,

2026). Project-Based Learning (PjBL), meanwhile, is an educational approach that engages students in real-world projects, such as creating a pop-up book model of the atmospheric layers or conducting climate simulations to hone problem-solving skills. The advantages of using the PjBL approach include concrete conceptual understanding, the promotion of problem-solving, and the development of comprehensive skills. Meanwhile, its disadvantages include the need for long-term observation and uneven participation among groups (Macdalena & Benardi, 2026). Furthermore, discovery learning is an instructional approach that encourages students to develop their own understanding of atmospheric layers and weather anomalies (such as the impacts of El Niño or global warming) through data analysis. The advantage of the discovery learning approach is that it fosters stronger conceptual understanding, whereas its disadvantage is that it may not be equally effective for all students (Winarti et al., 2021).

Meanwhile, the science literacy framework is a learning approach that utilizes direct meteorological observation data to interpret air pressure, temperature, and humidity—factors that trigger daily weather changes. The advantages of the science literacy framework include a holistic, contextual, and evidence-based understanding, while its disadvantages include high complexity and susceptibility to misconceptions (Syahni et al., 2026). Considering the atmospheric layers and their associated phenomena, as well as the limitations of the learning approaches mentioned above, this study employs a Geospatial Artificial Intelligence (GeoAI) approach and deep learning to understand Earth's atmospheric phenomena.

The geospatial approach visualizes and analyzes atmospheric phenomena using spatial dimensions on Earth's surface. Meanwhile, the Geospatial Artificial Intelligence (GeoAI) approach combines machine learning and remote sensing data to analyze atmospheric patterns spatially and temporally. The GeoAI approach to understanding Earth's atmospheric phenomena integrates remote sensing data with Geographic Information Systems (GIS). This approach aims to process, analyze, and predict atmospheric stability and large-scale weather and climate data with greater accuracy. Furthermore, the Deep Learning approach to understanding Earth's atmospheric phenomena is revolutionizing atmospheric science through big data processing. This approach aims to build meaningful understanding, develop critical thinking skills, and identify complex weather and climate patterns from massive geoscience datasets. In light of these two objectives, this study employs GeoAI and Deep Learning approaches to understand Earth's atmospheric phenomena and to automatically process and analyze large-scale Earth observation data. Processing data at scale can improve the accuracy of atmospheric stability and weather forecasts and support real-time climate change mitigation.

## METHODS

Methods for processing, analyzing, and predicting large-scale atmospheric stability, weather, and climate with greater accuracy integrate Machine Learning (ML) and Deep Learning with Geographic Information Systems (GIS). Meanwhile, the application of geospatial AI employs a Graph Neural Network (GNN) approach. The GNN approach uses an AI architecture to model the Earth as a graph of nodes, thereby enabling more accurate processing of atmospheric data and prediction of extreme weather patterns (Khoerun et al., 2026).

Atmospheric stability can be analyzed using two approaches: one based on the vertical movement of air masses in the other on solar radiation, cloud cover, and wind speed. Atmospheric stability, based on the vertical movement of air masses, results in differences in air mass density across atmospheric layers. These differences in air mass during vertical motion are used to forecast the formation of convective clouds, rain, or low-pressure systems (Spiridonov et al., 2025).

The variation in temperature with altitude is called the temperature lapse rate, which significantly influences air movement; in this context, the vertical transport of air is linked to the adiabatic lapse rate. Based on the vertical movement of air masses, atmospheric stability influences rainfall conditions in a given region. Cloud development and rainfall result from unstable atmospheric conditions. Clear or slightly cloudy skies result from stable atmospheric conditions (Xu et al., 2025). A key indicator of atmospheric stability is the formation of convective clouds, such as cumulonimbus (Cb) clouds. The formation of these clouds begins with unstable atmospheric conditions resulting from bottom-up heating by solar radiation, which warms the ground. Unstable air creates disturbances that trigger convective processes (Kim et al., 2026). Severe weather caused by cumulonimbus clouds includes thunderstorms and lightning. Unstable air allows for the formation of clouds—particularly those with a striking vertical extent—which typically bring severe weather; conversely, clear, cloudless weather results from stable air.

The primary factor affecting atmospheric stability in the vertical movement of air masses is the relationship between the rates of atmospheric temperature decrease. There are three rates of temperature decrease: the environmental temperature lapse rate (Γe), the dry adiabatic lapse rate (Γd), and the wet adiabatic lapse rate (Γs). Based on this, the classification of the atmosphere according to temperature changes with altitude is as follows:

a) The atmosphere is unstable if:
$$\frac{d\theta}{dz} < 0$$
b) A neutral atmosphere, if:
$$\frac{d\theta}{dz} = 0$$
c) The atmosphere is stable if:
$$\frac{d\theta}{dz} > 0$$

$$\frac{d\theta}{dz} = \left[\frac{d\Gamma}{dz}\right]_e + \Gamma_d = \left[\frac{d\Gamma}{dz}\right]_e - \left[\frac{d\Gamma}{dz}\right]_d \quad \text{... (1)}$$

Equation (1) shows that the greater the difference between the Earth's surface temperature and the temperature in the atmospheric layer, the more unstable the atmosphere becomes.

Atmospheric stability depends on the vertical motion of air masses; in this case, air parcels move adiabatically. Atmospheric stability depends on the ratio of the rate of environmental temperature decrease (Γe) to the rate of dry adiabatic temperature decrease (Γd) and the rate of wet adiabatic temperature decrease (Γs). The relationship among these three temperature-decrease rates is shown in Figure 1 below.

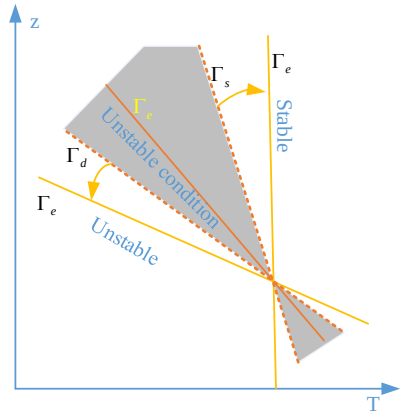


Figure 1. Atmospheric stability

Figure 1 shows atmospheric stability as a function of vertical air movement. The classification of the atmosphere based on this figure is as follows:

a) The atmosphere is unstable if:
Γe > Γd
b) The atmosphere is neutral if:
Γe = Γd
c) The atmosphere is stable if:
Γe < Γd

Based on the limits of the environmental temperature lapse rate (Γe) and the dry adiabatic lapse rate (Γd), as well as temperature changes with altitude, atmospheric stability is divided into three categories, as follows:

a) Neutral conditions: Under neutral conditions, the environmental cooling rate (actual) is equal to the dry adiabatic cooling rate, so that an air parcel moving (either upward or downward) will have the same temperature as the surrounding air, the densities will become equal, and it will be in equilibrium
b) Unstable conditions: Under unstable conditions, the rate of environmental cooling (actual) is greater than the rate of dry adiabatic cooling. When an air parcel rises, its temperature is higher than that of the surrounding air; its density decreases, and it continues to rise. As the parcel rises, the temperature difference increases, accelerating the ascent of the air parcel
c) Stable conditions: Under stable conditions, the rate of environmental cooling (actual) is less than the rate of dry adiabatic cooling, and as the air parcel rises, its temperature is lower than that of the surrounding air. Consequently, its density is greater, and the parcel will sink immediately once its temperature equals that of the surrounding air.

To determine atmospheric stability based on temperature changes with altitude, stability indices are used, as shown in Figure 2 below.

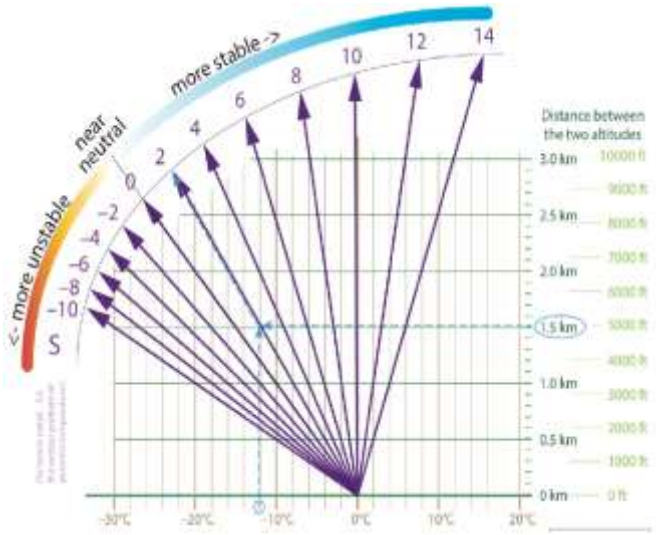


Figure 2. Atmospheric stability as a function of temperature and altitude

Atmospheric stability, based on solar radiation, cloud cover, and wind speed, is used to predict atmospheric stability in the presence of air pollutants. These three variables are expressed on an hourly, so atmospheric stability is determined on an hourly. Based on these variables, atmospheric stability is classified into six categories, as shown in Table 1 below.

Table 1. Atmospheric conditions in various classes

| Surface wind speed(m/detik)[a] | Daytime solar radiation | | | Nighttime conditions | |
|---|---|---|---|---|---|
| | Strongb | Moderate[c] | Low | Cloudy (≤ 4/8)$_d$ | Clear (≤ 3/8)$_e$ |
| < 2 | A | A – B | B | E | F |
| 2 - 3 | A – B | B | C | E | F |
| 3 – 5 | B | B – C | C | D | E |
| 5 – 6 | C | C – D | D | D | D |
| >6 | C | D | D | D | D |

Sumber: Koehn, 2013

Legend: A = highly unstable, B = unstable, C = slightly unstable, D = neutral, E = somewhat stable, and F = stable

Table 1 shows that wind speed is the dominant variable in determining atmospheric stability. However, the wind speed (u) used here is the speed at a height of 10 meters above the Earth's surface. According to Assegaf (2018), wind speed varies with altitude and must be corrected using a logarithmic law, with the following equation:

$$\frac{u_s}{u} = \left( \frac{h_s}{h_g} \right)^n \quad \text{... (2)}$$

Where u is the wind speed, us is the wind speed at the stack, hs is the stack height (m), hg is the standard height of a wind measurement station (10 m above ground level), and n indicates the atmospheric stability class.

A stable atmosphere tends to keep the air stationary in one place, causing pollutants to become trapped near the ground. Meanwhile, an unstable (labile) atmosphere causes air to rise, helping to disperse pollutants into higher layers of the atmosphere. To analyze atmospheric stability based on solar radiation, cloud cover, and wind speed, the following data are required:

a) Surface wind speed is measured at a height of 10 meters above the ground
b) A sunny summer afternoon with the sun at an elevation of > 60 ° above the horizon
c) A summer afternoon with scattered clouds or a clear summer afternoon with the sun's altitude (35–60)o above the horizon
d) A late afternoon or a cloudy summer afternoon, or an afternoon during the season with the sun's altitude angle (15–35)o
e) Cloud cover, defined as the fraction of the sky obscured by clouds

Atmospheric stability, based on the vertical motion of air masses, is classified by the dry adiabatic lapse rate (DALR) and the environmental lapse rate (ELR). Meanwhile, atmospheric stability, as determined by solar radiation and wind speed, is characterized by the value of n. The relationship between atmospheric classification and atmospheric stability is as follows:

a) Atmospheric stability classification ABC
b) Atmospheric stability classified as ABC indicates an unstable atmosphere, while the relationship between ELR and DALR is: Γe >> Γd
c) Atmospheric stability classification D
d) Atmospheric stability classified as D indicates a neutral atmosphere, while the relationship between ELR and DALR is: Γe = Γd
e) Atmospheric Stability Classification E
f) Atmospheric stability classified as E indicates a slightly stable atmosphere, while the relationship between ELR and DALR is: Γe < Γd

g) Atmospheric Stability Classification F

Atmospheric stability classified as F indicates a stable atmosphere, while the relationship between ELR and DALR is: Γe << Γd.

## RESULTS AND DISCUSSION

Using a GeoAI approach and machine learning with the following climate data:

1) Air temperature

Daily temperature variations play a significant role in the dispersion of air pollution. During the day, when surface temperatures are significantly higher than those of the overlying air layer, air tends to rise, carrying pollutants upward and resulting in a wider dispersion area. Conversely, at night and in the morning, when surface temperatures are low and below the temperature of the overlying air layer, air tends to remain still or sink, increasing the deposition rate and thus narrowing the area of pollutant dispersion.

The monthly average air temperature in Cilegon shows no significant fluctuations or variations, ranging from a low of 21.0 oC in August to a high of 34.4 oC in April. The highest temperature occurs around 1:00 p.m. local time, and the lowest in the morning around 7:00 a.m. local time.

Annual temperature variations are not very large compared to daily temperature variations. This is because the sun is almost always above the equator. The average difference between the maximum and minimum temperatures is around 14 degrees; annual temperature variations are shown in Table 2 below.

Table 2. Annual Temperature Variations (°C)

| Station | Temp | Jan | Feb | Mar | Apr | Mei | Jun | Jul | Ags | Sep | Okt | Nop | Des |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cengkareng | Max | 30,1 | 30,2 | 31,3 | 32,0 | 31,9 | 31,8 | 31,6 | 31,7 | 32,4 | 32,5 | 32,2 | 31,1 |
| | Avg[2] | 26,3 | 26,2 | 26,8 | 27,1 | 27,2 | 26,7 | 26,4 | 26,4 | 26,9 | 27,2 | 27,1 | 26,7 |
| | Min | 23,6 | 23,4 | 23,6 | 23,7 | 23,8 | 23,2 | 22,7 | 22,4 | 22,8 | 23,3 | 23,6 | 23,5 |
| Curug | Max | 30,5 | 30,5 | 31,7 | 32,4 | 32,6 | 32,4 | 32,4 | 32,8 | 33,4 | 33,1 | 32,4 | 31,3 |
| | Avg[2] | 25,9 | 25,7 | 26,2 | 26,5 | 26,6 | 26,3 | 25,9 | 26,0 | 26,5 | 26,7 | 26,5 | 26,2 |
| | Min | 23,2 | 23,0 | 23,1 | 23,2 | 23,2 | 22,5 | 21,7 | 21,6 | 21,9 | 22,7 | 23,2 | 23,0 |
| Serang | Max | 30,5 | 30,7 | 31,7 | 32,2 | 32,2 | 31,5 | 31,4 | 31,3 | 32,4 | 32,5 | 32,0 | 30,7 |
| | Avg[2] | 26,3 | 26,1 | 26,5 | 26,7 | 26,9 | 26,7 | 26,2 | 26,2 | 26,6 | 26,8 | 26,7 | 26,9 |
| | Min | 23,5 | 23,8 | 23,8 | 24,0 | 23,5 | 23,0 | 22,8 | 22,4 | 22,9 | 23,2 | 23,3 | 23,4 |

1) Wind direction and speed

Wind has a significant impact on the spread of air pollution. Wind direction determines the direction in which pollutants spread, and wind speed determines how far they are carried. The average monthly wind speed in Cilegon ranges from 0.2 m/s in January to 4.0 m/s in December. To determine the frequency distribution of these winds, wind data were analyzed, and a wind rose was created, as shown in full in Figure 3. The results of the wind rose analysis for the city of Cilegon reveal varying patterns between morning, afternoon, evening, and night. Generally, from November through March, winds typically blow from west to east. The lowest frequency of westerly winds was 36.7% in November, and the highest was 87.1% in December. Meanwhile, from April through October, winds generally blow from north to south. The lowest frequency of northerly winds was 46.7% in June, and the highest was 67.7% in August.

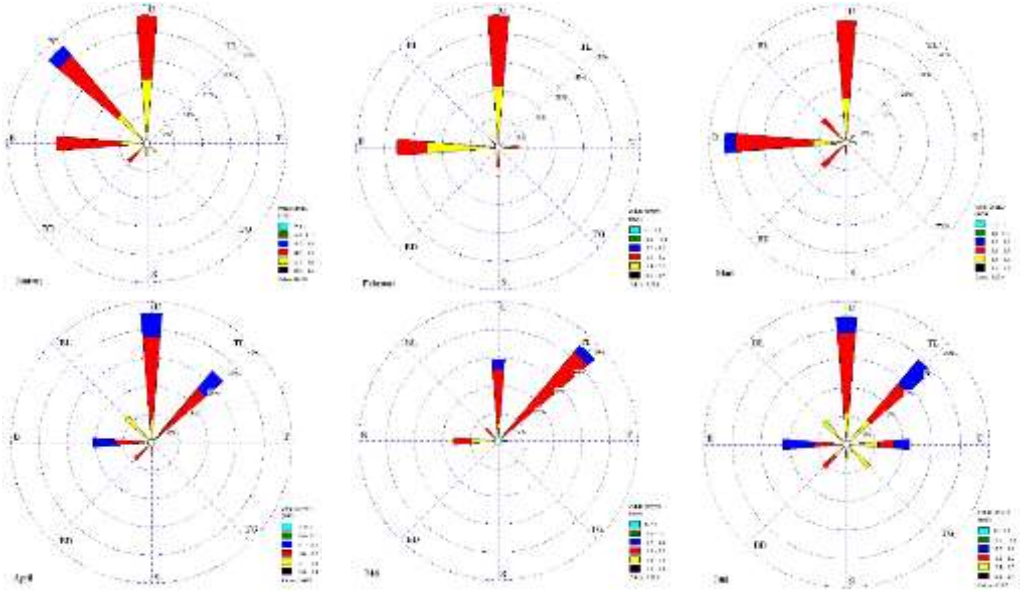

Figure 3. Wind rose for the city of Cilegon

2) Atmospheric stability

Sunshine duration is the ratio of the length of time or period during which the sun shines brightly in a day to the length of the day, expressed as a percentage. Data on average monthly sunshine duration show that sunshine duration follows a seasonal pattern, with the lowest value of 36% in January and the highest of 72% in August and September.

In practice, the Pasquill air stability scale is used in analyzing air pollution dispersion patterns; in this context, atmospheric stability is divided into six classes based on wind speed, solar radiation, and cloud cover at that time. The Pasquill air stability in Cilegon, measured periodically in the morning, afternoon, evening, and at night, is shown in full in Table 3 below.

Table 3. Pasquill Air Stability

| Location | Time | | | |
|---|---|---|---|---|
| | 07.00 | 13.00 | 19.00 | 22.00 |
| Cilegon | A - C | B – D | B - D | D - E |

The results of the atmospheric stability analysis show that stability in the morning, afternoon, evening, and night varies from A (very unstable) to E (somewhat stable). This indicates that atmospheric conditions in the city of Cilegon range from unstable to somewhat stable, in accordance with Pasquill's criteria for atmospheric stability.

## CONCLUSION

An analysis of the local atmospheric conditions in Cilegon City reveals that the average monthly air temperature ranges from a low of 21 °C in August to a high of 34.4 °C in April. The highest temperature occurs at 1:00 p.m. and the lowest at 7:00 a.m. local time. Wind direction from November through March generally shifts from west to east. From April through October, winds generally shift from north to south. The annual average wind speed is 2.3 m/s. Generally, the rainy season occurs from November through March, and the dry season from April through October. Atmospheric stability varies from A (very unstable) to E (somewhat stable) in the morning, afternoon, evening, and night. This indicates that atmospheric

conditions in Cilegon range from unstable to somewhat stable, in accordance with the Pasquill stability criteria.

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