Proceedings of the 6th ITB International Graduate School Conference
Multidisciplinary Collaboration for Sustainable Energy: Science, Technology, Policy, and Society

Analysis of MetOcean Changes in the Coastal Waters Surrounding Paiton Coal-Fired Power Plant, East Java

Harry Slamet Setiawan[1,2], Putri Mutianingsih[1,3], Zuhda Nur Prabowo[1,3], Lamona Irmudyawati Bernawis[1,4] & Andi Egon[1,4,5]

[1] Earth Sciences Master Program, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Indonesia
[2] Eastern Kalimantan Construction Unit, PT PLN (Persero), Indonesia
[3] Project Management Center, PT PLN (Persero), Indonesia
[4] Research Group of Applied and Environmental Oceanography, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Indonesia
[5] Centre for Coastal and Marine Development, Bandung Institute of Technology, Indonesia

Email: harryslamet.s@gmail.co.id

Abstract. The Paiton Coal-Fired Power Plant (CFPP), located on the northern coast of East Java, Indonesia, has been in operation since 1994. This study examines meteorological and oceanographic (MetOcean) characteristics, such as sea surface temperature (SST), winds, and waves, in coastal waters adjacent to the Paiton CFPP from 1993 to 2024. The analysis utilized ERA5 reanalysis data provided by Copernicus, along with periodic monitoring reports and field observations. The results indicate a seasonal variation in the sea surface temperature (SST) following the Indonesian monsoon cycle, with warmer temperatures during the rainy season and lower temperatures during the dry season. A temperature rising trend of approximately 0.0178°C annually was identified, with further increases potentially associated with thermal discharges from the cooling system of the plant. The dominant wind predominantly blows from east to southeast during the dry season, with speeds of 2–3 m/s. Analysis based on ERA5 data also reveals the wave is almost entirely composed of local windwaves, with heights ranging from 0.2 to 0.4 meters and rarely surpassing 0.4 meters. This study examines the impact of significant climatic phenomena in the study area, including the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The findings highlight the importance of continuous oceanographic monitoring and integrated environmental management to support the sustainable operation and long-term resilience of coastal power-generation facilities.

Keywords: *metocean; paiton cfpp; sea surface temperature; wind, wave, ENSO, IOD monsoon.*

1 Introduction

The Paiton Coal-Fired Power Plant (CFPP) is Indonesia's largest coal-based power generation facility, located on the northern coast of the Probolinggo Regency in East Java. Since its commissioning in 1994, the plant has been instrumental in supplying electricity to the regions of Java and Bali (PLN in [1]). Nevertheless, fossil fuel-based power plants may also exert environmental impacts, particularly influencing coastal meteorological and oceanographic (MetOcean) conditions (Yuniarti, *et al.* in [2]) where seawater is used as a condenser coolant that is subsequently discharged into the sea through canals, thereby introducing thermal input into the marine environment (Fudlailah and Zikra in [3]). These discharges, combined with natural climatic variations, may affect local sea surface temperature (SST), wind patterns, and wave characteristics, which are essential components of MetOcean parameters.

This study aims to analyze changes in MetOcean conditions, specifically sea surface temperature (SST), wind patterns, and wave characteristics, in the coastal waters surrounding the Paiton CFPP between 1993 and 2024. Furthermore, this study examines the effects of large-scale climatic phenomena, particularly the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) and their impact on these MetOcean parameters (Pintubatu, *et al.* in [4]). Through a scientific approach based on historical data and field observations, this study is expected to contribute to a better understanding of the coastal environmental dynamics influenced by Paiton CFPP operations and to serve as a basis for developing strategies for sustainable coastal resource management (Susilowati, *et al.* in [5]).

2 Data and Method

2.1 Location

The study area includes the coastal water around the Paiton CFPP, located at Longitude 113.3 º–113.8 º E and Latitude 7.5 °–7.75 °S**.** Paiton CFPP was selected as the study location because it is the largest coal-based power generation complex in Indonesia. With an operational scale of approximately 4600 MW for over two decades of gradual operation, it is presumed that environmental impacts, ranging from atmospheric, aquatic, and social dimensions, have accumulated over time.

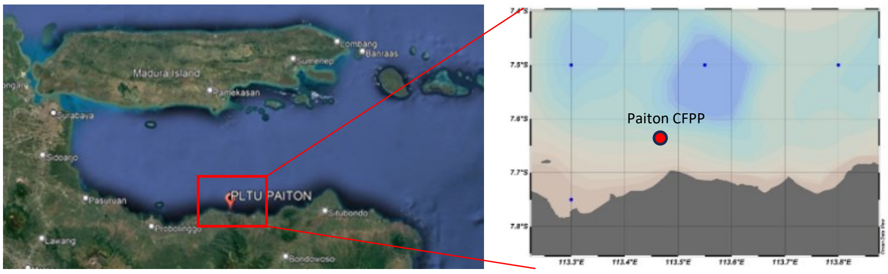

Figure 1 Study Location in the Coastal Waters Surrounding Paiton CFPP.

2.2 Data

Primary data for MetOcean parameters were gathered through field measurements in May 2025 at various sampling sites in waters adjacent to the Paiton CFPP. The data were collected using a Rinko Water Quality profiler, which measures conductivity, temperature, depth, DO, pH, turbidity, and chlorophyll-a.

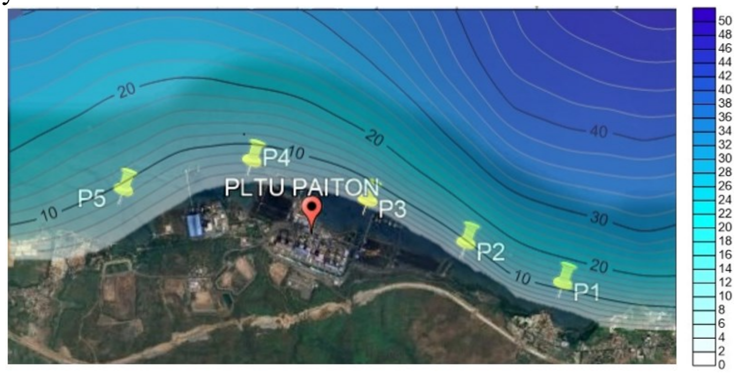

Figure 2 Location of monitoring points and field data sampling for sea surface temperature around the waters near the Paiton coal-fired power plant.

Table 1 Location of monitoring points and field data sampling coordinates and descriptions.

Point	Latitude	Longitude	Description
1	07°43'10.5"S	113°36'36.6" E	(P1) *desa banyuglugur*
2	07°42'54.8"S	113°35'57.2"E	(P2) cooling water oufall
3	07°42'38.2"S	113°35'17.4"E	(P3) cooling water intake
4	07°42'22.9"S	113°34'30.6"E	(P4) near ex-toyo office
5	07°42'35.1"S	113°33'39.0"E	(P5) *desa binor*

This study also utilises a long-term monthly analysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 and Copernicus for SST, wind speeds, and waves from 1993 to 2024 in the waters surrounding the Paiton CFPP and Probolinggo. This dataset is available on a monthly basis, with a spatial resolution of ~31 km (0.25° × 0.25°). Details of the data sources are provided in Table 2. Additionally, secondary data from the periodic monitoring reports in the surrounding CFPP, covering the years 2022–2024, were provided by the operator for the analysis conducted in this study.

Table 2 Secondary data source.

Data	Source
Sea surface temperature	ERA-5 monthly averaged SST data on single levels from 01-1994 to 10-2023 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download (Downloaded on December 16, 2024)
Wind speed and vector	ERA-5 monthly averaged 10m u and v component of wind from 01-1994 to 10-2023 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download (Downloaded on December 16, 2024)
Wave speed and vector	ERA-5 monthly averaged significant height of combined wind waves and swell, and mean wave direction from 01-1994 to 10-2023 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download (Downloaded on December 16, 2024)

2.3 Method

Temporal analysis of SST was conducted to identify long-term changes in oceanic dynamics influenced by global climate variability, such as the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). In this study, a Simple Linear Regression approach was employed on the SST data calculated on a monthly scale. This approach aims to quantify the magnitude and direction of temperature trends over time as well as to assess whether there has been a significant increase or decrease in SST during the observation period. This method has been used widely in oceanographic and climatic studies. Al-Taha, *et al*. [6] analyzed SST trends in the Persian Gulf using linear regression and found a significant increase over the past three decades.

Formula for linear regression equation to analyze SST trends:

$$y = a + b \cdot x \tag{1}$$

Explanation:
y = predicted SST value at time
x = time (e.g., in months or years)
a = intercept (SST value when
b =slope (gradient of the regression line indicating the rate of SST change per unit time)

Wind vector analysis was conducted to identify the dominant wind direction and speed patterns that contribute to ocean dynamics. Daily or monthly wind vector data from reanalysis models, such as ERA5 or NCEP, are used to generate quiver plot visualizations, which illustrate the spatial distribution of wind direction and intensity over the sea surface. Simanjuntak and Lin [7], in their study of the Lesser Sunda region, demonstrated that the seasonal wind patterns obtained from quiver plots are strongly correlated with the distribution of SST and chlorophyll-a during ENSO and IOD phases and also influence Ekman transport dynamics.

Wind rose and wave rose analyses were used to illustrate the frequency distribution of the wind and ocean wave directions and intensities. Wind data from atmospheric reanalysis models, such as ERA5, are used to generate wind roses, while wave data from numerical models, such as WAVEWATCH III, are used to construct wave roses. These visualizations allow for the identification of the dominant wind and wave directions that influence ocean dynamics, including currents, sediment transport, and coastal structure design. Chen, *et al*. [8] explicitly applied both methods to analyze the marine environmental conditions around the Xisha Islands in the South China Sea. The study revealed that wind and wave directions are largely governed by the monsoon season and that these prevailing directions have significant implications for wave energy and maritime infrastructure in the region.

3 Result

3.1 Sea Surface Temperature Condition

Figure 3 shows the time series of Sea Surface Temperature (SST) in coastal waters near the Paiton Coal-Fired Power Plant, East Java, from 1993 to 2024. All the monitoring stations exhibited similar patterns, with the western station (113.3 °E and 7.5 °S) consistently having a higher temperature. This phenomenon may be attributed to the shallow and narrow characteristics of the Madura Strait, coupled with weak circulation, resulting in prolonged residence time and greater heat accumulation. However, as indicated in Table 1, the eastern stations demonstrated a more pronounced warming trend, with the SST values across all locations becoming more similar after 2020. The SST data at the station (7.75 °S & 113.3 °E) showed lower values than other stations, likely due to its proximity to land, resulting in the data being less representative of actual field conditions.

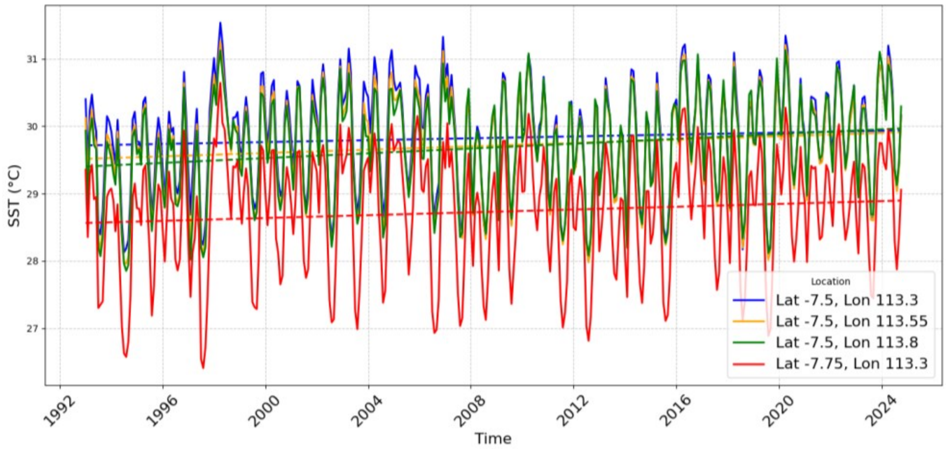

Figure 3 Sea surface temperature and trendline for 4 station surrounding CFPP.

Table 3 Summary of trendline temperature rise.

Location	Trendline Equation	Rate of Increase (°C/year)
7.5ºS &113.3ºE	y=0.0070x+15.8097	0.007
7.5ºS & 113.8ºE	y=0.0124x+4.8299	0.0124
7.5ºS & 113.8ºE	y=0.0178x−6.1283	**0.0178 (highest)**
7.75ºS & 113.3ºE	y=0.0105x+7.7155	0.0105

Based on Figure 4, the sea surface temperature (SST) in Paiton's coastal waters shows a regular seasonal pattern that matches the Indonesian monsoon cycle, which is split into December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). During the rainy season (DJF), SST is over 29.5°C, which is relatively higher than the annual average due to westerly winds bringing moisture and more clouds, which trap the ocean heat. As the dry season (MAM) begins, SST reaches its peak between 30–30.5°C with less cloud cover and maximum solar radiation. During the dry season (JJA), SST drops to 27–29°C as strong easterly winds originating from Australia intensify coastal upwelling. As the transition to the rainy season (SON) occurs, the SST rises again to approximately 30°C, coinciding with the weakening easterly winds and the start of the westerly monsoon.

Overall, seasonal SST variability in Paiton was strongly influenced by monsoon dynamics. Higher SSTs occur during the rainy season (DJF) and the transition toward rain (SON), whereas lower SSTs are observed during the dry season (JJA) due to upwelling, which is consistent with the typical conditions of Indonesia's tropical coastal areas.

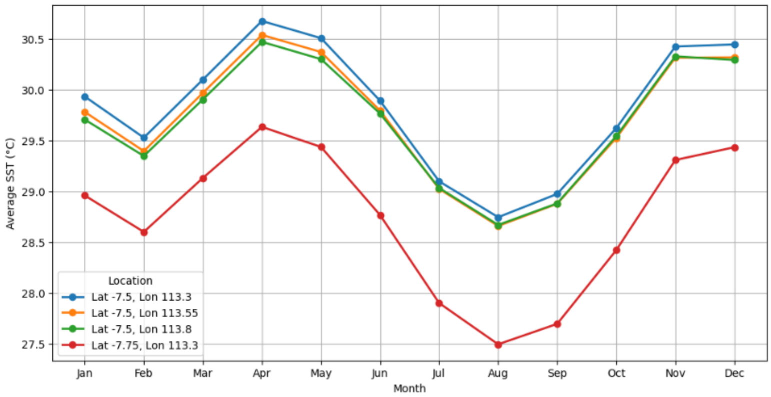

Figure 4 Average monthly sea surface temperatures from 1993 to 2024 for each reanalysis station.

Figure 5 presents a time series graph of sea surface temperature (SST) at five monitoring points based on monitoring reports conducted by the Paiton Coal-Fired Power Plant and a one-time field observation carried out in May 2025. These measurements were compared with time-series data from a reanalysis station (7.5 °S, 113.55 °E). The graph indicates two locations with consistently higher SST values, attributed to the thermal discharge activities from the power plant: one near the cooling water outlet and another near Bhinor Village, where Unit 9 cooling water outlet is located.

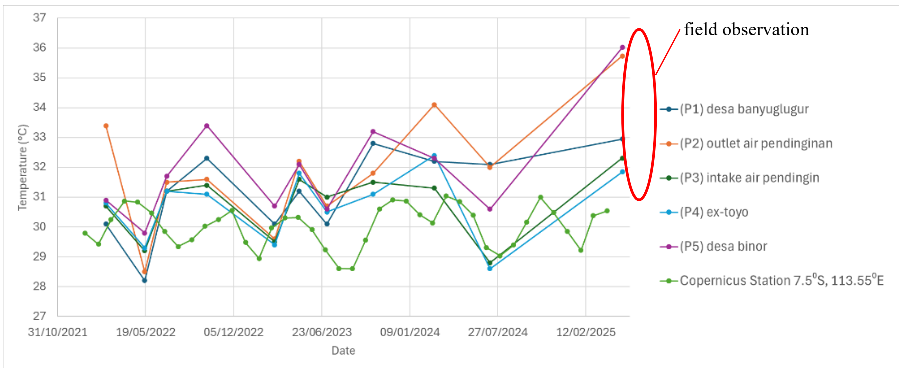

Figure 5 Sea surface temperature from monitoring locations based on periodic reports, direct observations, and reanalysis stations in 2022-2025.

The average SST from the monitoring stations ranges between 31.20°C and 31.94°C, and the average SST from the reanalysis station was 29.98°C. On average, a 1.96°C temperature difference was observed between the monitoring locations and the surrounding waters, as indicated by the reanalysis data. Based on the highest SST recorded from direct field observations, which reached 36.02°C, and assuming a maximum trendline increase of 0.0178°C per year, projections suggest that within the next 100 years, SST could rise to approximately 37.8°C. This projected value approaches the temperature threshold regulated for thermal discharge into coastal waters surrounding a power plant.

In addition to the influence of monsoons, another climatic variability affecting Indonesia's climate is the IOD phenomenon. The IOD is characterized by differences in SST between the western and eastern parts of the Indian Ocean, which drive changes in wind patterns and rainfall distribution in the surrounding regions. During the positive IOD phase, the western Indian Ocean (near Africa) was warmer than that in the eastern part (near Indonesia). This leads to decreased SST around Indonesia, particularly near Sumatra and Java, potentially causing droughts and reduced rainfall. Conversely, during a negative IOD phase, the SST in the eastern Indian Ocean near Indonesia becomes warmer than that in the west, leading to increased SST across Indonesia and a higher risk of heavy rainfall and flooding. Figure 6 illustrates a consistent correlation where positive IOD events in 1994, 1997, and 2019 coincided with negative SST anomalies. Similarly, strong relationships were observed during negative IOD events in 1999, 2016, and 2023, when SSTs increased. These variations indicate that IOD is a major driver of oceanic dynamics along the northern coast of East Java, along with the influence of ENSO and regional monsoon patterns.

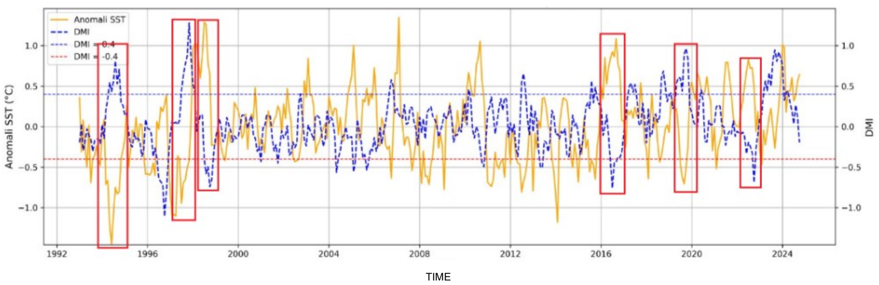

Figure 6 Sea surface temperature anomaly versus dipole mode index.

Another major large-scale climate variability influencing Indonesia's climate is ENSO, which significantly impacts regional climatic conditions. ENSO is driven by changes in SST in the central and eastern Pacific Ocean, leading to shifts in air pressure patterns, atmospheric circulation, and rainfall distribution across tropical regions. These fluctuations caused Indonesia to experience drier dry seasons during El Niño events, and wetter rainy seasons during La Niña events.

In Figure 7, an analysis of the relationship between sea surface temperature (SST) anomalies in Probolinggo and the ENSO index (Oceanic Niño Index, ONI) for the period 1992–2024 reveals a pattern indicating a negative correlation between the local SST variability along the northern coast of Java and the ONI. The graph illustrates that when the ONI entered a positive phase, signifying an El Niño event, SST in the Probolinggo region generally decreased. Conversely, local SST increased when the ONI was negative, indicating a La Niña event. This observation is consistent with the findings of Putra, *et al*. [9] and Yananto, *et al*. [10], who reported that SSTs across Indonesia generally decline during El Niño phases. During La Niña events, strengthened trade winds enhance the westward transport of warm water from the western Pacific, resulting in higher SSTs across Indonesian waters, including Probolinggo.

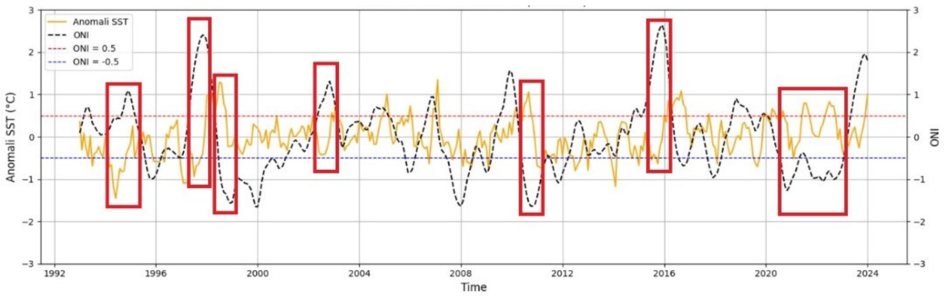

Figure 7 Sea surface temperature anomaly versus ONI index from 1993 to 2024.

The interaction between ENSO and IOD can either amplify or counteract their influence on SST in Probolinggo, as a positive (or negative) IOD often coincides with a positive (or negative) ENSO phase, resulting in SST cooling (or warming) in the region, depending on their respective phases and relative strengths. This temporal variability highlights the importance of simultaneously considering large-scale climatic phenomena when understanding and predicting changes in coastal sea surface temperatures in Indonesia.

3.2 Wind Condition

Figure 8 shows that on average, from 1993 to 2024, the wind predominantly blows from the southeast toward the west between April and November. This wind direction contributes to higher SST in the western and southwestern coastal waters near the Paiton CFPP. Additionally, the monthly wind direction at the observation station near the Paiton CFPP exhibited a distinct seasonal dynamic, which was consistent with the monsoonal characteristics of East Java. These data reflect changes in the wind direction and speed, which are closely linked to Indonesia's dry and rainy season cycles.

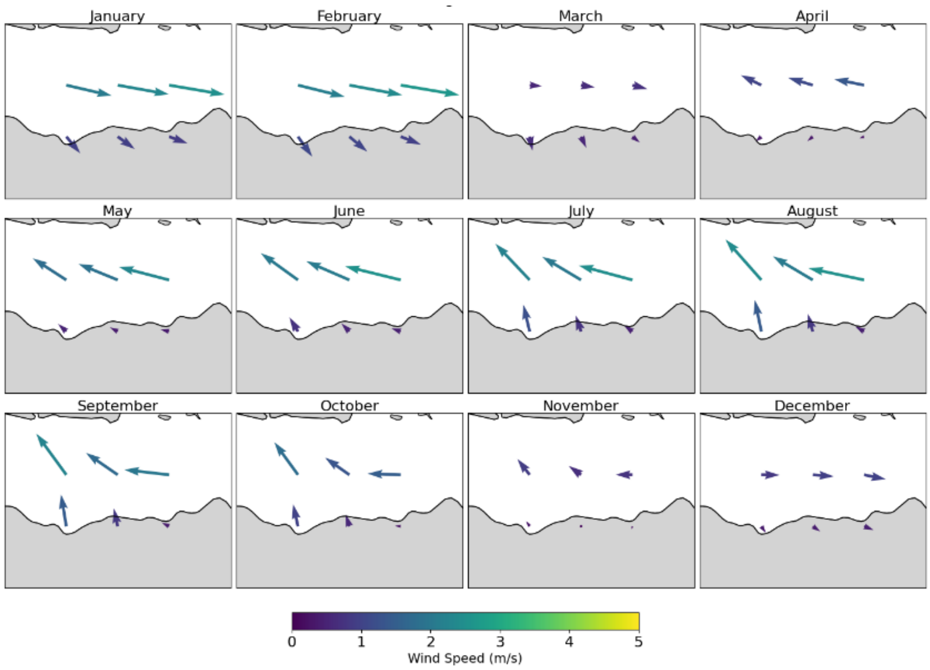

Figure 8 Average monthly wind speed and direction from 1993 to 2024.

The wind patterns in the Paiton area exhibited consistent seasonal changes following the monsoon cycle. From December to February (DJF), winds predominantly blow from west to east at speeds of 2–3 m/s, reflecting the influence of the West Monsoon, which brings moist air and supports the rainy season in East Java. The wind weakens and fluctuates between March and May (MAM), indicating a transition phase from the rainy to the dry season. In April and May, the winds shift toward the southeast, marking the early dominance of the east monsoon. During the dry season from June to September (JJA–SON), winds blow from the east-southeast toward the northwest at stronger speeds, averaging 3–5 m/s. The peak wind speed occurred in August, coinciding with the peak of the dry season. From October to November, the easterly winds weakened, and the directions became unstable, indicating a transition back to the rainy season. These weakened warm sea surface temperatures support cloud formation and increased rainfall.

Figures 9 and 10 present the wind rose and the operational wind conditions for the period 1993–2024 at the station located at coordinates (113.55 °E and 7.5 °S). These figures illustrate the characteristic and consistent patterns of the wind direction and speed, reflecting the seasonal dynamics of the northern coastal region of East Java. The distribution of wind directions showed a dominant flow from the east to southeast sectors, accounting for approximately 60–70% of the total recorded wind occurrences. Additionally, a minor secondary contribution from the west indicates seasonal wind variability despite its lower frequency. Wind speeds were mostly within the 1–3 m/s range, with the most frequent falling into the 2–3 m/s category. Wind speeds above 4 m/s were relatively rare, indicating that the wind conditions at this location were generally moderate to weak.

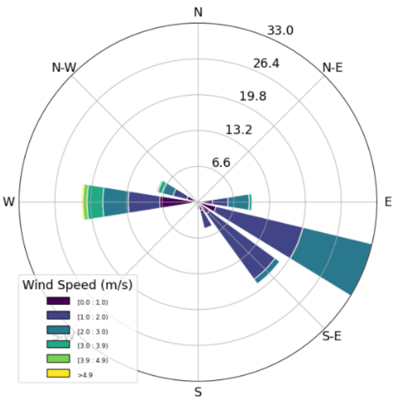

Figure 9 Wind rose diagram of the observation station (7.5 °S 113.55 °E) from 1993 to 2024.

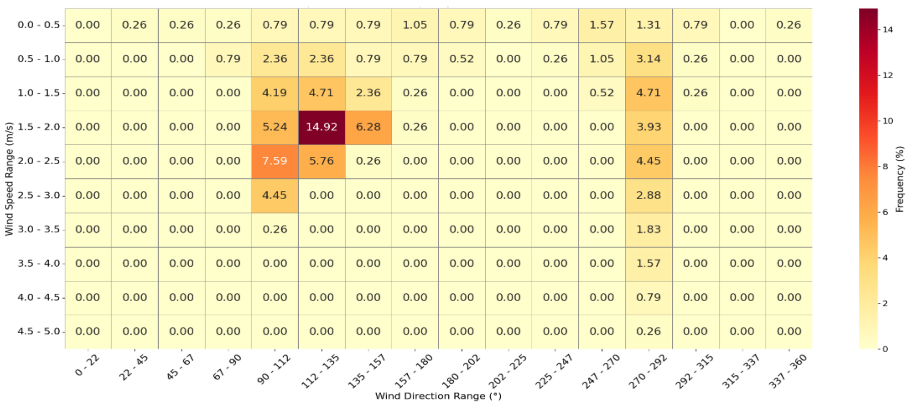

Figure 10 Operational wind conditions at observation station (7.5ºS 113.55ºE) from 1993-2024.

3.3 Wave Condition

The distribution of wave direction and height in the coastal waters of Paiton, East Java, showed a clear seasonal pattern that was strongly influenced by regional wind circulation. The wave rose in Figure 11 shows the dominant waves coming from the east to the southeast (45°–90°). This phenomenon aligns with the dominance of the eastern monsoon during the dry season, which brings a dry airflow from Australia to Indonesia. This is consistent with the wind data, which indicated that winds predominantly blow from the east-southeast toward the northwest, especially during the dry season (June–September).

The wave conditions in Figure 12 show that the significant wave height (Hs) at the observation station is between 0.2 and 0.4 m, with the highest frequency (~14.92%) recorded from directions 67°–90° and 90°–112°. H_S exceeding 0.4 m are rare, suggesting that this area remains relatively calm and is predominantly influenced by local wind-generated waves rather than by distant swell waves.

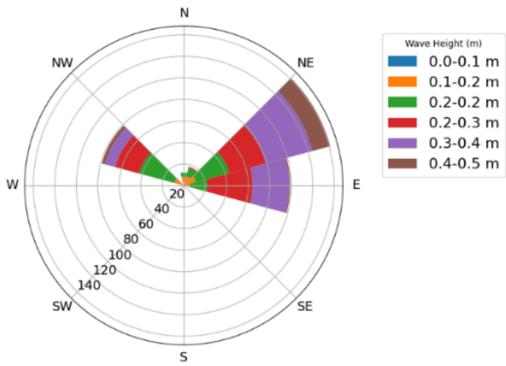

Figure 11 Wave rose diagram at observation station (7.5ºS 113.5ºE) from 1993 to 2024.

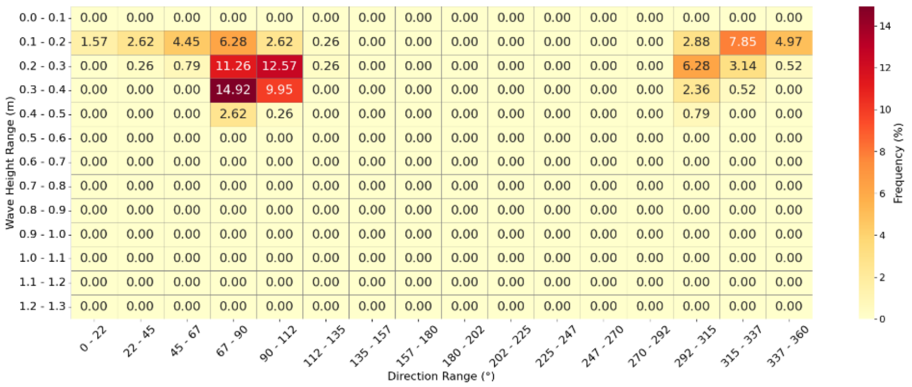

Figure 12 Operational wave condition observation station (7.5 °S 113.5 °E) from to 1993-2024.

4 Conclusion

This study demonstrates that oceanographic dynamics in the coastal waters surrounding the Paiton CFPP have a significant influence on plant operations and vice versa. The SST in this area exhibits strong seasonal variations that match the monsoon cycle, with higher temperatures (>30°C) during the rainy season, and a decrease to approximately 28°C during the dry season. This study also estimated a warming trend of 0.0178°C per year for SST, which, over the long term, could potentially impact the cooling system's efficiency and compliance with thermal discharge quality standards.

Large-scale climate variability, such as ENSO and IOD, further modulates SST conditions in the Paiton coastal region. El Niño phases and IOD positivity were generally associated with reduced SST, whereas La Niña and IOD-negative phases tended to increase SST. During the dry season, the wind direction is predominantly from east to southeast, with average speeds of 2–3 m/s. These conditions increase the evaporation risk in open cooling facilities and enhance the potential for salt-spray corrosion of metallic structures. During the rainy season, wind directions become more variable with higher atmospheric humidity, increasing the risk of condensation on electrical equipment.

Analysis of the waves reveals that the dominant direction originates from the east-southeast, with H_s mostly varies between 0.2 and 0.4 m. While these conditions are generally safe for cooling water intake operations, occasional waves exceeding 0.4 m. Overall, variations in the sea surface temperature, wind patterns, and wave characteristics interact and collectively affect the performance and reliability of power plant systems. Therefore, continuous oceanographic monitoring and the integration of large-scale climate data are essential components for developing effective risk management strategies, preventive maintenance planning, and long-term operational optimization for coastal-based power plants.

5 References

[1] PLN, *Laporan kinerja dan statistik PLN 2020*, PT PLN (Persero), Jakarta, 2020.

[2] Yuniarti, A., Sutrisno, & Widodo, R., *Analisis dampak operasi PLTU terhadap lingkungan pesisir di Jawa Timur*, Jurnal Teknik Lingkungan, 15(3), pp. 89–97, 2018.

[3] Fudlailah, P. & Zikra, M., *Pemodelan penyebaran limbah panas di wilayah pesisir (studi kasus outfall PLTU Paiton)*, Jurnal Teknik Kelautan, 1, pp. 1–8, 2013.

[4] Pintubatu, K.L., Widada, S., Marwoto, J. & Satriadi, A., *Studi pola sebaran suhu permukaan laut akibat air bahang pembangkit listrik tenaga uap (PLTU) Paiton Probolinggo Jawa Timur*, Indonesian Journal of Oceanography, 2(2), 2020.

[5] Susilowati, I., Nugroho, T. & Suryadi, B., *Pengelolaan lingkungan pesisir berbasis ekosistem*, Gadjah Mada University Press, Yogyakarta, 2020.

[6] Al-Taha, K.S., Alkarkhi, A.F.M., Albahadily, R.N., & Al-Juboury, M.A., *Trend analysis of sea surface temperature (SST) in the Arabian Gulf using remote sensing and linear regression*, Marine Pollution Bulletin, 182, p. 113915, 2022.

[7] Simanjuntak, F. & Lin, T.H., *Influence of AAM wind on chlorophyll-a, sea surface temperature, and Ekman dynamics along the Lesser Sunda Islands*, Remote Sensing, 14(7), p. 1682, 2022.

[8] Chen, S., Zhu, Y., Jiang, X., Yang, Y., Liu, S., Liu, Y., Guo, W., Chen, Z. & Li, H., *Study on the wind and wave environmental conditions of the Xisha Islands in the South China Sea*, Journal of Marine Science and Engineering, 10(10), p. 1459, 2022.

[9] Putra, D.P., Amin, T. & Asri, D.P., *Analisis pengaruh IOD dan ENSO terhadap distribusi klorofil-a pada periode upwelling di perairan Sumbawa Selatan*, Jurnal Meteorologi Klimatologi dan Geofisika, 4(2), Jul. 2017.

[10] Yananto, Ardila & Dewi, S., *Analisis kejadian El Nino tahun 2015 dan pengaruhnya terhadap peningkatan titik api di wilayah Sumatera dan*

Kalimantan, Jurnal Sains & Teknologi Modifikasi Cuaca, 17(1), p. 11, 15 Jun. 2016.

[11] Kusmanto, E., Hasanudin, M. & Setyawan, W.B., *Amplifikasi pasang surut dan dampaknya terhadap perairan pesisir Probolinggo*, Oseanologi dan Limnologi di Indonesia, 2(3), 2016.

[12] Patty, S. I., Huwae, R., & Kainama, F., *Variasi musiman suhu, salinitas, dan kekeruhan air laut di perairan Selat Lembeh*, Jurnal Ilmiah Platax, 8(1), pp. 111–120, 2020.

[13] Tessema, A., et al., *Pengaruh parameter fisik-kimia terhadap keanekaragaman fitoplankton di Waduk Wonogiri*, Jurnal Sains & Matematika, 22(1), pp. 1–10, 2014.

[14] Wardhani, E. & Hanifa, D.A., *Perhitungan mutu air laut di perairan sekitar pembangkit listrik tenaga uap*, Jurnal Serambi Engineering, 9(1), pp. 8010–8021, 2024.

[15] PT SKY Pacific Indonesia, *Laporan Hasil Pengujian: PT PJB UP Paiton*, SPI-22010087A1, PT SKY Pacific Indonesia, Bogor, 3 Feb. 2022. (Data dari 2022-2024)