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Historical analysis of ocean climate hazard indicators and sea level projection in the Karawang region, Indonesia

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ABSTRACT Karawang, located on the northern coast of Java, Indonesia, is highly vulnerable to climate change impacts such as rising sea levels, increasing sea surface temperatures (*SST*s), and shifting weather patterns. As a key industrial and agricultural region, these environmental changes threaten both the local economy and coastal communities, especially those relying on marine resources. This study analyses high-resolution oceanographic data from 1994 to 2024, including *SST*, salinity, sea surface height (*SSH*), and wave direction, to examine trends and future projections. Results show clear seasonal patterns in *SST* and *SSH*, with peaks during April–May and November, influenced by monsoon cycles. Sea levels show a gradual rise, with projections indicating an increase of up to 0.895 m by 2059 using the Forecast.ETS method. Salinity also follows a seasonal pattern, peaking in October, while wave direction varies with monsoonal shifts. These findings highlight the importance of the continuous monitoring of marine variables to better understand climate change impacts. The study emphasises the need for effective mitigation and adaptation strategies to help coastal areas like Karawang respond to climate-related challenges and strengthen overall climate resilience. This comprehensive analysis not only identifies significant trends in ocean climate indicators but also provides critical insights into their potential socio-economic ramifications, particularly for vulnerable coastal communities. These findings underscore the urgency for targeted climate interventions. Furthermore, the study offers novel sea level projections that can inform policy and guide the development of adaptive strategies, ensuring long-term sustainability of the Karawang marine ecosystems and resources in the face of escalating climate threats.

Key words: Karawang, climate change, sea level rise, ocean climate indicators, climate resilience.

1. Introduction

Karawang is a coastal region located on the northern shore of Java, Indonesia. Known for its abundant natural resources, particularly in the marine and fishery sectors, Karawang plays a crucial role in the country's economy. However, this prosperity is increasingly under threat from the escalating effects of global climate change. Rising sea surface temperatures (*SST*s), sea level rise, and altered weather patterns are directly impacting the coastal environment, putting both the economy and local communities at risk (Fathiyaturahma, 2023; Tim VOI, 2024). As a key industrial hub, Karawang's vulnerability to these environmental changes is substantial, with adverse effects already being felt. Given its strategic location and significance, Karawang serves as an ideal case study for analysing marine spatial variables and understanding their role in detecting and mitigating the impacts of climate change.

The consequences of climate change for the marine environment are extensive and far-reaching. In Karawang, visible impacts such as coastal erosion, more frequent tidal flooding, and the destruction of mangrove forests are already evident (Fauzie, 2016; Ikhsani *et al.*, 2021; Solihuddin *et al.*, 2021). These environmental shifts not only threaten local biodiversity but also destabilise the livelihoods of coastal communities dependent on marine resources for food, income, and cultural practices. A deeper understanding of these changes is essential to designing effective mitigation and adaptation strategies, which require robust scientific studies that can provide actionable insights into the evolving state of the marine environment. Monitoring key marine spatial variables such as *SST*, salinity, sea surface height (*SSH*), and wave direction are necessary for early detection of climate change effects, enabling timely responses to mitigate these impacts.

Seasonal precipitation plays a critical role in shaping the spatial and temporal variability of oceanographic conditions in coastal regions such as Karawang. Changes in rainfall intensity and distribution, driven by monsoonal dynamics and large-scale climate phenomena like the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), affect surface salinity, ocean temperature, and sea level anomalies (*SLAs*) through freshwater fluxes and energy balance. Recent research also indicates that shifts in the timing and strength of wet and dry seasons are emerging in Java (Iskandar *et al.*, 2020), making it essential to incorporate long-term precipitation data into ocean climate hazard assessments.

Scientific evidence is the backbone of any climate change mitigation and adaptation effort. Oceanography, as a discipline, offers critical insights into marine dynamics by analysing variables such as *SST*, *SSH*, salinity, and wave direction. Monitoring and analysing these variables are essential for detecting early signs of climate change and predicting its long-term effects on coastal regions. In the case of Karawang, these data are not only vital for understanding the local marine environment changes but also for informing broader national and global climate strategies aimed at addressing climate change. By aligning local scientific research with national and global climate action plans, Karawang's situation can contribute valuable data to global efforts to combat climate change and its associated risks.

This study is aligned with the national policy goals for enhancing the resilience of coastal regions to climate change (Indonesian Ministry of Environment and Forestry, 2018, 2024). It emphasises the importance of using local scientific data to inform climate action at both regional and national levels. Integrating these findings into policy frameworks will enable coordinated and impactful climate actions, enhancing the resilience of coastal regions and their communities. The analysis of marine spatial variables provides a foundation for developing adaptive strategies tailored to the unique challenges faced by coastal regions like Karawang. By grounding local, regional, and national strategies in scientific evidence, this approach ensures that climate action is both effective and sustainable, supporting long-term climate resilience and sustainable development in Karawang, as well as in other coastal areas facing similar threats.

2. Materials and methods

2.1. Materials

This study utilises high-resolution reanalysis and satellite-based datasets to analyse four key oceanographic variables in the Karawang region: *SST*, salinity, *SSH*, and wave direction. The study area is located between 106.7° E, 5° S and 108° E, 6.3° S, representing a typical coastal system of northern West Java (Fig. 1).

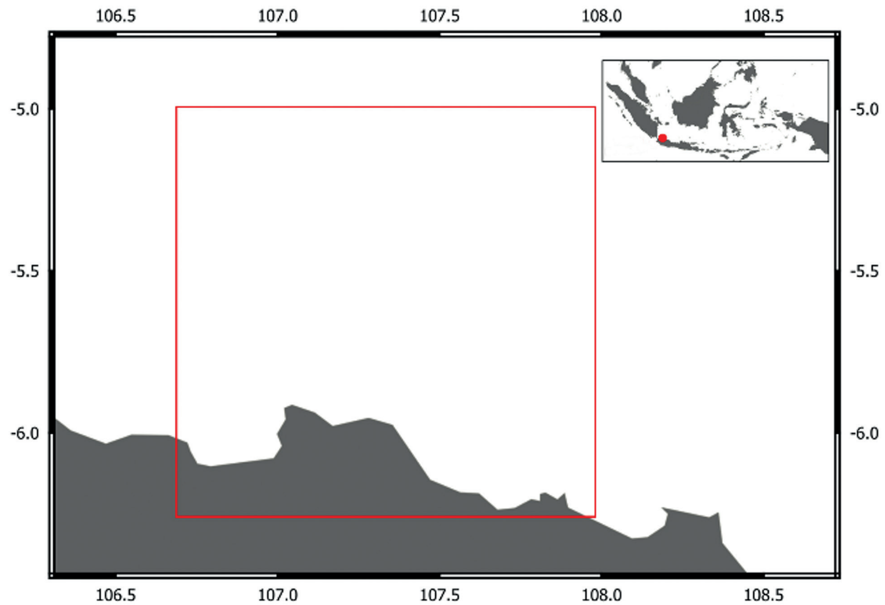

Fig. 1 - Karawang waters are located in the coastal region in the western part of Java Island. The red dot indicates the research location.

SST, salinity, and *SSH* data were sourced from the Global Ocean Physics Reanalysis (GLORYS12V1, GLOBAL_MULTIYEAR_PHY_001_030), developed by Mercator Ocean using the NEMO model and atmospheric forcing from the ECMWF ERA5 reanalysis. These datasets cover the period from 1 January 1994 to 22 October 2024, with a horizontal resolution of 1/12° (~9.25 km) and 50 vertical layers. Wave direction data were obtained from the Global Ocean Waves Reanalysis (GLOBAL_REANALYSIS_WAV_001_032) covering the same period. Additionally, total precipitation data were extracted from the ERA5 reanalysis (Hersbach *et al.*, 2020) over the same spatial domain for the period from 1 January 1994 to 22 October 2024. The precipitation data, provided at a spatial resolution of 0.25°, were used to analyse the seasonal rainfall patterns and assess the relationship between atmospheric conditions and oceanographic variability.

To ensure model reliability, validation was conducted using observational satellite datasets. The *SSH* outputs were validated with the Global Ocean Gridded Level 4 Sea Surface Heights (SEALEVEL_GLO_PHY_L4_MY_008_047) dataset, while the *SST* was validated using the OSTIA *SST* and Sea Ice Reprocessed dataset (SST_GLO_PHY_L3S_MY_010_039). Validation was performed by comparing modelled and observed values using correlation analysis to assess temporal consistency (Table 1).

In addition to the reanalysis of the datasets, this study incorporates sea level projections from two major sources:

i) the CMIP6 SSP2-4.5 scenario, retrieved through the NASA Sea Level Change Portal (2023) and
ii) tidal-based projections from Sistem Referensi Geospasial Indonesia (2024), Indonesian Geospatial Information Agency (BIG).

Table 1 - Summary of the datasets used in the study.

Dataset name	Data type	Source	Time period	Web page
Global Ocean Physics Reanalysis (GLORYS12V1)	Sea surface temperature (*SST*), salinity, sea surface height (*SSH*)	E.U. Copernicus Marine Service Information (2024c)	1 January 1994 – 22 October 2024	https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030
Global Ocean Waves Reanalysis (GLOBAL_REANALYSIS_WAV_001_032)	Wave direction	E.U. Copernicus Marine Service Information (2024d)	1 January 1994 – 30 September 2024	https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_WAV_001_032
Global Ocean Gridded Level 4 Sea Surface Heights and Derived Variables Reprocessed 1993 Ongoing (SEALEVEL_GLO_PHY_L4_MY_008_047)	*SSH*	E.U. Copernicus Marine Service Information (2024a)	1 January 1994 – 31 December 2023	https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047
Global Ocean OSTIA SST and Sea Ice Reprocessed (SST_GLO_PHY_L3S_MY_010_039)	*SST*	E.U. Copernicus Marine Service Information (2024b)	1 January 1994 – 31 May 2022	https://data.marine.copernicus.eu/product/SST_GLO_PHY_L3S_MY_010_039
The ERA5 global reanalysis	Precipitation	Hersbach *et al.*, (2020)	1 January 1994 – 22 October 2024	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels

The selection of high-resolution reanalysis products and satellite validation datasets in this study follows established practices in recent oceanographic research focusing on tropical and marginal seas. For instance, Lubis *et al.* (2025) analysed decadal and seasonal oceanographic trends in the Gulf of Thailand using similar datasets, while Lubis *et al.* (2024) examined annual *SSH* variability in the Indonesian seas. Wang *et al.* (2024) demonstrated the effectiveness of reanalysis and data-driven forecasting models in simulating global ocean dynamics. Hiron *et al.* (2025) utilised satellite and machine learning approaches to improve coherence predictions of eddy structures, further validating the importance of high-resolution temporal datasets. In the Indonesian context, Setiawan and Habibi (2011) emphasised the importance of combining reanalysis and satellite data to understand seasonal and interannual variability in *SST* and biological productivity in the Gulf of Tomini.

The integration of these datasets ensures that the quality and methodological framework adopted in the present study are robust, enabling a comprehensive assessment of historical variability and future projections of ocean climate hazards in the Karawang region.

2.2. Methods

2.2.1. Data validation

Model validation was conducted to assess the accuracy of the model outputs against satellite imagery. The validation process was based on the correlation coefficient between the two datasets. Model output data were compared with satellite observation data, including the *SLA* and *SST* derived from the datasets used in this study. The *SLA* was calculated using the following equation:

$$SLA(t) = SSH_{\text{daily}}(t) - \overline{SSH}_{\text{temporal}} \quad (1)$$

where $SLA(t)$ is the SLA on day, $SSH_{\text{daily}}(t)$ is the daily SSH on day, and SSH_{temporal} is the temporal mean SSH over the analysis period.

The model's ability to represent actual conditions was evaluated by calculating the correlation coefficient using the equation from Thomson and Emery (2014), as shown below:

$$r = \frac{1}{N-1}\sum_{i=1}^{N}\frac{(x_i - \bar{x})(y_i - \bar{y})}{S_x S_y} \quad (2)$$

where r is the correlation coefficient, N is the total number of data points, i is the index of elements, in latitude and longitude, x_i is the i^{th} value of the model data, y_i is the i^{th} value of the satellite data, $\bar{x}$ is the mean of the model output data, $\bar{y}$ is the mean of the satellite data, and S_x,S_y are the standard deviations of the model data (x) and satellite data (y).

High correlation values indicate that the model accurately represents the temporal and spatial variability of ocean climate variables in the Karawang region. The application of such validation techniques is consistent with recent oceanographic studies focusing on tropical coastal environments (Hiron *et al.*, 2025; Lubis *et al.*, 2025).

2.2.2. Historical analysis

The study integrates various analytical techniques to evaluate oceanographic variables. First, a time series analysis will be conducted to investigate trends in *SST*, *SSH*, salinity, and wave direction over three different time spans: 30, 15, and 5 years. This analysis facilitates the identification of long-term shifts and seasonal patterns in these oceanographic variables, providing a foundational understanding of their temporal dynamics.

Subsequently, a climatological analysis will be applied to evaluate the spatial distribution of these variables over a 30-year period. This approach focuses on characterising typical climatological behaviour and identifying seasonal fluctuations in *SST*, *SSH*, salinity, and wave direction within the Karawang region. These parameters are averaged monthly (Thomson and Emery, 2014). By analysing these patterns, the study aims to uncover significant variations and potential anomalies that may indicate broader climate change or anthropogenic impacts.

Spectral analysis using Fourier Transform will be performed to identify periodicity and dominant frequencies in the dataset. This analysis employs 370 data points, corresponding to the temporal coverage of the study, and extends the dataset to 512 points using zero-padding to meet computational requirements for spectral estimation. Frequencies are determined based on the adjusted data length, enabling a detailed examination of periodic components in variables such as *SST*, *SSH*, and salinity.

2.2.3. Sea level projection

This study visualises projections from CMIP6 and BIG, including mean sea level and highest sea level. Additionally, the study forecasts historical data using linear regression and the Exponential

Triple Smoothing (ETS) method, as shown in the following equations:

linear regression equation: $y = 0.0003x + 0.5409$ (3)

where x is the projection value and y is the nth month (e.g. Jan 1994 = 1, Feb 1994 = 2, etc.);

forecast.ETS equation: $\widehat{y_{t+k}} = \left(\alpha \cdot (y_t - S_{t-m})\right) + (1-\alpha) \cdot \widehat{y_{t-1}}$ (4)

where y_{t+k} is the forecasted value for future time $t+k$, α is the smoothing constant, y_t is the actual value at time t, S_{t-m} is the seasonal component of the data at time $t-m$, y_{t-1} is the forecasted value at time $t-1$, and m is the length of the seasonality period.

The model's ability to represent actual conditions was evaluated by calculating the correlation coefficient using the equation from Thomson and Emery (2014):

$$r = \frac{1}{N-1}\sum_{i=1}^{N}\frac{(x_i - \bar{x})(y_i - \bar{y})}{S_x S_y} \quad (5)$$

where r is the correlation coefficient, N is the total number of data points, i is the index of elements, in latitude and longitude, x_i is the i^{th} value of the model data, y_i is the i^{th} value of the satellite data, $\bar{x}$ is the mean of the model output data, $\bar{y}$ is the mean of the satellite data, and S_x,S_y are the standard deviations of the model data (x) and satellite data (y).

3. Results and discussion

SLA and *SST* are crucial indicators in understanding ocean-climate interactions, particularly in assessing ocean climate hazards. *SLA* provides insights into changes in sea level that can lead to coastal hazards such as flooding, while *SST* reflects the thermal state of the ocean, influencing weather patterns and marine ecosystems. These parameters are integral to evaluating the potential impacts of climate change on coastal regions, making them essential for the validation process presented in this study. Through the historical analysis of these key variables, it is possible to ascertain the accuracy and reliability of the hazard assessments and projections derived from them, ensuring that they accurately reflect the prevailing oceanic and climatic conditions.

3.1. Data validation

Data validation was performed for the period from 1 January 1994 to 31 December 2023, for *SLA*, and from 1 January 1994 to 31 May 2022, for the *SST*, covering the same region used in the analysis. Validation results indicate a high degree of agreement between reanalysis model outputs (*SSH* model, *SST* model) and satellite observations (sea surface height satellite, sea surface temperature satellite). For the *SLA*, the Pearson correlation coefficient was found to be 0.92, indicating excellent temporal and spatial consistency (Fig. 2a). For the *SST*, the correlation coefficient was even higher at 0.96, demonstrating the model's strong capability in reproducing observed thermal variability (Fig. 2b).

These high correlation values suggest that the model performs well in representing the key

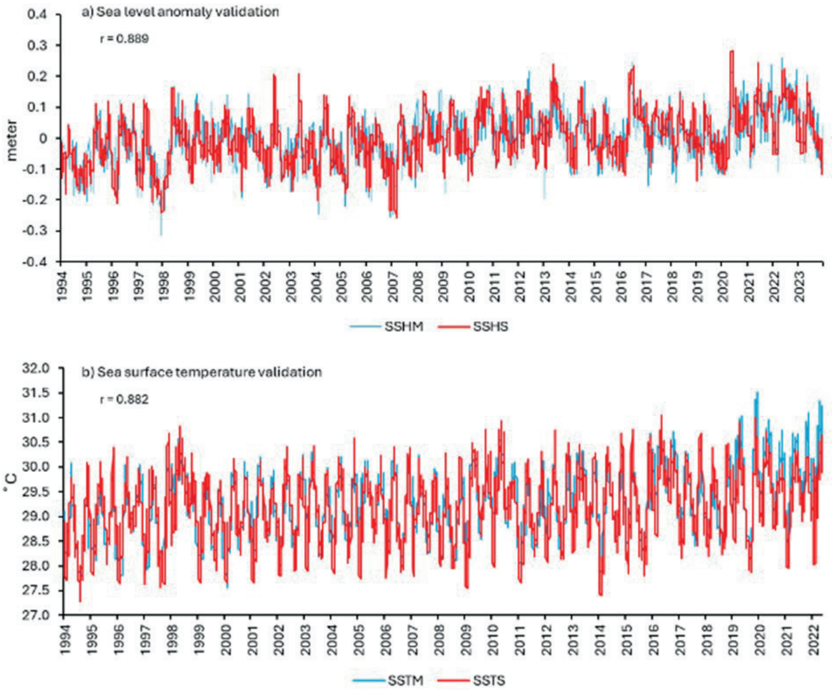

Fig. 2 - Data validation results: a) *SLA*, b) *SST*. The validation results show a strong correlation between the reanalysis model outputs (SSHM: Sea Surface Height Model, SSTM: Sea Surface Temperature Model) and satellite observations (SSHS: Sea Surface Height Satellite, SSTS: Sea Surface Temperature Satellite).

oceanographic variables in the Karawang coastal region. The close alignment between model and observation time series provides confidence in the subsequent use of the datasets for climatological pattern identification, historical trend analysis, and future sea level projection assessments.

3.2. Climatological and spectral analysis

The climatological and spectral analysis of the average *SST*, *SSH*, salinity, total precipitation, and wave directions show various patterns in Karawang waters (Fig. 3). The spectral analysis of *SST*, *SSH*, and salinity highlights dominant periodicities corresponding to semi-annual and annual cycles (Fig. 3a). The six-month periodicity aligns with the bimodal seasonal patterns observed in the climatological analysis. The one-year periodicity represents the broader annual variability characteristic of oceanographic systems influenced by seasonal changes. The strongest magnitudes in the spectral analysis at these periodicities emphasise the importance of seasonal and semi-annual cycles in driving variability within the region's oceanographic environment.

The climatological average *SST* over the study period demonstrates a clear bimodal seasonal pattern (Fig. 3b). Two prominent peaks are observed annually, with the first occurring from April to May and the second in November. These peaks suggest distinct seasonal drivers influencing temperature variability, likely tied to atmospheric and oceanographic phenomena such as monsoonal transitions or variations in solar radiation.

From the spatial data analysis of the *SST*, it becomes evident that coastal regions exhibit distinct patterns of temperature variability (Fig. 4). During periods of elevated *SST*, the coastal areas consistently demonstrate higher temperatures compared to offshore zones. Conversely,

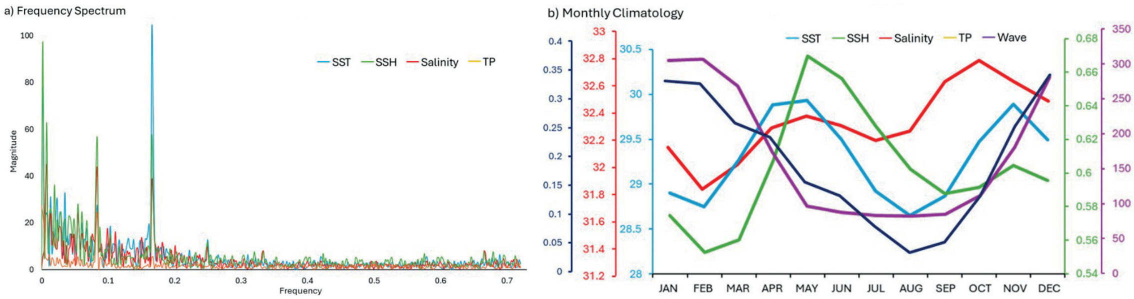

Fig. 3 - a) Frequency spectrum of *SST*, *SSH*, salinity, and total precipitation; b) monthly climatology of *SST*, *SSH*, salinity (%), total precipitation and wave direction.

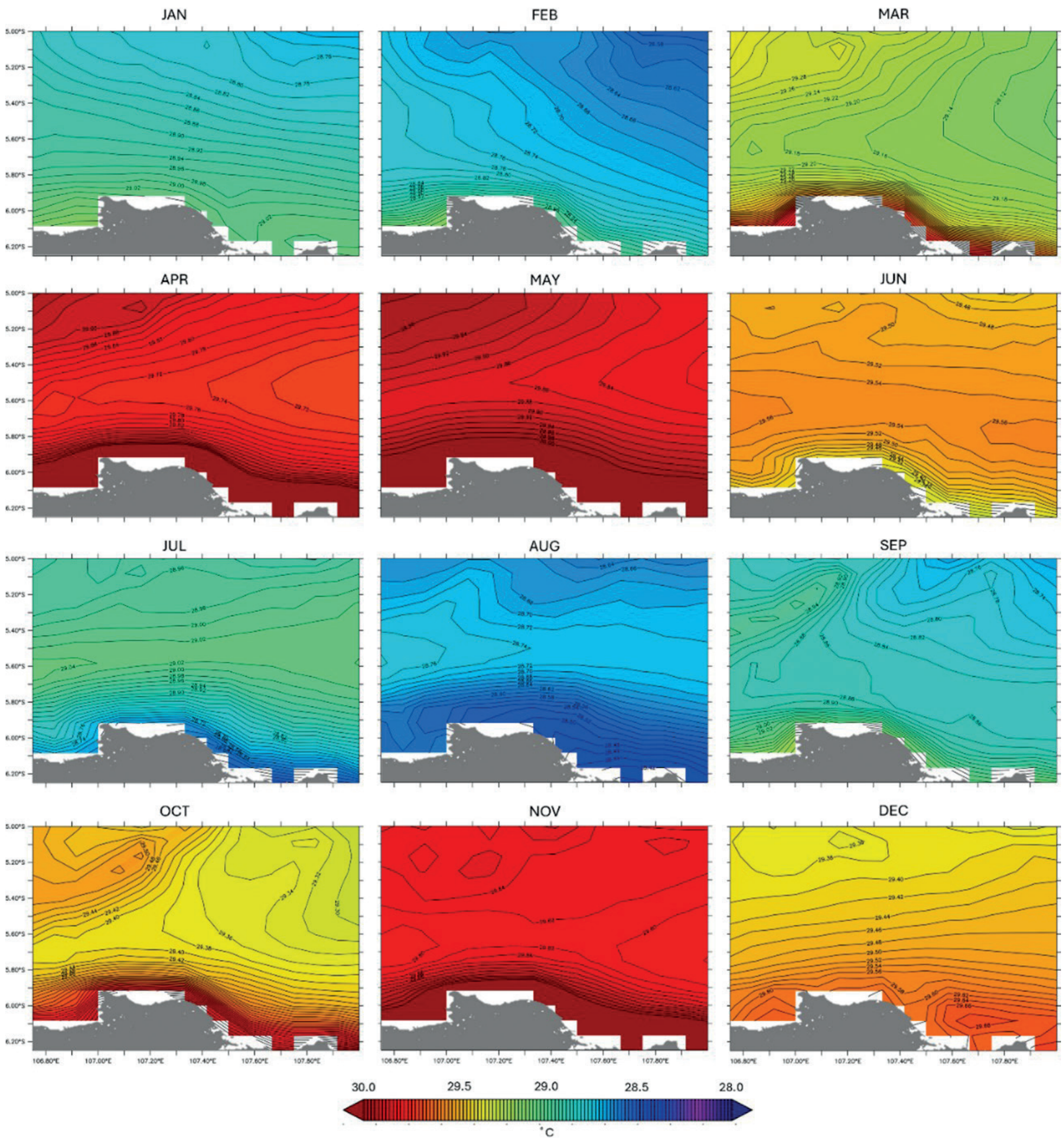

Fig. 4 - Spatial distribution of monthly average *SST* over the past 30 years.

during cooler *SST* phases, the coastal zones tend to show lower temperatures relative to the open sea. This spatial disparity highlights the influence of coastal dynamics, such as shallow water depths, localised heating, and freshwater inflows, which can amplify temperature extremes near the shore.

The pronounced *SST* variability along the Karawang coastline is likely a reflection of land-sea interactions, including heat exchange processes, freshwater input from rivers, and anthropogenic influences such as urban heat effects and industrial discharges. These factors contribute to creating localised hotspots and coldspots, which can have significant impacts on marine ecosystems and coastal communities. Understanding the spatial heterogeneity of *SST* in coastal areas is crucial, especially in the context of climate change. Higher *SSTs* in coastal waters can exacerbate stress on marine organisms, worsen stratification, and affect the productivity and distribution of key species. Conversely, lower *SSTs* during cooler periods can impact larval development and nutrient cycling, further influencing the resilience of marine ecosystems.

The variability of *SST* in the Karawang region is strongly influenced by land-sea interactions, where heat exchange between land and ocean, combined with freshwater inputs from river discharges and human activities, creates localised temperature extremes (Bahtara and Zikra, 2019). Coastal dynamics, including the influence of shallow water depths, can exacerbate these effects, leading to higher *SSTs* near the shore during periods of elevated temperatures. Urbanisation and industrial discharges further amplify this trend, particularly in areas where infrastructures limit natural coastal buffering. These localised warming hotspots have significant implications for marine ecosystems, as increased *SST* can lead to coral bleaching, can disrupt fish migration, and harm marine biodiversity (Iskandar *et al.*, 2020).

The *SSH* in the Karawang coastal region follows a pronounced seasonal pattern, influenced by various oceanographic and atmospheric processes. The *SSH* exhibits a bimodal distribution with peaks in May and November, corresponding to significant seasonal transitions (Figs. 3b and 5). The variability in the *SSH*, just like the *SST*, is strongly influenced by both local and larger-scale climate systems, including precipitation, freshwater inflow, evaporation, and atmospheric pressure patterns.

The first peak of the *SSH* typically occurs in May, during the transition from the wet to the dry season. This peak is likely associated with the increased river discharge from the rainy season, which adds freshwater to the coastal ocean and raises the local sea level. River discharges are significant during this time, contributing to higher *SSH* values. In contrast, the secondary peak in November is likely linked to a decrease in rainfall and reduced freshwater input, leading to a more stable or slightly elevated *SSH*, influenced by the residual effects of seasonal ocean circulation patterns (Bahtara and Zikra, 2019).

In addition to these atmospheric processes, *SSH* variability in Karawang is strongly influenced by the broader monsoonal cycle in SE Asia. During the north-western monsoon (December–March), the prevailing north-westerly winds push water towards the coastal areas, which can raise the *SSH*. In contrast, the south-eastern monsoon (May–October) tends to push water away from the coastline, leading to a lower *SSH* during the dry season. This monsoonal wind-driven SSH variability reflects the interaction between large-scale atmospheric circulation patterns and local coastal dynamics (Iskandar, 2014).

The salinity analysis reveals a gradual increase throughout the year, starting from January and reaching its maximum in October (Figs. 3b and 6). Two peaks are evident, with the first in May and the second, more pronounced, in October. This seasonal progression indicates that salinity is influenced by a combination of factors, including precipitation patterns, freshwater influx, and evaporation rates.

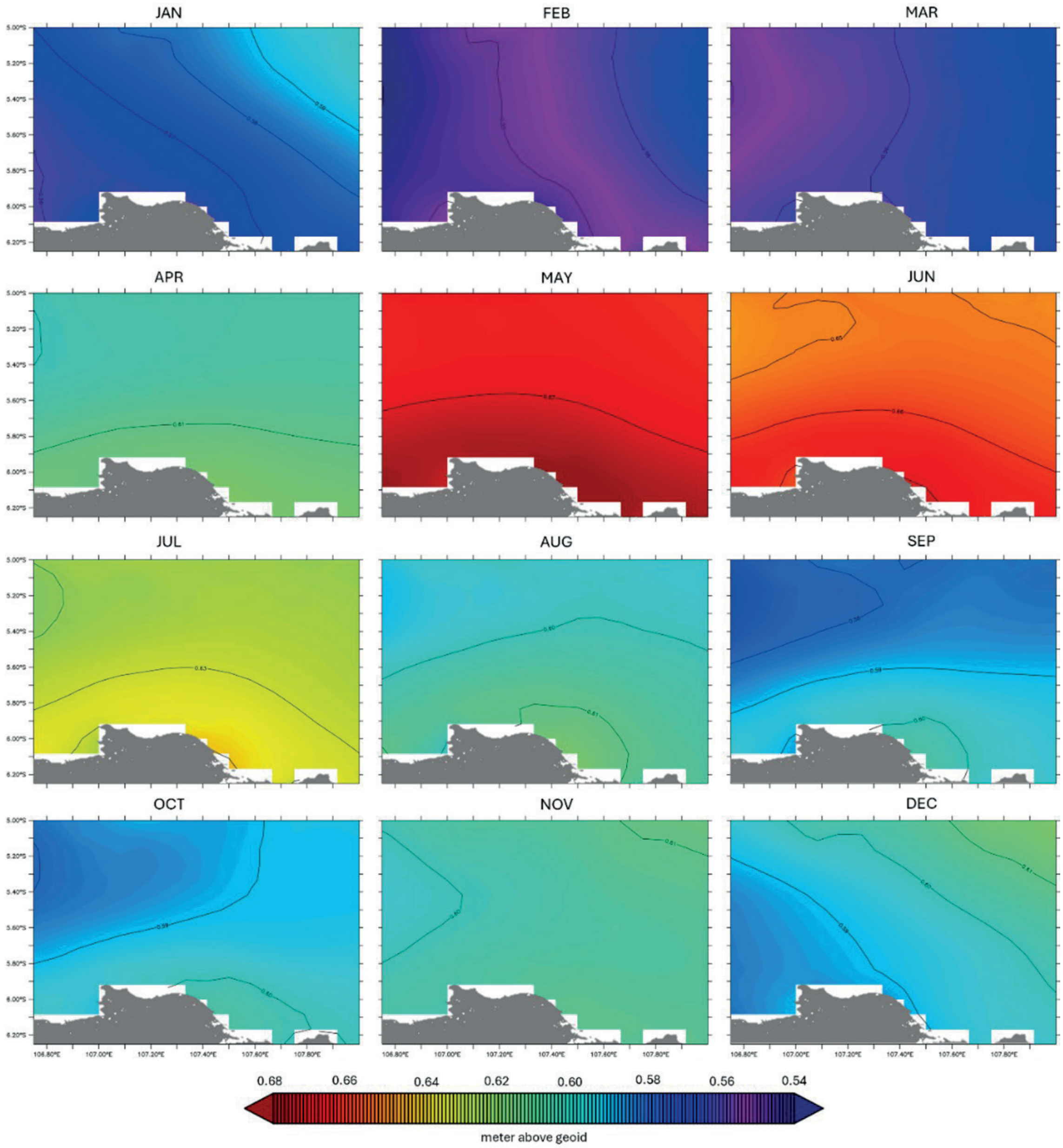

Fig. 5 - Spatial distribution of monthly average *SSH* over the past 30 years.

The climatological spatial distribution of average monthly salinity over one year in the Karawang region reveals a gradient between coastal and offshore areas (Fig. 6). This pattern is likely influenced by river discharge, evaporation processes, or mixing variations due to tidal activity. The salinity distribution exhibits a seasonal cycle, with higher salinity values during the dry season and lower values during the rainy season (Fig. 3b).

The seasonal variability in precipitation patterns is intricately linked to salinity, *SST*, and *SSH* in the Karawang region. As shown in Fig. 3b, there is a clear contrast between the dry and rainy seasons, with the peak precipitation occurring in December and January, and the driest period in August. This precipitation cycle plays a crucial role in regulating salinity levels and influencing *SST* and *SSH* dynamics.

During the dry season, which spans from May to November, rainfall is minimal, with precipitation levels as low as 0.02 mm/month in August (Figs. 3b and 7). This lack of freshwater influx from precipitation, combined with higher evaporation rates due to increased *SST*, leads to an increase in salinity, especially in coastal waters. The absence of significant rainfall prevents the dilution of seawater, enabling the accumulation of salt in the surface layer. The higher *SST* during this period, driven by the lack of cloud cover and minimal rainfall, further enhances evaporation, contributing to higher salinity levels along the coast.

As precipitation begins to rise in October, albeit slightly, the influx of freshwater from rainfall starts to reduce salinity (Perigaud *et al.*, 2003; Supply *et al.*, 2020), but the impact is limited due to the relatively dry conditions compared to the peak rainy season. This transitional period is marked by persistent higher salinity levels, which can be attributed to the continued dominance of evaporation over freshwater input. The slight increase in precipitation, however, signals the beginning of a gradual shift towards fresher coastal waters, especially as the rainy season begins in December.

From December to April, the rainy season brings a sharp increase in precipitation, peaking at approximately 0.34 mm/month in December and January. This influx of freshwater significantly dilutes the seawater, leading to a decrease in salinity, particularly near the coast. The freshening effect is also accompanied by a slight cooling of the *SST*, as the increased cloud cover reduces solar radiation and rainfall directly cools the surface waters. The cooling of the *SST*, although less pronounced than the salinity changes, can still influence the overall thermal structure of the coastal waters, which in turn affects the local marine environment.

Furthermore, the rise in precipitation during the rainy season can also lead to an increase in *SSH*, as the freshwater influx raises the local sea level, adding to the already existing seasonal variations in *SSH*. This is particularly evident in the Karawang region, where river discharge and precipitation combine to influence local sea level, contributing to the observed seasonal fluctuations in both *SSH* and salinity.

The interannual variability of precipitation over the past 30 years, as shown in Fig. 4b, indicates consistent annual peaks during the rainy season without significant shifts in the onset timing. This reinforces the classification of December–April as the primary rainy season, providing a predictable framework for understanding how seasonal precipitation influences the hydrographic conditions in the Karawang coastal zone. The regularity of this precipitation cycle further underscores the seasonal predictability of salinity, *SST*, and *SSH* patterns, all of which play a crucial role in shaping the ecological conditions of the region.

Wave direction exhibits a marked seasonal shift (Figs. 3b and 7). From December to March, waves predominantly originate from the NW to north, reflecting the influence of the monsoon season. In contrast, from May to October, the prevailing wave direction shifts to the east, indicative of a different atmospheric circulation regime dominating during this period.

During the rainy season (December-April), the dominant waves come from the NW-N direction (Figs. 3b and 7). This aligns with the north-western monsoon wind pattern, which brings wind and waves from that direction. The wave direction shifts to the SE, in line with the easterly monsoon wind pattern that dominates the dry season (May-November), particularly in April and November. The wave pattern in the Karawang waters shows a strong influence from the annual monsoon pattern.

The seasonal variation of wave direction in the Karawang coastal region is primarily governed by changes in monsoonal wind patterns rather than precipitation or evaporation processes.

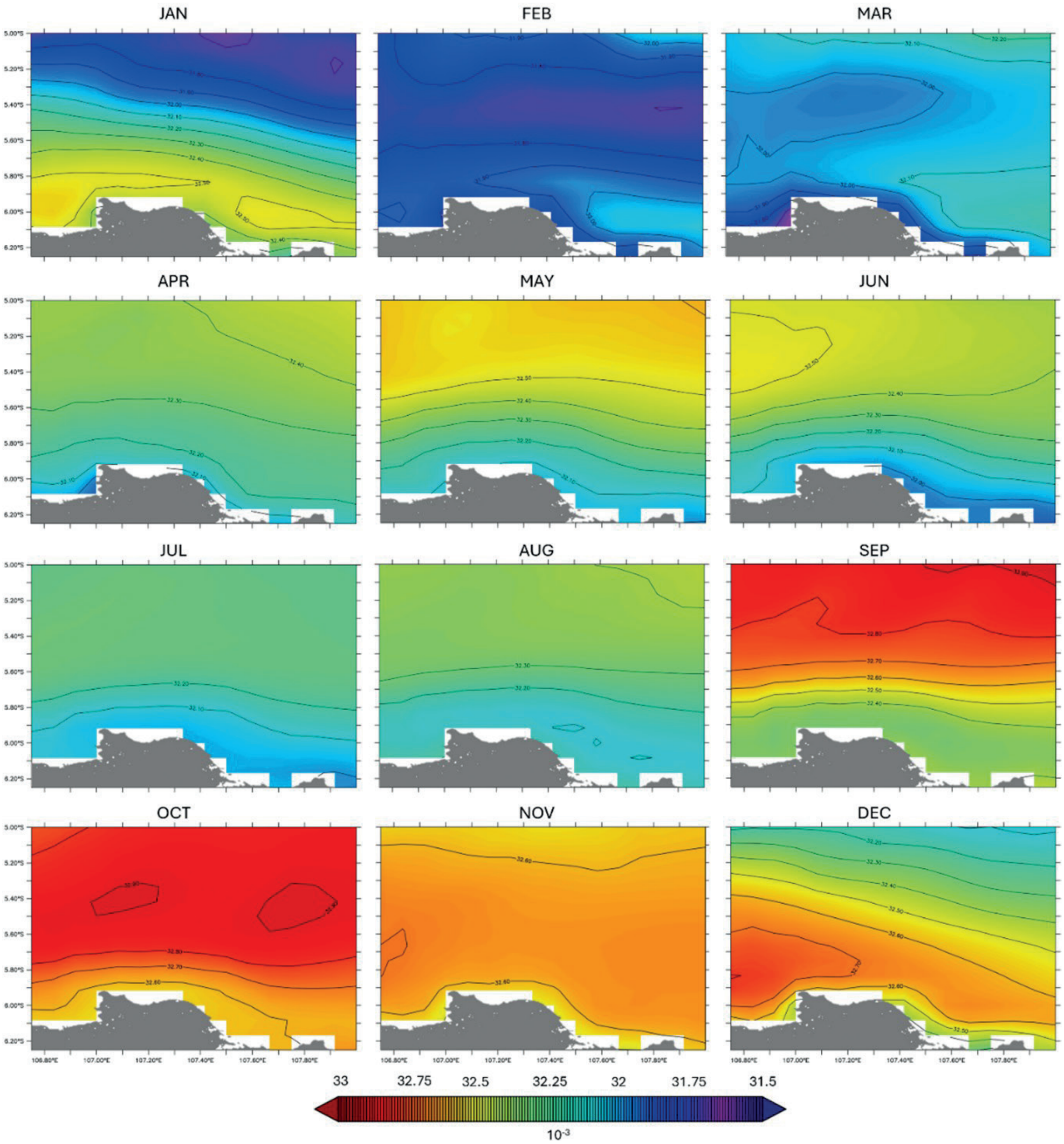

Fig. 6 - Spatial distribution of monthly average salinity over the past 30 years.

During the north-western monsoon season, from December to March, prevailing winds originate from the NW, resulting in wave directions predominantly from the NW to north. Conversely, during the south-eastern monsoon season, from May to October, the dominant winds shift to the SE, generating waves that predominantly approach from the SE to east. Transitional periods, such as April and November, are characterised by more variable wave directions due to the shifting wind regimes. These seasonal wave patterns align with the broader regional monsoonal cycle observed across the Indonesian seas and play a critical role in shaping coastal dynamics, including sediment transport and shoreline morphology changes.

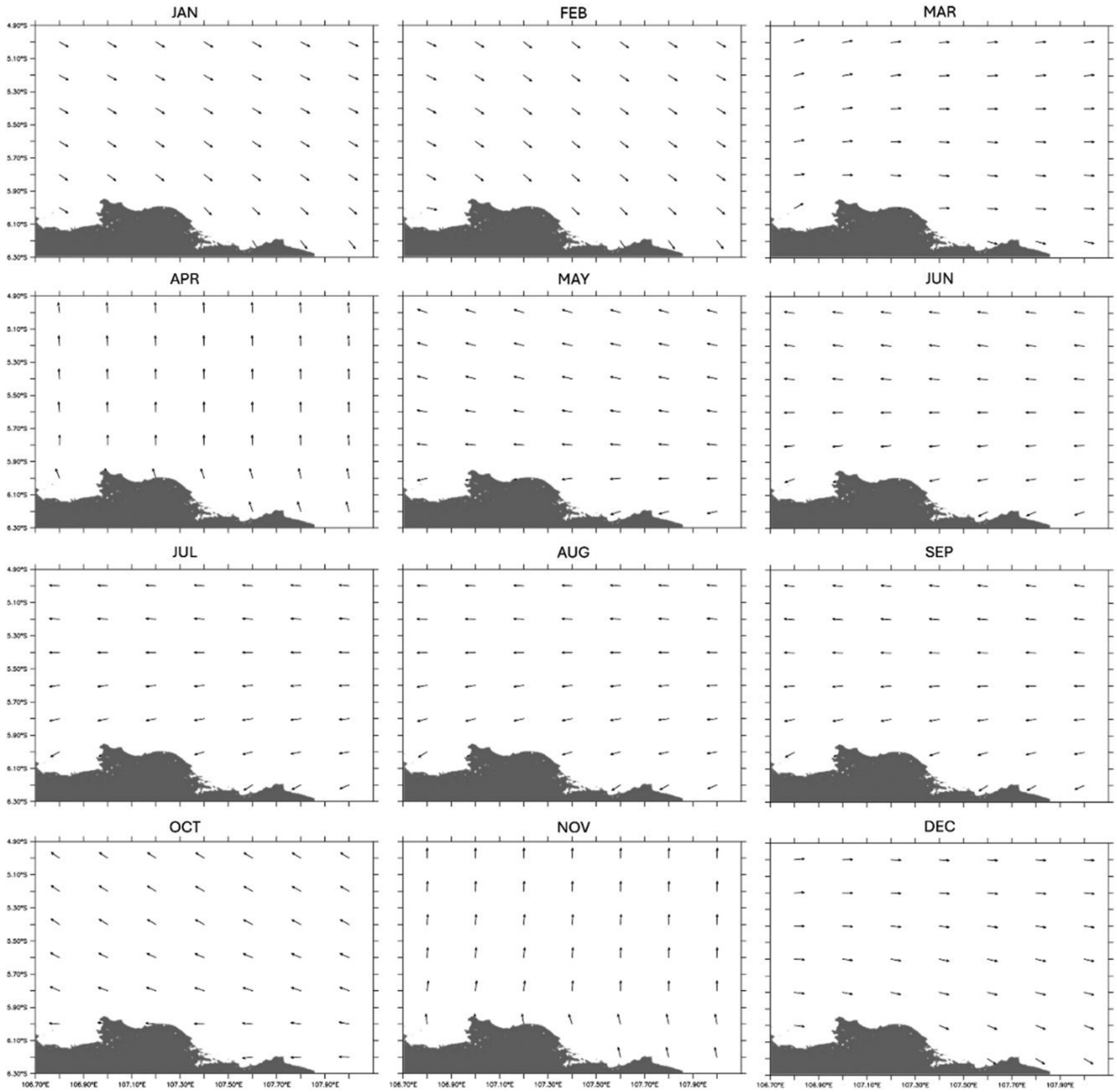

Fig. 7 - Spatial distribution of monthly average wave direction over the past 30 years.

3.2.1. Trends and extreme events

The *SST*, *SSH*, and salinity trends are divided into three different time periods (Fig. 8): 30 years (red line), 15 years (cyan line), and 5 years (green line). A total of 370 data points were used to represent 370 months from January 1994 to October 2024. The *x*-axis represents the data points, with the leftmost value (1) representing January 1994, and the rightmost value (370) representing October 2024. The *y*-axis shows the measured values of the variables, namely *SST*, *SSH*, or salinity.

During the 30-year period, the trends show an increase in *SST* and *SSH*, while salinity decreases. This pattern can be attributed to several factors including climate change effects that lead to increased ocean temperatures and altered hydrological cycles. Studies have shown that local variability in the Indonesian seas significantly influences these dynamics, particularly through

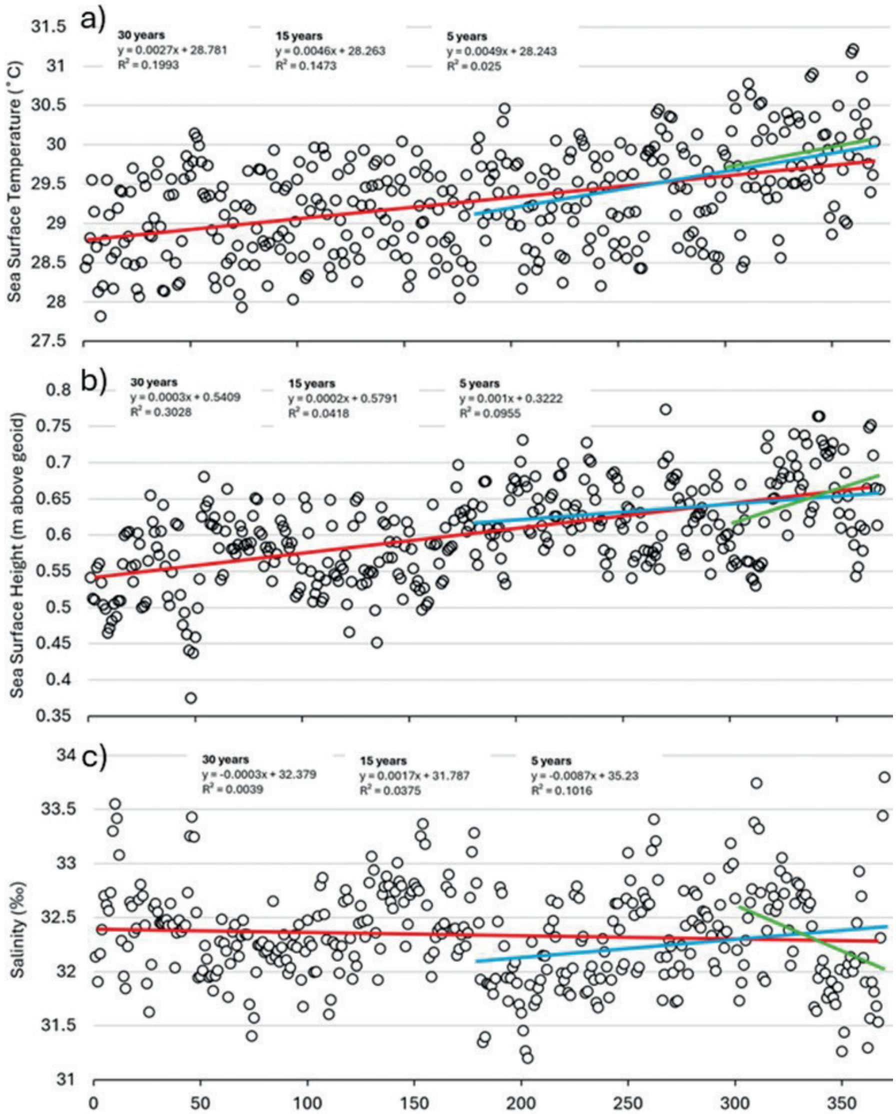

Fig. 8 - Trends over 30, 15, and 5 years for a) *SST*, b) *SSH*, and c) salinity.

the flow of warm tropical waters between the Pacific and Indian oceans, which affects both *SST* and *SSH* patterns (Gordon, 2005). In the 15-year period, all three variables, *SST*, *SSH*, and salinity, show an increasing trend. This could indicate a phase of intensified oceanic processes influenced by climate variability such as ENSO events that typically result in warmer *SST*s and altered salinity patterns due to shifts in precipitation and evaporation dynamics. The Indonesian seas are particularly sensitive to these variations due to their unique geographical configuration and oceanographic characteristics (Lubis *et al.*, 2024). Meanwhile, in the 5-year period, *SST* and *SSH* continue to show an upward trend, but salinity again shows a decreasing trend. This analysis provides valuable temporal insights into the changing sea conditions in the study area.

The extreme climate analysis in this study focuses on the tidal flooding phenomenon, which is closely related to extreme events affecting *SSH* In this analysis, the *SSH* is examined in relation to the ENSO and IOD indices. The results of the analysis show that during the strong El Niño and strong IOD+ event in 1998, the sea level decreased. A similar pattern occurred in 2015, when a strong El Niño and weak IOD- led to a decrease in the *SSH*. In contrast, during the La Niña and IOD- event in 1999, the *SSH* tended to increase. This increase in *SSH* was also observed in 2022 when La Niña coincided with IOD+ (Fig. 9).

Prior to the analysis, the NINO3.4, IOD, and *SSH* indices were normalised using the min-max normalisation method to transform the data range to 0-1 (Fig. 9). This step was taken to ensure that each variable could be consistently compared, despite having different initial scales. Statistical analysis revealed a negative relationship between the NINO3.4 index (ENSO indicator) and *SSH*, with a correlation coefficient of -0.4159, indicating that the *SSH* tends to decrease during El Niño periods. Conversely, the relationship between the IOD index and *SSH* had a much weaker correlation coefficient of -0.0382, suggesting that the influence of the IOD on the *SSH* in this region is relatively small.

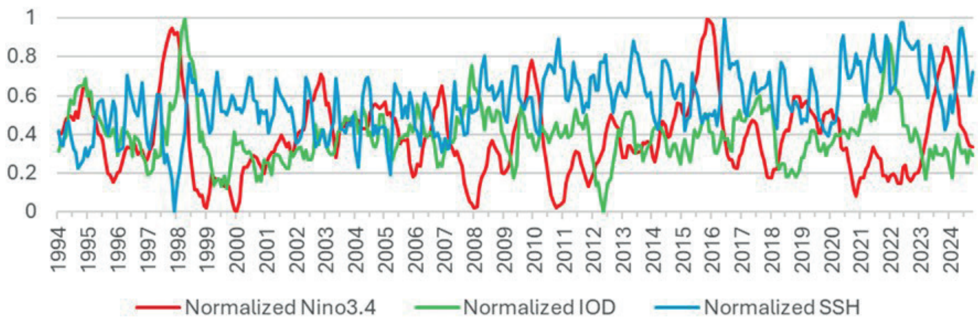

Fig. 9 - Time series of normalised Nino3.4 index, IOD, and *SSH*.

The *SSH* variability in the Karawang region, as shown in Figs. 8 and 9, closely reflects the influence of large-scale climate phenomena such as the ENSO and IOD. During strong El Niño events, the *SSH* tends to decrease, while La Niña periods are associated with elevated *SSH* levels. This relationship is consistent with previous studies that highlighted the modulation of Indonesian coastal sea levels by ENSO phases and the Indonesian Throughflow (Iskandar *et al.*, 2020; Lubis *et al.*, 2025). Specifically, La Niña conditions enhance the Throughflow, leading to higher *SSHs* along the southern Indonesian coast, including Karawang. In contrast, Du *et al.* (2008) reported that during El Niño events, reduced precipitation and altered wind patterns contribute to lower *SSHs* off Java and Sumatra. These findings underscore the critical role of regional ocean-atmosphere interactions in shaping interannual *SSH* variability, with direct implications for coastal flooding risks in the Karawang region.

3.2.2. Sea level projection

In general, there are three types of sea level projections presented in this study: projections from SSP2-4.5 CMIP6, projections from the Indonesian Geospatial Reference System – BIG (SRGI – BIG), and projections derived from trends.

<u>CMIP6</u>. The sea level projection based on the SSP2-4.5 scenario in the CMIP6 model is presented in this study. The SSP2-4.5 scenario represents a moderate emission scenario, where mitigation policies are applied in a moderate manner. This increase is expected to continue if global

emissions are not fully curtailed. The model shown in this report illustrates a gradual increase from 2020 to 2060. The specific projected sea level change values for the years 2030, 2040, 2050, and 2060 are 0.08, 0.13, 0.19, and 0.25 m, respectively. The pink-coloured area represents the uncertainty range in this projection, which widens over time, reflecting increasing uncertainty in long-term projections (Fig. 10).

The projected sea level rise of approximately 0.25 m by 2060 under the SSP2-4.5 scenario is consistent with observed trends and regional projections for SE Asian coastal zones. For instance, Jaroenongard *et al.* (2021) projected a relative sea level rise in the Upper Gulf of Thailand using outputs from 35 climate models under RCP4.5 and RCP8.5 scenarios, revealing rates of 0.94–1.05 mm/year and 1.07–1.18 mm/year, respectively. Similarly, an analysis of sea level trends in the Gulf of Thailand from 1977 to 2019 by Taninpong *et al.* (2021), utilising data from 18 tide gauge stations, reported a spatially variable rate of increase ranging from 3.44 to 19.19 mm per year, with the most pronounced increases observed along the eastern coastline. These findings highlight the critical need for localised assessments that incorporate region-specific factors to accurately understand and prepare for the multifaceted impacts of future sea level rise in vulnerable coastal regions, including those in Indonesia.

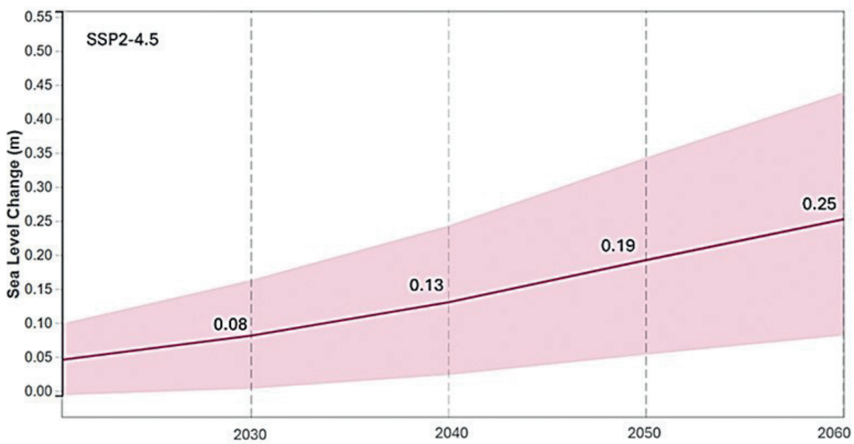

Fig. 10 - Projected sea level changes based on CMIP6 SSP2-4.5.

Indonesian Geospatial Reference System, Geospatial Information Agency (SRGI – BIG). Based on information from the Indonesian Geospatial Reference System (SRGI) released by BIG, sea level modelling uses a combination of data from 138 tidal stations up to 2018 and satellite data from Topex, Jason-1, Jason-2, and Jason-3 from the period of 25 September 1992 to 25 August 2019. The displayed graph highlights two key aspects: monthly mean sea level (MSL) and monthly highest high water level (HHWL). The monthly MSL graph (Fig. 11a) shows small fluctuations, with changes ranging from -0.003 to +0.003 m. The projected rise in MSL between 2030 and 2059 is very small, at 0.0000303 m and 0.0000886 m, respectively (Fig. 11a). In 2030, the maximum projected HHWL reaches approximately 0.60 m, while the minimum monthly HHWL is around 0.40 m. By 2059, the maximum HHWL remains close to 0.62 m, whereas the minimum monthly HHWL slightly decreases to approximately 0.41 m (Fig. 11b). It should be noted that Fig. 11a presents MSL variations relative to a tidal datum, encompassing both positive and negative deviations, while Fig. 11b solely illustrates the peak tidal heights above the reference level. This

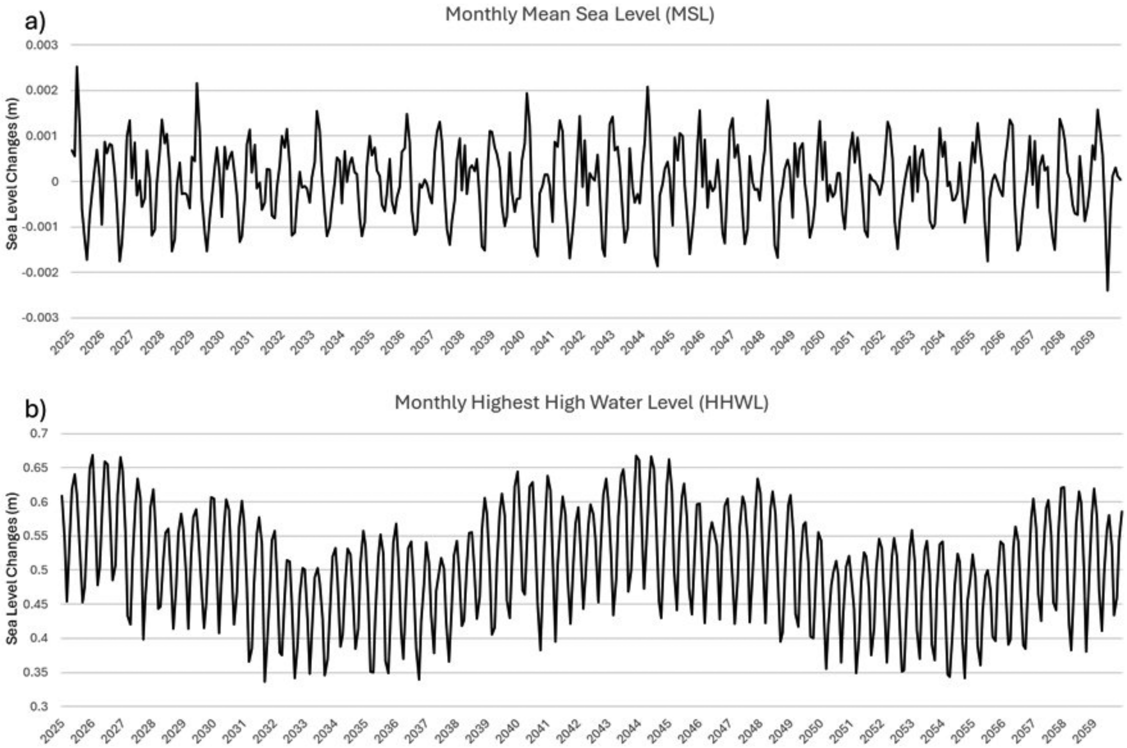

Fig. 11 - Projected sea level change based on SRGI-BIG.

focus on positive values in Fig. 11b underscores the critical role of extreme high tides in assessing coastal flooding risks and evaluating climate-induced impacts on vulnerable coastal communities.

Historical trend. The sea level projection based on data from January 1994 to October 2024, with projections extending until December 2059 (Fig. 12), is presented in this study. The projection uses the Forecast.ETS method, considering a seasonal component of 60 months. The analysis results show an increasing trend in data over time. Based on the linear regression projection, the maximum value is projected to be 0.7782 m in December 2059. Meanwhile, the projection using the Forecast.ETS method indicates the highest value of 0.895 m in May 2059.

3.2.3. Key findings and their implications

This study provides valuable insights into the impacts of climate change on the oceanographic conditions in the Karawang region. By analysing high-resolution oceanographic datasets spanning 30 years (1994–2024), key trends and patterns were identified in variables such as *SST*, salinity, *SSH*, and wave direction. *SST* and *SSH* exhibit significant increasing trends, highlighting the ongoing influence of global warming, while salinity shows a declining trend, potentially linked to shifts in precipitation and freshwater inputs. Research indicates that wind patterns and significant wave heights also play a role in these fluctuations within Indonesian waters (Bahtara and Zikra, 2019). Seasonal cycles, driven by monsoonal weather patterns, further underscore the dynamic nature of local climate systems. Additionally, these changing oceanographic conditions are contributing to increased coastal erosion in the Karawang region, which is exacerbated by rising sea levels and human activities along the shoreline (Pasaribu *et al.*, 2020; Nopiana *et al.*, 2024).

Future projections suggest that sea levels in the region could rise by up to 0.895 m by 2059, posing significant risks to coastal communities and infrastructures. These findings emphasise the urgency for region-specific adaptation strategies that align with national and global climate action plans. Moreover, the study underscores the importance of leveraging local data to inform policymaking and enhance the resilience of coastal areas to climate change. The results also provide a robust foundation for ongoing research and monitoring efforts, which are essential for anticipating and mitigating the long-term effects of climate variability in the region.

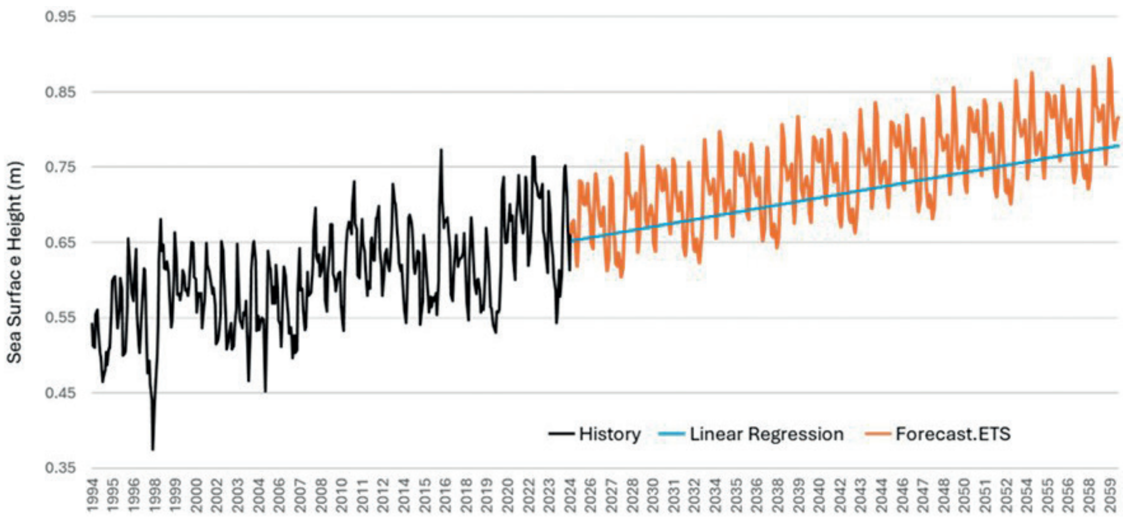

Fig. 12 - Projected *SSH* change based on historical trends using linear regression and the Forecast.ETS method.

4. Conclusions

This study highlights the significant impact of climate change on oceanographic conditions in the Karawang region, Indonesia, underscoring the urgent need for targeted mitigation and adaptation strategies. By analysing high-resolution datasets spanning from 1994 to 2024, key oceanographic variables, including *SST*, *SSH*, salinity, total precipitation, and wave direction, were examined. The results revealed clear trends of increasing *SST* and *SSH*, alongside declining salinity, reflecting the ongoing effects of global warming, altered precipitation patterns, and increased freshwater influx. These findings point to the heightened vulnerability of Karawang's coastal ecosystems and communities.

Seasonal variations, shaped by monsoonal weather patterns, further demonstrate the complexity and dynamism of local climate systems. Future projections indicate a potential sea level rise of up to 0.895 m by 2059, posing substantial risks to coastal infrastructure and livelihoods. These trends emphasise the critical need for long-term climate resilience planning and the development of region-specific adaptation strategies.

The results of this study underscore the necessity of developing comprehensive climate action frameworks that systematically integrate localised oceanographic data into broader national and global strategies, ensuring that policy responses are tailored to the specific vulnerabilities of coastal regions. Furthermore, it calls for the establishment and enhancement of robust research and monitoring programs dedicated to the continuous assessment of oceanographic and climatic variables. These efforts will be critical for improving the anticipation of future climate impacts, informing adaptive management approaches, and safeguarding the resilience of Karawang and other similarly threatened coastal areas.

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