Variability in sea surface temperature and sea surface height in connection with global warming in the Java Sea

[1,3]Mega L. Syamsuddin, [2]Hafidz D. Haq, [1,3]M. Rudyansyah Ismail, [1,3]Fadli Syamsudin, [1,3]Sunarto, [1,3]Umar Abdurrahman

[1] Department of Marine, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, 45363, Jatinangor, West Java, Indonesia; [2] Marine Sciences Study Program, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, 45363, Jatinangor, West Java, Indonesia; [3] Center for Climate and Maritime Area Management, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, 45363, Jatinangor, West Java Indonesia. Corresponding author: M. L. Syamsuddin, mega.syamsuddin@unpad.ac.id

Abstract. The variability of sea surface temperature (SST) and sea surface height (SSH) in the Java Sea is closely linked to ocean warming. Climate change, driven by global warming, has led to an annual rise in SST and SSH. According to the Intergovernmental Panel on Climate Change (IPCC), the past decade saw a global surface temperature increase of 1.09°C, contributing to a warmer Earth. The Java Sea, situated between the Pacific and Indian oceans, is particularly affected by these global climatic changes. This study investigates the effects of global warming on SST and SSH variability in the Java Sea, using satellite data collected over an eleven-year period (2011-2021) and employing descriptive analytical methods. A continuous wavelet transformation (CWT) analysis tool was used to reveal the detailed structure of SST and SSH variability across time and frequency domains. Over the past eleven-year period, climate change has led to a global temperature rise, with the Java Sea experiencing a monthly mean SST increase of 0.31°C, from 28.82°C in 2011 to 29.13°C in 2021. Concurrently, the monthly mean SSH rose by 0.05 m, from 1.08 m to 1.13 m. These changes align with the global temperature trends and are further influenced by interannual pattern of the El Niño Southern Oscillation (ENSO) events and the seasonal system in the Java Sea.
Key Words: global warming, interannual, seasonal, temperature trends, wavelet.

Introduction. Shortwave radiation emitted by sunlight is the primary energy source for all life on Earth. Some of this radiation is reflected back into space, while the rest is absorbed by the atmosphere. The Earth's average surface temperature rises due to the atmosphere's retention of heat waves, leading to global warming (Latuconsina 2010). The Intergovernmental Panel on Climate Change (IPCC) compared in AR5 and AR6 the temperature change from 1850-1900 to 1986-2005, recorded at 0.08 [–0.01 to 0.12] °C. From 1850-1900 to 1995-2014, the global surface temperature increased by 0.85 [0.69 to 0.95] °C, and by the last decade (2011-2020) by 1.09 [0.95 to 1.20] °C. Each of the last four decades was successively warmer than any preceding decade since 1850. The IPCC notes that there has been a global surface temperature increase of 1.09°C over the past decade (2011-2020), resulting in a rise in the Earth's temperature. This has impacted the periodic trends in sea surface temperature (SST) and sea surface height (SSH) changes (IPCC 2021). Global warming is caused by anthropogenic factors, namely the use of fuel, coal, petroleum, and natural gas (Hook & Tang 2013; Ali et al 2022). Other studies by Zherebtsov et al (2017) and Anoruo & Okeke (2020) showed that temperature changes are also affected by solar variability and geomagnetic activity. Solar variability influences Earth's temperature via orbital alterations and variations in radiant energy emissions, hence contributing to both global and regional climate change as a result of fluctuations in solar activity (Anoruo & Okeke 2020).

According to Suryati et al (2018), CO_2 is a waste product from the use of motor vehicles. The heat from the sun trapped by the Earth causes the greenhouse effect. The Earth experiences a temperature increase due to the significant rise in greenhouse gas emissions (carbon dioxide/CO_2), methane (CH_4), nitrogen oxides (NOx), chlorofluorocarbons (CFCs), and other gases) (Latuconsina 2010). SST originates from the exchange of energy during the interaction between the ocean and the atmosphere, the impacts of which can then be analyzed from changes in SST trends (Deser et al 2010). Changes in the Intertropical Convergence Zone (ITCZ) and rainfall intensity are also influenced by fluctuations in SST (Wang et al 2023). Additionally, due to the expansion of seawater volume, the mass of seawater increases and affects SSH rise due to the increase in SST (Sofian & Nahib 2010). According to Kismawardhani et al (2018), compared to the global average temperature, the rise in SSH in the Indonesian region is twice as large. Nababan et al (2015) also stated that in 2012 there was an increase ranging from 2.5 to 6 mm. SSH increases significantly, leading to sea surface height rise due to expanding seawater volume and increased seawater mass as a direct result of thermal processes and glacier melting. These two occurrences, in addition to shifts in the mechanics of ocean circulation, caused the total increase in SSH on Earth by approximately ±63 m as per Sofian & Nahib (2010).

Global warming and the depletion of the ozone layer are the results of increased greenhouse gas emissions in the atmosphere caused by deforestation, fossil fuel use, and other human activities. Some negative impacts on the sustainability of coastal and ocean ecosystems include (1) coral bleaching (Westmacott 2000), which reduces coral fishery production, (2) the rise in ultraviolet-B radiation in marine waters is causing a decline in photosynthesis and the growth of phytoplankton, the primary producers and largest CO2 absorbers (Latuconsina 2010), (3) degradation of coastal environments that potentially threaten human life in coastal and ocean ecosystems, (4) the extinction and habitat shift of marine biota (Ranintyari et al 2018). Therefore, this phenomenon increasingly threatens the balance of ecosystems, including marine ecosystems (Latuconsina 2010).

The Java Sea, situated near the equator, is a region in Indonesia that significantly influences many terrestrial areas. Therefore, research is needed to examine the influence of global warming on the variability of SST conditions and the increase in SSH in the Java Sea to recommend disaster mitigation and adaptation steps to reduce the impacts that will occur due to global warming. This research focuses on examining the effects of global warming on SST and SSH variability in the Java Sea, utilizing satellite data spanning eleven years (2011–2021).

Material and Method

Description of the study sites. The research was conducted from February 2022 to May 2022 in the Java Sea, designated as part of Fisheries Management Area (FMA) 712. The area is defined by the coordinates 2°48’49” - 7°56’80” S and 105°48’18” - 116°16’19” E (Figure 1). The Java Sea lies between Borneo to the north and Java to the south.

Oceanography datasets. This research consisted of three stages: the data collection stage, the data processing stage, and the analysis stage. The data collection stage involved the process of downloading SST image data from the Aqua-MODIS Satellite through the website https://oceancolor.gsfc.nasa.gov/l3/ and SSH image data from CMEMS (Copernicus Marine Environmental Monitoring Service) through the website http://marine.copernicus.eu/. The downloaded image data was then cropped according to the research location coordinates. The downloaded SST and SSH data were Level 3 images with a spatial resolution of 4 km and monthly temporal resolution in netCDF format (.nc).

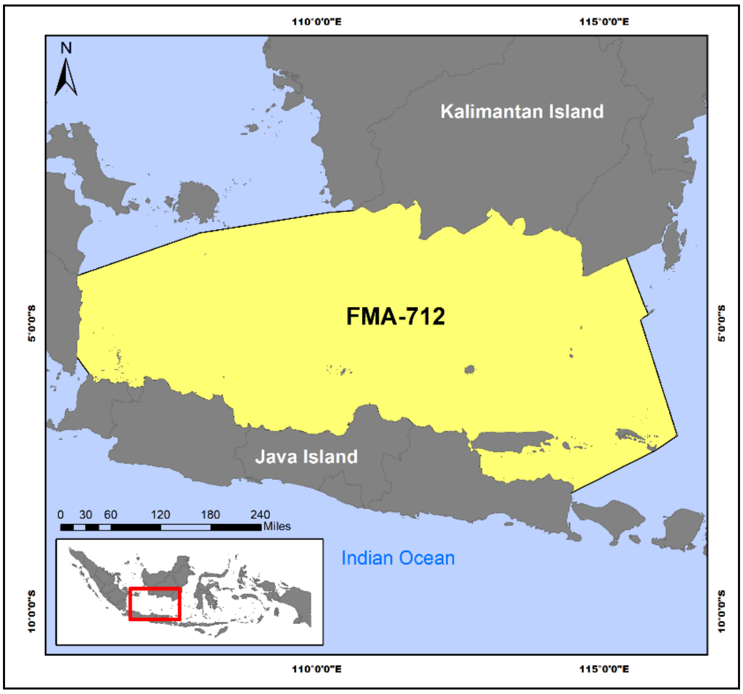

Figure 1. Map of the study area in the Java Sea, including fisheries management area 712.

Processing data. The downloaded SST and SSH image data were then processed to produce monthly and annual spatial visualizations. For temporal analysis, the monthly SST and SSH values were averaged and then displayed in the form of a time series graph (temporal distribution). The impact of global warming was analysed by observing the changes in SST and SSH conditions. In this study, the SST and SSH values were used for further descriptive analysis, which included temporal and spatial analysis. Temporal analysis was conducted to determine the changes in SST and SSH based on the time series from January 2011 to December 2021. Meanwhile, to determine the distribution of SST and SSH in the study area, spatial analysis was conducted by identifying colour degradation on the average monthly distribution map.

Wavelet spectrum analysis. Wavelet transform analysis was used to obtain a more detailed structure of variability in the time and frequency domains. Wavelet transform was also used to detect the temporal structure of multiscale variations, becoming a series of certain limited and nonstationary time data (Lau & Weng 1995). Wavelet analysis was used to analyze the dominant signal time frequency, decompose the signal into various time scales, and identify how this signal varies over time. The temporal variability of certain frequencies was the most important aspect of wavelet analysis (Silva et al 2019). In this study, the continuous wavelet transform (CWT) was applied to monthly SST and SSH data over an 11-year period (2011-2021).

Results. The following results present the temporal and spatial variations of SST in the Java Sea. In general, the average SST in the Java Sea had a relatively consistent pattern of change each year. From 2011 to 2021, the average SST experienced an increase from March to May and a decrease from August to September, followed by another increase from October to November (Figure 2). These changes are attributed to the monsoon system affecting the Java Sea. The average monthly fluctuations in SST values in the Java Sea ranged from 27.40 to 30.42°C.

Based on the monthly mean values from 2011 to 2021 in the Java Sea, generally, the highest average SST values occurred in April-May (transition season I) with SST values ranging from 29.41 to 30.42°C. This is consistent with the study conducted by Dewi et al (2020) and Simanjorang et al (2018), which mentioned that SST values in the Java Sea increased during transition season I. Meanwhile, the lowest average SST values occurred in August-September (southeast season) with SST values ranging from 27.40 to

29.31°C. Generally, the SST pattern in the northwest season (December-February) experienced the highest increase in January and a decrease in February. The geographical location of southern Java significantly affects its SST, resulting in higher SST during the northwest monsoon compared to the southeast monsoon (Ahmad et al 2019).

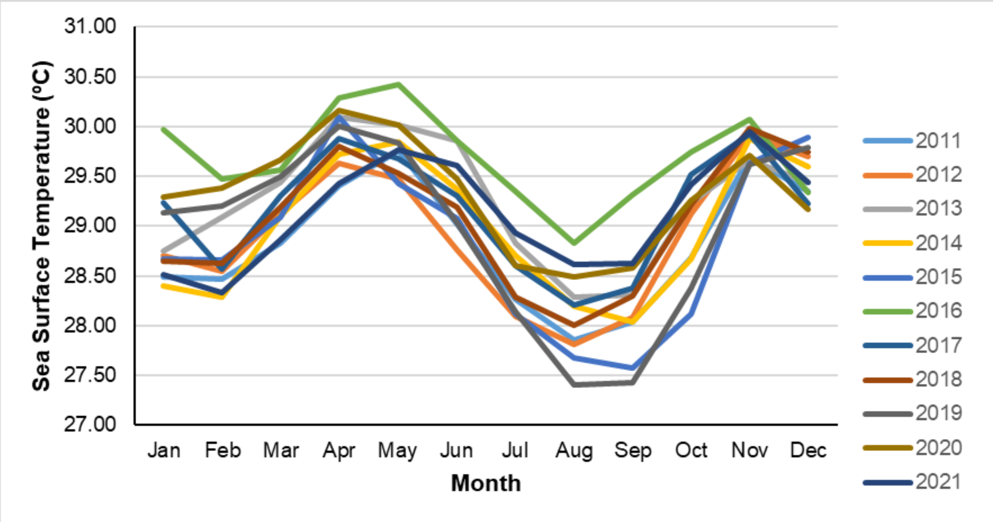

Figure 2. Monthly mean SST from 2011-2021 in the Java Sea.

According to Harahap et al (2020) and Syamsuddin et al (2023), the temporal SST pattern in the Java Sea exhibits a pronounced seasonal variation. The variation in SST values occurs due to the influence of lower water mass from the South China Sea in the northwest season and the influence of colder water mass from the Makassar Strait in the southeast season (Siregar et al 2017). In the first transition season (March-May), there is the highest increase in April and the lowest decrease in the southeast season (June-August). Subsequently, SST rose during the second transition season (September to November), influenced by monsoon winds carrying water masses from the east, which led to a monthly temperature increase (Simanjuntak & Lin 2022). Wirasatriya et al (2019) stated that the seasonal variability of SST in the Java Sea is influenced by wind speed. The monsoon winds blowing over the Java Sea cause vertical mixing of water masses and evaporation, which can change the SST to be cooler or warmer (Clark et al 2000). To better understand the spatial variability of SST conditions annually, the following result will discuss the spatial distribution of SST in the Java Sea over 11 years of observation (Figure 3).

The spatial distribution of the annual average SST in the Java Sea from 2011 to 2021 shows relatively different conditions each year. From 2011 to 2013, the average SST value increased by 0.43°C from 28.82 to 29.25°C. Then, in 2014 and 2015, there was a decrease until the average SST value dropped to 28.84°C. After that, the highest SST increase occurred in 2016, with an increase of 0.84°C, bringing the average SST to 29.68°C. In 2017-2019, the SST decreased from 29.15 to 28.95°C. The following year, the SST increased again to 29.31°C, then decreased by 0.18°C in 2021 to 29.13°C, but remained in the warm category compared to previous years. Overall, there was an SST increase of 0.31°C from 28.82°C in 2011 to 29.13°C in 2021. From year to year during the period 2011-2021, the extent of warm SST distribution became broader, not only around the coast but almost throughout the Java Sea. The decrease in SST in 2015 can be linked to the occurrence of the El Niño phase, while the increase in SST in 2016-2017 and 2020-2021 can be attributed to the La Niña phase, which raised SST in Indonesian seas.

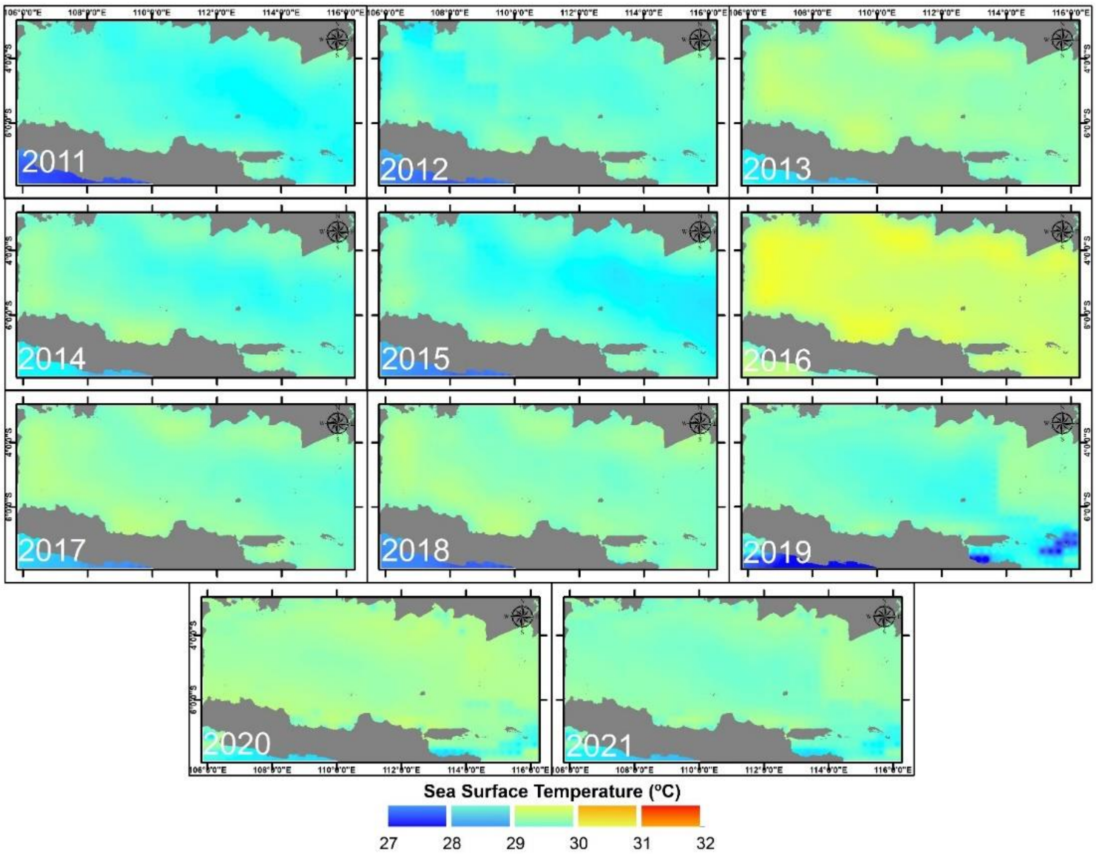

Figure 3. Spatial distribution of annual SST from 2011 to 2021 in the Java Sea.

Temporal and spatial distribution of SSH in the Java Sea. The temporal and spatial distribution of SSH in the Java Sea has been observed from 2011 to 2021. On average, monthly SSH values followed a consistent pattern, peaking in December and January. The monthly SSH fluctuations in the Java Sea varied between 0.91 and 1.21 m, with the highest recorded value in December 2021 and the lowest in September 2015, as illustrated in Figure 4.

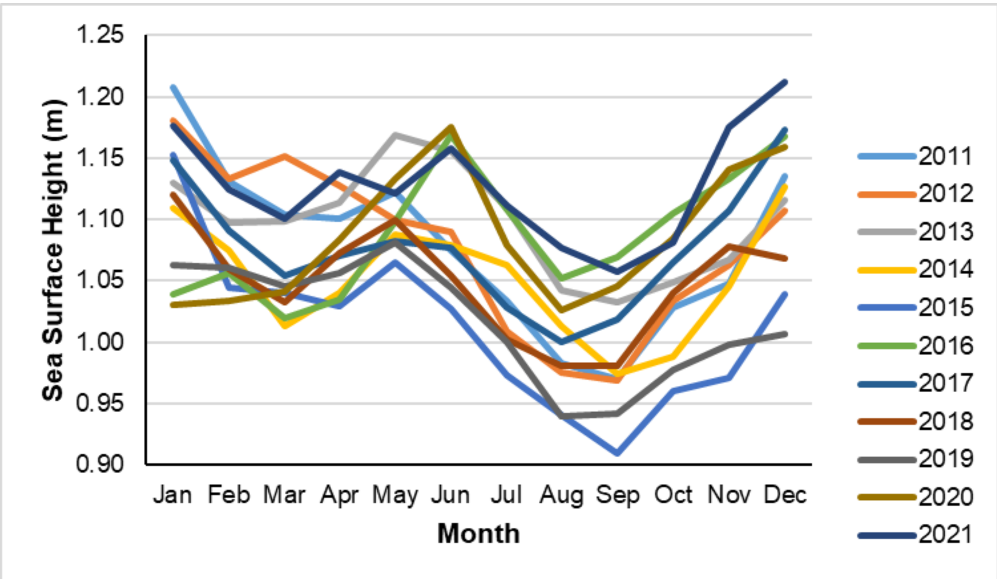

Figure 4. Monthly average of sea surface height from 2011 to 2021 in the Java Sea.

Over an 11-year observation period, the SSH in the Java Sea generally reaches its lowest in August-September (southeast season), with values between 0.91 and 1.06 m, and peaks in December-January (northwest season), with levels from 1.01 to 1.21 m. During the northwest season, winds in the Java Sea shift from west to east, while from June to August, in the southeast season, they reverse from east to west, influencing the inflow and outflow of water masses in the Java Sea. Climate change impacts sea surface dynamics, affecting the volume of water entering and leaving the Java Sea. Rising SSH due to global warming also plays a role in altering rainfall patterns (Dhage & Widlansky 2022).

Figure 5 depicts the variation of spatial distribution of the average annual SSH from 2011 to 2021 in the Java Sea. Looking at the average annual SSH values from 2011 to 2021 in the Java Sea, 2011 and 2012 recorded the same average SSH at 1.08 m. In 2013, there was a rise to an average SSH of 1.10 m. This was followed by a notable decrease over the next two years, with the SSH falling to 1.05 m in 2014 and further to 1.01 m in 2015. The year 2016 saw the most substantial increase of 0.08 m, bringing the SSH to 1.09 m. However, a gradual decline ensued until 2019, with the SSH reaching 1.02 m. A significant rise occurred again in 2020, with the SSH climbing to 1.09 m, and the upward trend continued into 2021, reaching 1.13 m. Global warming, which leads to an increase in ocean heat content, and the resultant thermal expansion of seawater, significantly contribute to the elevation of sea surface levels (Mimura 2013).

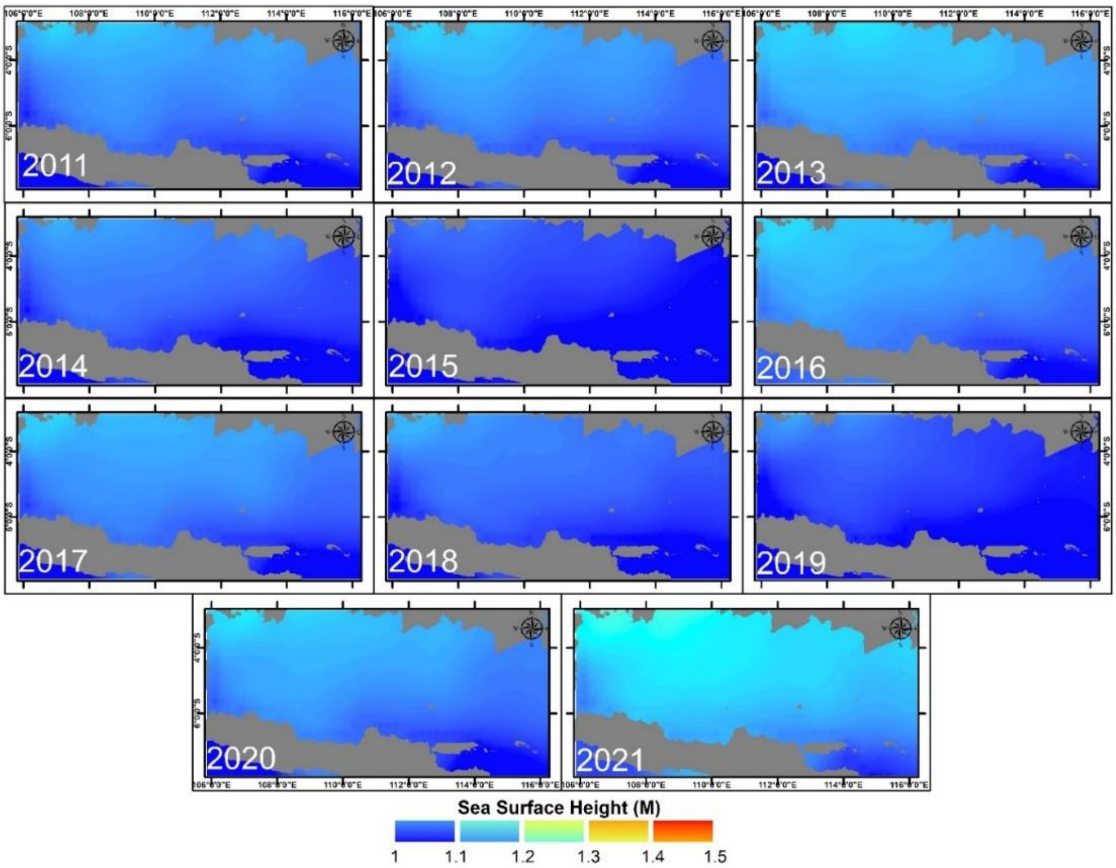

Figure 5. Spatial distribution of average annual sea surface height (SSH) from 2011 to 2021 in the Java Sea.

Based on Hu et al (2017) research indicates that the La Niña phenomenon raises SST in the Pacific Ocean, which in turn causes an elevation in the SSH during 2010/2011. The La Niña phenomenon was recorded four times between 2011 and 2021, specifically in the years 2011, 2016, 2017-2018, and 2021, with SSH ranging from 1 to 1.1.2 m. A correlation exists between the variations in SST and SSH in the Java Sea, a finding supported by Kismawardhani et al (2018), who observed that the rise in SST from 1993 to 2015 corresponded with the increase in SSH.

Variability of SST and SSH in the Java Sea. This research employed wavelet analysis to identify the primary modes of variability in the Java Sea's SST and SSH from 2011 to 2021 and their temporal fluctuations. Wavelets are significant at the 95% confidence level, with a color scale that delineates high and low wavelet amplitudes. Solid contours represent the 95% confidence level with thick black lines, while thin black lines denote the cone of influence (COI) where edge effects are notable in the wavelet spectrum. According to Torrence & Compo (1998), wavelet analysis decomposes the time series into time-frequency space to ascertain the dominant modes of variability and their changes over time. The CWT analysis with monthly SST and SSH time series data spanning 2011-2021 is displayed in Figures 6 and 7.

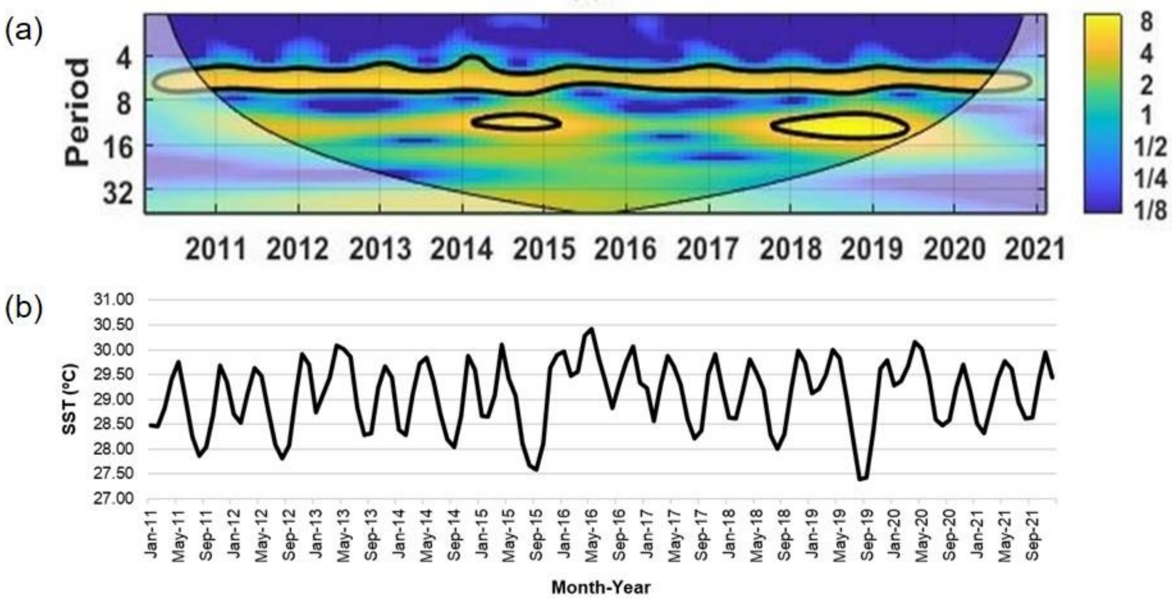

Figure 6. (a) Wavelet spectrum analysis of monthly average SST; (b) Monthly average SST from January 2011-December 2021 in the Java Sea.

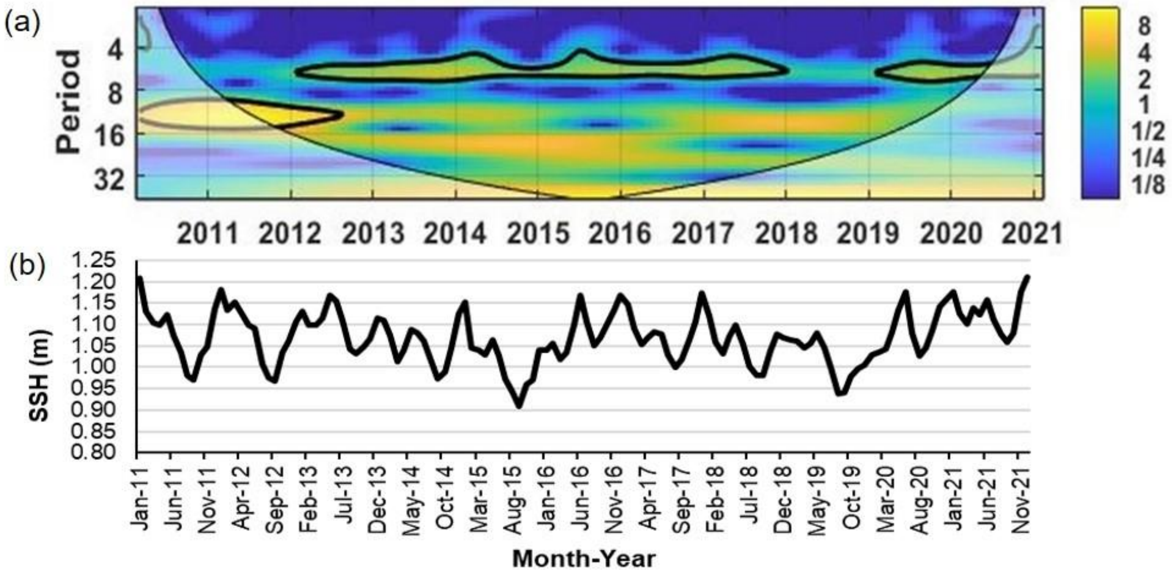

Figure 7. (a) Wavelet spectrum analysis of the monthly average sea surface height (SSH); (b) monthly average SSH from January 2011 to December 2021 in the Java Sea.

The wavelet analysis results reveal dominant periods related to the amplitude and phase of the time series indicated that SST has a strong seasonal pattern (4-8 months period) throughout the observation year and an interannual signal (12-16 months period), particularly notable in 2014-2015 and 2018-2019. In general, the graph supports Xu et al's (2021) finding that SST has two peaks in one year, during the transition season. These findings align with the SST time series graph in Figure 6b, which exhibits a fluctuation pattern in SST values corresponding to seasonal changes. The interannual pattern is evident during specific periods, such as in 2015 and 2019, marked by significant SST decreases associated with El Niño events. The extreme El Niño phenomenon in 2015 and the strong El Niño phase in 2019 had widespread and significant impacts on the rise of SST along the equator (Cai et al 2021). El Niño, a dynamic interaction between the atmosphere and the ocean, not only affects the continental climate but also impacts the SSH fluctuations in Indonesian waters (Lubis et al 2025).

The Niño 3.4 index graph sourced from the NOAA Climate Prediction Center, indicated a strong El Niño phase occurred in July 2015 and decreased to a moderate El Niño phase in April 2016. The Niño Index values ranged from 1.6 to 2.95, indicating a strong El Niño with the peak value recorded in November 2015 (Yananto & Dewi 2016).

According to the IPCC (2021), global warming has led to an upward trend in global temperatures over the past 11 years. The increase amounted to 0.24°C from 2011 to 2021. The period from 2011 to 2016 saw a continuous rise in global temperatures, with the most significant increases recorded in 2016 and 2020, amounting to 1.02°C. However, there was a decrease to 0.85°C in 2017, which lasted until 2018, followed by a rise from 2019 to 2020. In 2021, there was another temperature decrease of 0.85°C. Compared to the changes in SST from 2011 to 2021 in the Java Sea, the average SST increased by 0.31°C. From an average SST of 28.82°C in 2011 to 29.13°C in 2021. The highest increase in global temperature occurred in 2016 (IPCC 2021). Similarly, the SST changes in the Java Sea had the highest average value in 2016, which was 29.68°C.

The rise in global temperatures impacts many things, one of which is the rise in SSH. Because warmer water has a lower density compared to cooler water, areas with higher SSH tend to be warmer than areas with lower SSH. Therefore, changes in SSH can be linked to changes in SST and heat content (Tsai et al 2023). From 2011 to 2021, global SSH continued to rise by 0.048 m. From 2011, the average global SSH increased from 51.5 to 99.7 mm. Two factors that influence it are the additional water from melting ice sheets or glaciers and the expansion of seawater volume when it warms up.

When compared to the changes in SSH from 2011 to 2021 in the Java Sea, the global SSH has increased. Similarly, the average SSH change from 2011 to 2021 in the Java Sea has increased by 0.05 m. From 2011, the average SSH of 1.08 m increased to 1.13 m in 2021. The global SSH change experienced its highest increase in 2021. Likewise, the SSH change in the Java Sea had the highest average value in 2021, which was 1.13 m. The increase in temperature is the cause of the rise in SSH each year. This results in significant thermal expansion of seawater and an increase in seawater volume due to the melting of glaciers in Greenland and Antarctica (Strassburg et al 2015). Presented here is the wavelet spectrum analysis alongside the monthly average SSH for the Java Sea, spanning from 2011 to 2021 (Figure 7).

The wavelet analysis indicates a strong seasonal signal in SSH, especially during 2012-2018 and 2019-2020, with a semi-annual signal detected in 2012. This aligns with the research conducted by Cheng et al (2017), which stated that SSH displayed a 3 and 6-month signal pattern. Figure 7b illustrates a recurring pattern of significant SSH increases and decreases. Between 2014 and 2015, there was a notable drop in SSH from 1.08 m to 1.01 m, followed by a rise to 1.09 m in 2016. It fell again to 1.02 m from 2017 to 2019, with the last surge peaking at 1.13 m in 2021. The SSH fluctuations in the Java Sea from 2011 to 2021 were likely influenced by concurrent air temperature and SST conditions. The long-term effect of increasing air temperatures is a rise in SSH, which is associated with higher SST. These temperature increases can lead to short-term events like changes in rainfall, the Indian Ocean Dipole (IOD), and El Niño and La Niña events, impacting rainfall levels (Akhsan et al 2023). Additionally, global warming, which results in the melting of Arctic ice, contributes to rising SSH in various parts of the world, affecting current sea surface conditions (Unnikrishman & Shankar 2007; Gregory et al 2013).

Conclusions. Sea surface temperature (SST) and sea surface height (SSH) are two oceanographic parameters that serve as indicators for monitoring global warming impacts in the Java Sea. From 2011 to 2021, global warming has led to a 0.24°C increase in SST trends. The average SST during this period rose by 0.31°C. Concurrently, the SSH in the Java Sea increased by 0.05 m. The rise in SST and SSH is influenced not only by global temperature increases and the monsoon system but also by the El Niño phase, which induces fluctuations in the Java Sea's SST and SSH. Wavelet spectrum analysis confirmed that SST and SSH were affected by the monsoon system (seasonal period, 4-8 months) and the El Niño Southern Oscillation, including both El Niño and La Niña phases (interannual period, 8-16 months). This study's findings can inform mitigation and adaptation strategies for global warming by enabling regular monitoring of oceanographic changes through satellite data on SST and SSH.

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Conflict of interest. The authors declare that there is no conflict of interest.

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Authors:
Mega Laksmini Syamsuddin, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Raya Bandung-Sumedang street, km. 21, 45363 Jatinangor, West Java, Indonesia, e-mail: mega.syamsuddin@unpad.ac.id
Hafidz Dienul Haq, Marine Sciences Study Program, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, 45363, Jatinangor, West Java, Indonesia, e-mail: hafidzdienulhaq98@gmail.com
Mochamad Rudyansyah Ismail, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Raya Bandung-Sumedang street, km. 21, 45363 Jatinangor, West Java, Indonesia, e-mail: m.rudyansyah@unpad.ac.id
Fadli Syamsudin, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Raya Bandung-Sumedang street, km. 21, 45363 Jatinangor, West Java, Indonesia, e-mail: fadli.syamsudin@unpad.ac.id
Sunarto, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Raya Bandung-Sumedang street, km. 21, 45363 Jatinangor, West Java, Indonesia, e-mail: sunarto@unpad.ac.id
Umar Abdurrahman, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Raya Bandung-Sumedang street, km. 21, 45363 Jatinangor, West Java, Indonesia, e-mail: u.abdurrahman@unpad.ac.id

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