Annual Sea Surface Height Variability in the Indonesian Seas from Satellites During the 2021-2023

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Abstract: The role of oceanography is very important for archipelagic countries, especially Indonesia. Indonesia's maritime activities, including shipping, fisheries, marine tourism, and coastal and marine environmental protection, greatly benefit from the comprehensive knowledge of ocean currents, water properties, and ocean ecosystems derived from oceanographic studies. Indonesia has quite a large water area and quite a lot of islands. This research aims to provide a better quantitative description of the spatial-temporal variability of sea surface height (SSH) in the Indonesian Sea. Stations in Batam waters, Riau Islands, Indonesia provided the data. The analysis was carried out using SSH satellite data with a spatial resolution of 0.25° × 0.25° at Copernicus Marine Service (CMEMS). We analyzed the variability of SSH values from 2021-2023, focusing on sample points in Batam. The results show a pattern of decreasing and increasing SSH values, with a significant influence on ocean currents and sea waves in the region. The distribution of SSH values varies each month, with some months showing high values. Local geographic factors, such as ocean current patterns and seabed topography, can influence the distribution of SSH values. RMSE analysis shows changes in the distribution pattern of SSH values from year to year. This study highlights the importance of geographic factors in analyzing the distribution of SSH values in certain water areas, as well as showing different trends in SSH values from 2021 to 2023 in Indonesian waters.

Keywords: Oceanography; sea surface height (SSH); Indonesia Sea; RMSE; Batam waters

1. Introduction

Sea surface height (SSH) is one of the important parameters in ocean satellite altimetry, which allows for continuous global viewing of this data. This progress is a very good thing in altimetry technology for the use of SSH data in the world of remote sensing and oceanography[1,2]. The results of these developments can document physical phenomena that connect all different regions globally[3]. We use altimeter data from the Copernicus Marine Service's Global Ocean Physics Analysis and Forecast (CMEMS) for this investigation. Additionally, this package provides a unique surface current dataset known as SMOC (Surface Merged Ocean Current), which takes into account wave and tidal drift. There are few studies of the SSH in the Indonesian seas[4,5] that show that seasonal SSH is mainly in the southeast monsoon and northwest monsoon. One prominent mode of variability in the global ocean is the yearly cycle. Depending on the processes involved, the ocean reacts to these changes on different time and spatial scales. These forcings are linked to a significant annual cycle[6,7].

Mechanisms contributing to the yearly cycle may also initiate fluctuations at other levels (such as modifications in the environment); the Indonesian Sea's sea surface height remains relatively low, prompting regular annual research. We carried out this research with this objective in mind. We conducted this research by examining changes in SSH each year. We will observe these SSH changes in the years 2021–2023. This study generates SSH values in Indonesian waters. This article examines a comprehensive sample from a single location, specifically the waters of Batam, to examine the trends in the SSH values from 2021 to 2023. This cannot necessarily represent the trend in detail for the SSH value, but the resulting variability image will help provide information. In the field of biological science, marine organisms will adapt to annual cycles. Changes in seasonal amplitude and phase can significantly influence the productivity and community structure of marine ecosystems. The value and annual variability of SH still have an impact on this[8,9].

Different contributions can be used to categorize the yearly variability of sea level change[10]. Firstly, the response to changes in air pressure is significant (on the scale of several centimetres at high latitudes) but dynamically uninteresting, as water characteristics and currents rarely alter. Second, the barotropic response to changes in wind stress causes a tiny variation in sea level and a corresponding change in bottom pressure, Pb. Thirdly, the water column's expansion and contraction above the seasonal thermocline cause a steric shift in sea level. Fourth, changes in wind stress caused (a) changes in heat and salinity that meet in the mixed layer and (b) Ekman pumping, which moves the main seasonal thermocline out of the way (baroclinic reaction). Our goal is to provide a better quantitative description of spatial-temporal SSH variability in the Indonesian Seas. This is a prerequisite to being able to clearly identify any long-term trends. Even though our study doesn't directly address these issues, it is still a necessary step. This research also produces SSH values by taking one of the stations, namely in the waters of Batam, Riau Islands, Indonesia.

2. Data and Method

2.1 Preparation Stage

Figure 1 shows that our study site is in the Indonesian Sea, with coordinate limits of longitude 95–141 and latitude -11.6–6 (Indonesia Seas).

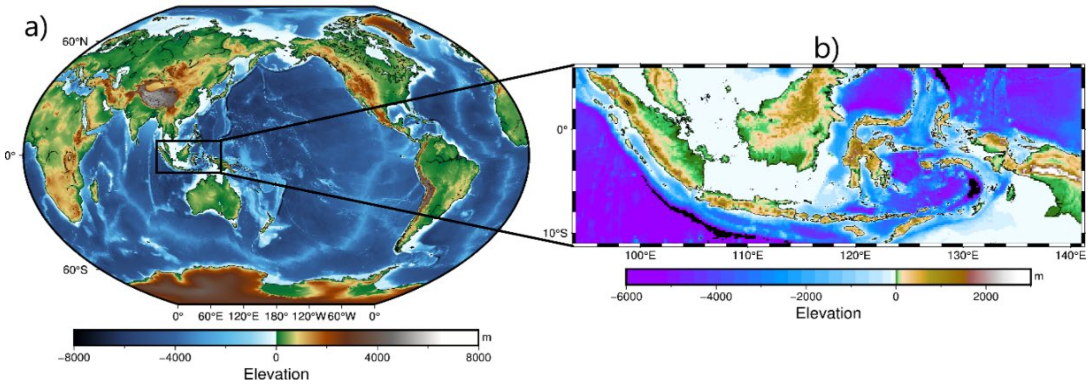


Fig. 1: Location of the Indonesian sea seen from the world map (a); zoom in with the black box study site (Indonesian sea) produced from pygmt.datasets.load_earth_relief with a resolution of 10m.

2.2 Data collection and analysis

The Global Ocean Multimission altimeter satellite-gridded sea surface heights daily maps are the satellite altimetry product that we employ. We produce these maps using E.U. Copernicus Marine Service Information (product identifier: GLOBAL_ANALYSISFORECAST_PHY_001_024; https://data.marine.copernicus.eu/), as illustrated in Fig. 2. We developed the study's outcomes using the filename cmems_mod_glo_phy_anfc_0.083deg_P1M-m. CMEMS supplied the forecast operational system, and Mercator analysis—henceforth referred to as CMEMS analysis (or Mercator analysis)—provided the data for our study. CMEMS database (which includes the SMOC (Surface Merged Ocean Current) satellite altimeter information for surface current, which also includes wave and tidal drift). We used daily gridded SSH satellite-derived data with a 0.25° × 0.25°spatial resolution. We produced the resulting images using Python version 3.11, elaborating on the research location and adjusting needs.

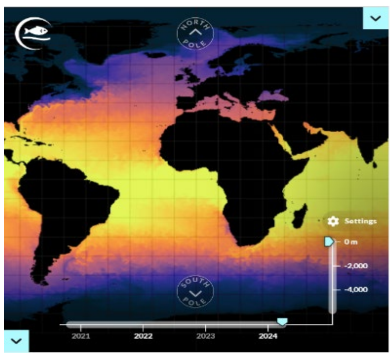


Fig. 2: Display of global data on the CMEMS GLOBAL ANALYSIS FORECAST website PHY_001_024; https://data.marine.copernicus.eu/).

This research looked at the variability of SSH values in 2021–2023. This result will also produce a temporal and scattering distribution pattern. In our research, we conducted a trend analysis using a single sample point. We took this sample point at the Batam location in Riau

Islands, Indonesia, with coordinates namely: longitude (103°–109°) and latitude (-1–2). We analyze these results by examining the root mean square error (RMSE) value using statistics, which reveals the magnitude of the annual variability of SSH in the Indonesian Sea. RMSE can provide valuable insight into the size of the predicted error of the used model when analyzing the annual variability of SSH in the Indonesian Sea. By knowing the RMSE value, researchers can assess how well the model describes the annual variability of SSH in Indonesian waters. Thus, the results of this analysis can provide important information regarding how accurate and reliable the model is in predicting SSH changes in the region.

Additionally, by using RMSE, researchers can compare how big the prediction error of different models is. Thus, RMSE can also help researchers choose the best model that is most suitable for describing the annual variability of SSH in Indonesian waters. Thus, RMSE is a useful tool for evaluating and improving prediction models to understand weather and climate changes in Indonesia. This is as done by[11,12], in research for SSH using satellite data.

3. Results and discussion

3.1 Variability in sea surface height in the Indonesian Seas in 2021.

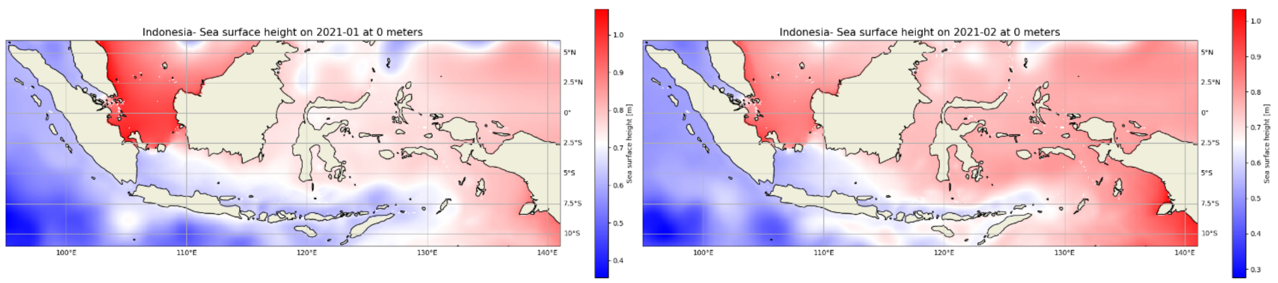
Altimetry satellite data from CMEMS in 2021 provided the sea surface height (SSH) (Fig. 3). These results indicate that the month of January has the highest SSH value. In January, with a value of 1.04 m, the distribution map yielded the lowest SSH value in July, measuring 0.65 m. The results of the distribution of SSH in Indonesian seas in 2021 show significant differences every month. Figure 3a displays the distribution of variability in SSH values in Indonesian seas in January, February, October, November, and December 2021.

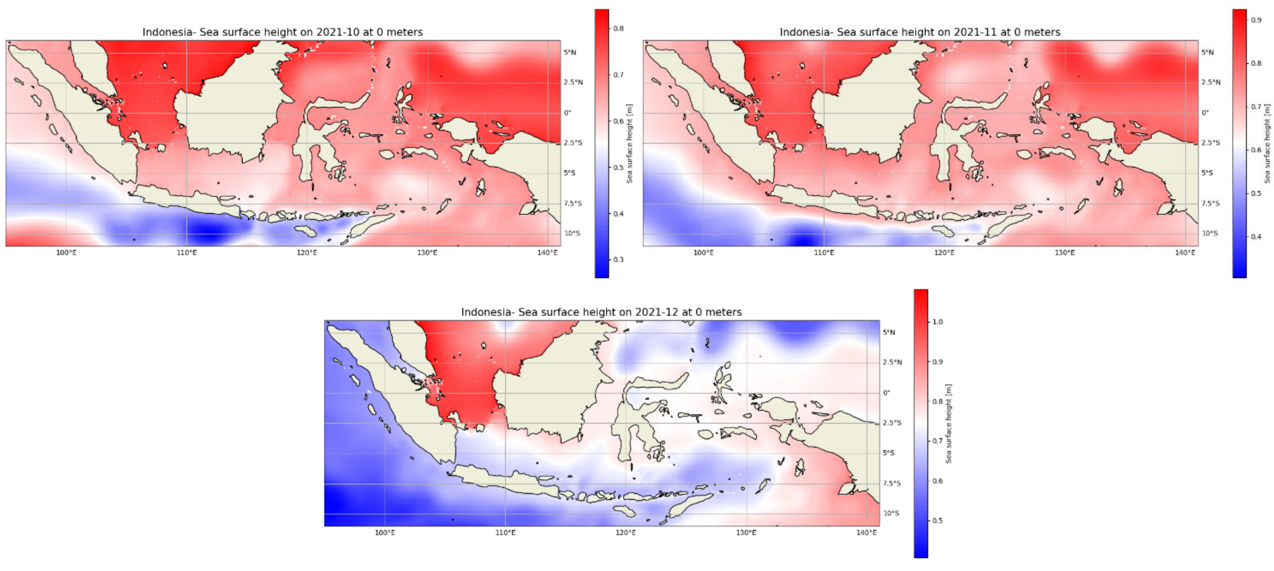
Variability in sea surface height (SSH) in Indonesian waters is important to understand in the context of global climate modification and its impact on coastal resilience[13] significant changes in SSH values can have an impact on environmental conditions, such as sea level rise, which can cause tidal floods in coastal areas. Therefore, continuous monitoring of SSH variability in Indonesian waters is essential to understanding climate change patterns and providing the information needed for mitigation and adaptation to climate change[14].

We can also use data from SSH measurements to understand ocean current patterns and oceanographic dynamics in Indonesian waters. The variability of SSH values recorded every month can provide information regarding changes in ocean current patterns, heat distribution, and water mass transfer in Indonesian waters. This is important for understanding the relationship between global climate change and oceanographic dynamics in Indonesian waters, as well as predicting potential natural disasters that could occur as a result of these changes.

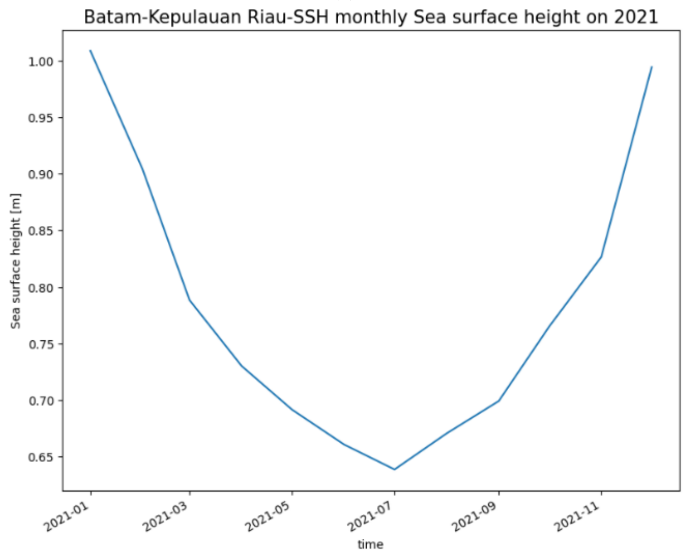
Scientists and researchers can form prediction models to predict climate change and ocean dynamics in Indonesian waters in the future through the analysis of SSH data recorded every month. We hope to carry out mitigation and adaptation efforts to combat climate change more effectively and on target. Thus, SSH data that is continuously monitored and analysed properly can become the basis for making sustainable policies to maintain the sustainability of Indonesia's aquatic ecosystem.

SSH results in 2021 experienced a decrease trend starting from February to July. The one-year graph of the SSH value produced a trend line that decreased from February to July. After the decline in the SSH value ended in July, the SSH value decreased from August to December after the decline ended in July (Fig. 3b). Figure 3c displays the distribution of SSH values for each year. These results indicate that variability with the colour scale results in 5 months scoring high in SSH. These months are January, February, October, November, and December. Meanwhile, SSH variability from March to September is still relatively low (Fig. 3c).





(a)



(b)

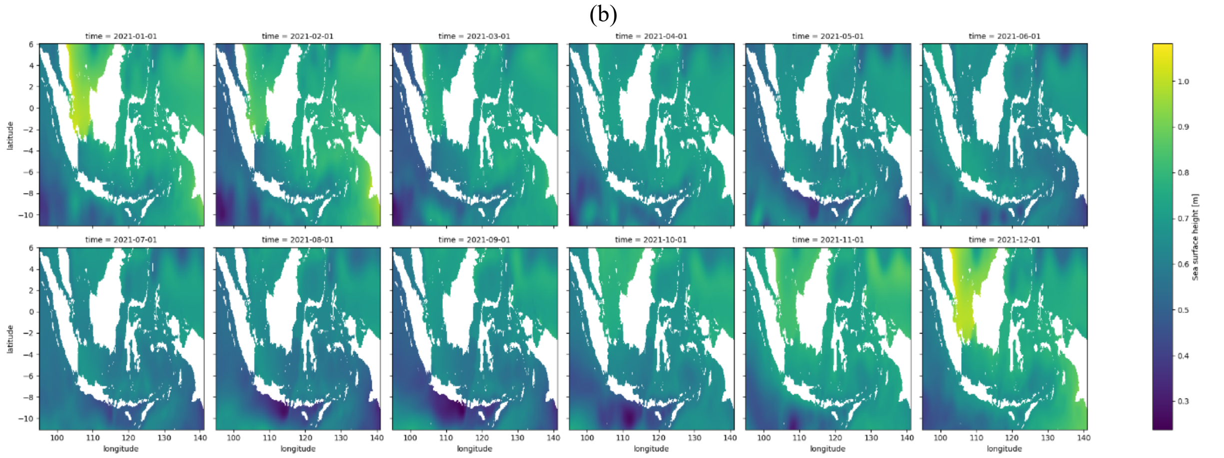


Fig. 3: Spatio-temporal results of sea surface height in the Indonesian Sea in 2021 in January, February, October, November, and December (a), graph of the value or trend line of SSH in Indonesian waters from January to December 2021 (b), and spatio-temporal of SSH values for 1 year in Indonesian seas (c).

We chose Batam waters, in the Riau Islands, as one of the sample points to assess the SSH condition in Indonesian seas because it consistently experiences the highest SSH value from 2021 to 2023. Taking sample points at the Batam location was due to the high value generated from SSH; this was the main parameter for selecting one sample location. This location is close to the Singapore Strait. The results of processing the data obtained show that the highest SSH distribution value in 2021 was in January, with a value of 1.04 m. The lowest value is 0.50 m in March. The decrease in the SSH value increased again from August to December (Fig. 4). The phenomenon of increasing and decreasing SSH values in Batam waters, Riau Islands, has a significant impact on changes in ocean currents and sea waves in the region. The increase in SSH values that occurs from August to December can have an impact on increasing strong sea currents, which can affect the navigation of ships passing around the Singapore Strait. Apart from that, increasing SSH can also potentially increase sea wave levels, which could endanger shipping activities in these waters.

Apart from that, changes in SSH values that occur in Batam waters can also have an impact on the marine ecosystem around the area[15–17]. Changes in ocean currents due to changes in SSH values can affect nutrient transport in these waters, which in turn can have an impact on the survival of marine biota. An increase in SSH values can also cause more pressure on coral reef ecosystems around these waters, which are vulnerable to extreme changes in the marine environment[18]. Therefore, we need to continuously monitor SSH values in Batam waters to understand the impact on human activities and marine ecosystems in the region.

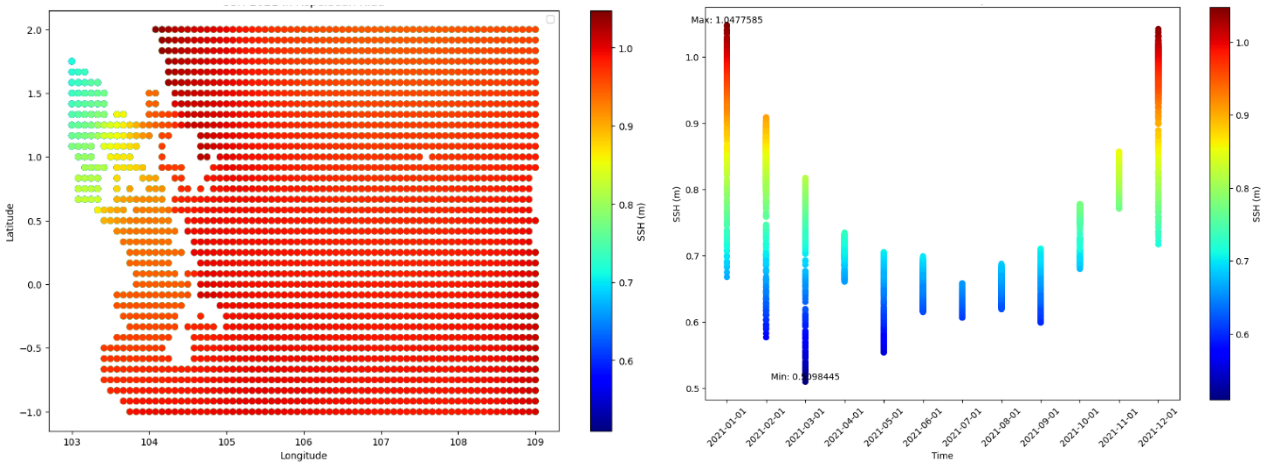


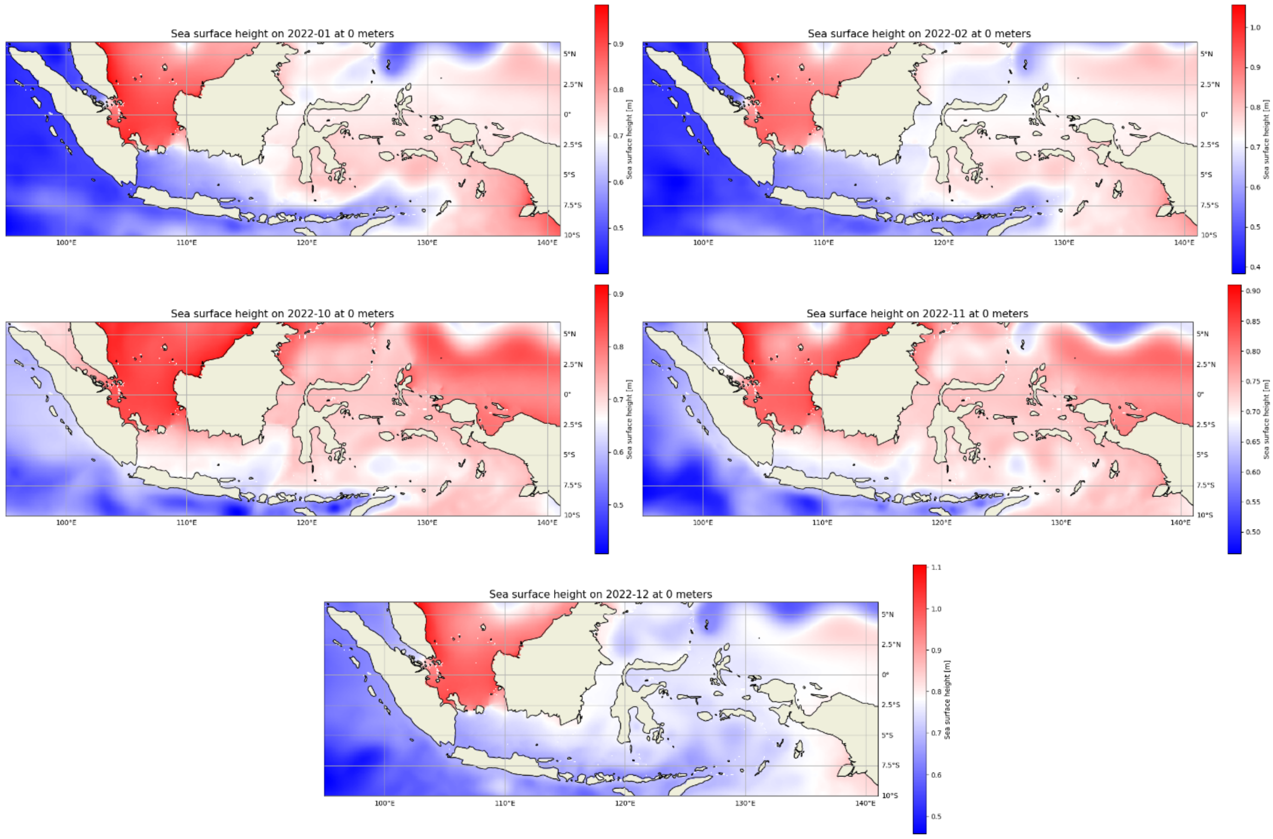
Fig. 4: Spatio-temporal SSH distribution showing the position (longitude and latitude) of SSH values and distribution of SSH values in time series every month in Batam Waters, Riau, in 2021.

The lowest value of the SSH distribution results in Batam waters, Riau Islands, is in the longitude coordinate range of 104.5°–103° with a latitude of -05°–1.8°. The dominant high SSH value is in the longitude coordinate range 104.6°–109°, with a latitude of -1.0°–2.0° (Fig. 4). As is well known, altimeter satellites monitor the earth's or sea's surface by observing the reflected signal's phase. With very high accuracy, this satellite also tracks the travel time from the point of signal emission to the sensor's reception of the reflected signal1[9]. Figure 4 shows the lowest value, namely in March, with a value of 0.50m. The highest value of SSH was in January, at 1.04m.

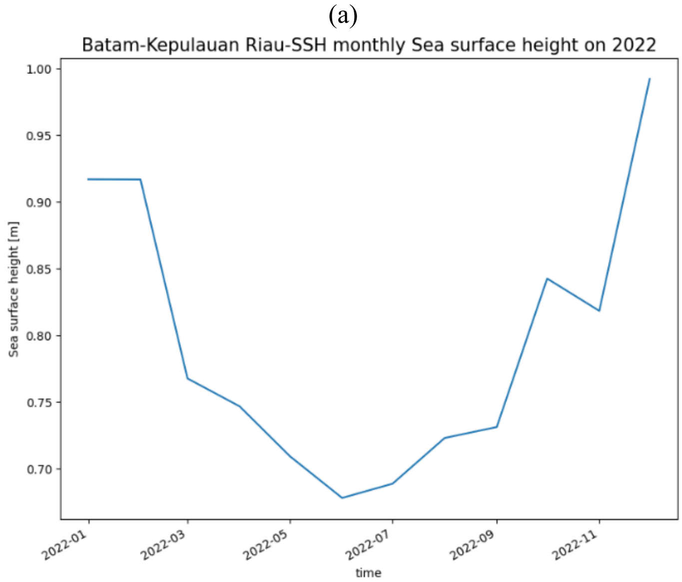
Data on the distribution of SSH values received from satellite altimeters in Batam waters, Riau Islands, provides a fairly clear picture of variations in sea level height in the area. The longitudinal coordinate ranges from 104.5° to 103°, with latitudes of -05° to 1.8° showing the lowest values of the SSH distribution. This may indicate that there are areas with relatively low sea levels in the region. Meanwhile, the longitudinal coordinate ranges from 104.6° to 109° with a latitude of -1.0° to 2.0°, showing the dominance of high SSH values. This indicates that there are areas with relatively high sea levels in the region. This information is very useful in understanding the dynamics of the sea around Batam, so that it can become a strong basis for planning the management of coastal and marine areas in the area. Further studies related to climate change, marine resource conservation, and various other aspects of the oceans around Batam and the Riau Islands can utilize this highly accurate data.

3.2 Variability in sea surface height in the Indonesian Seas in 2022.

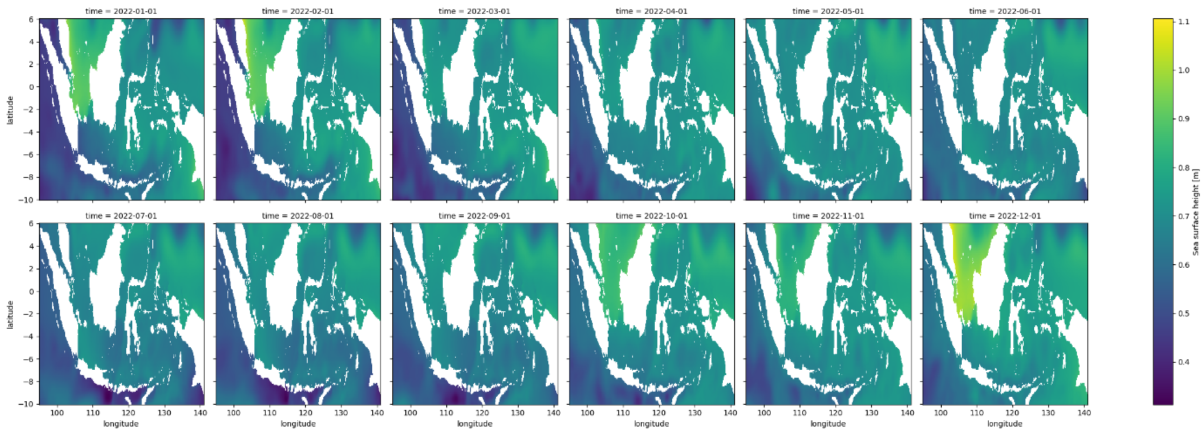
Altimetry satellite data from CMEMS in 2022 provided the sea surface height (SSH) (Fig. 5). These results indicate that the month of December has the highest SSH value. In December, with a value of 1.1 m, the distribution map yielded the lowest SSH value in July, measuring 0.67 m (Fig. 5a, 5b). The results of the distribution of SSH in Indonesian seas in 2022 show significant differences every month. Figure 5a displays the distribution of variability in SSH values in Indonesian seas in January, February, October, November, and December 2022.


Sea surface height on 2022-01 at 0 meters
Sea surface height on 2022-02 at 0 meters
Sea surface height on 2022-10 at 0 meters
Sea surface height on 2022-11 at 0 meters
Sea surface height on 2022-12 at 0 meters
Sea surface height [m]

(a)


Batam-Kepulauan Riau-SSH monthly Sea surface height on 2022
Sea surface height [m]
1.00
0.95
0.90
0.85
0.80
0.75
0.70
2022-01
2022-03
2022-05
2022-07
2022-09
2022-11
time

(b)



(c)

Fig. 5: Spatio-temporal results of sea surface height in the Indonesian Sea in 2022 in January, February, October, November, and December (a), graph of the value or trend line of SSH in Indonesian waters from January to December 2022 (b), and spatio-temporal of SSH values for 1 year in Indonesian seas (c).

SSH results in 2022 experienced a decreased trend starting from March to July; this is different from 2021. The one-year graph of the SSH value produced a trend line that showed a decrease beginning in March and ending in July. After the decrease in the SSH value ended in July, it rose again from August to October (Fig. 5b). The SSH value decreased in November and increased again in December. Figure 5c displays the distribution of SSH values for each year. These results indicate that variability with the colour scale results in 5 months scoring high in SSH. These months are January, February, October, November, and December. Meanwhile, SSH variability from March to September is still relatively low (Fig. 5c).

As opposed to the prior year's pattern, the SSH value saw a notable decrease from March to July of 2022. A number of variables, including variations in the sea surface temperature, atmospheric circulation patterns, and maritime weather patterns, may contribute to this value decline. The decline in SSH values may impact marine ecological systems, such as the distribution of plankton and fish, which depend on the availability of food in the water. In order to comprehend the dynamics of the marine environment and its possible effects on the sustainability of marine ecosystems in Indonesian seas, it is crucial to monitor the SSH value. Furthermore, the rise in SSH values in a few months—January, February, October, November, and December—indicates notable variations in the sea state during these times. This may affect a number of human endeavour's that rely on the sea, including tourism, fishing, and maritime transportation[20]. Therefore, a fuller understanding of the elements that determine the SSH value is necessary to foresee and control the impact of changes in sea conditions in 2022.

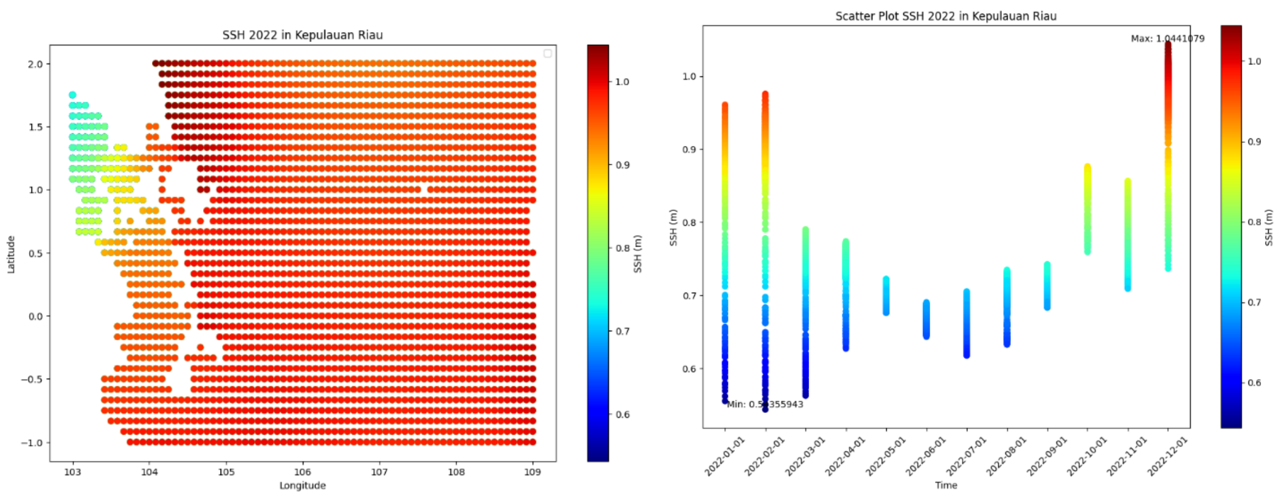


Fig. 6: Spatio-temporal SSH distribution showing the position (longitude and latitude) of SSH values and distribution of SSH values in time series every month in Batam Waters, Riau, in 2022

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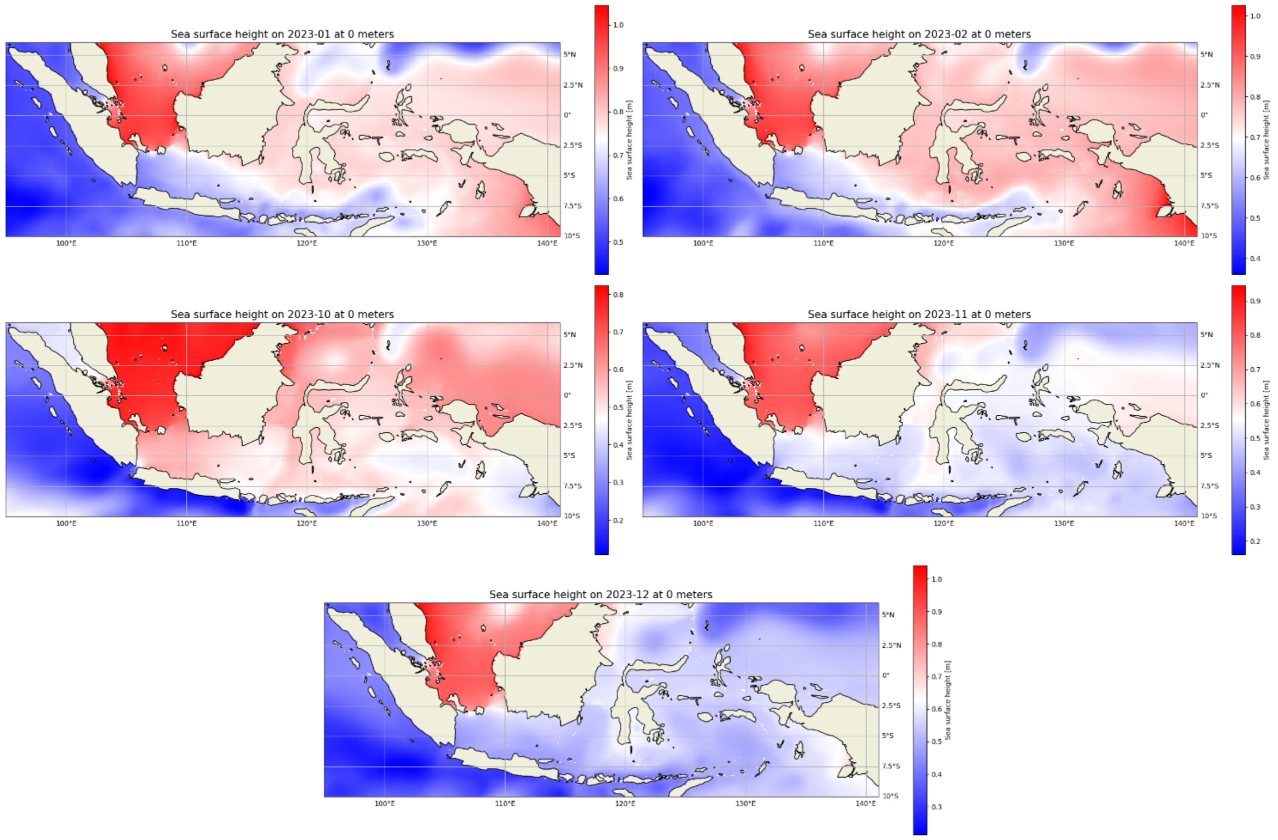
The lowest value of the SSH distribution results in Batam waters, Riau Islands, is in the longitude coordinate range of 105°–103° (different with 2021) and with a latitude of -05°–1.8°. The dominant high SSH value is in the longitude coordinate range 105.1°–109° (different with 2021), with a latitude of -1.0°–2.0° (Fig. 6). Figure 6 shows the lowest value, namely in March, with a value of 0.54m. The highest value of SSH was in December, at 1.04m (different from 2021).

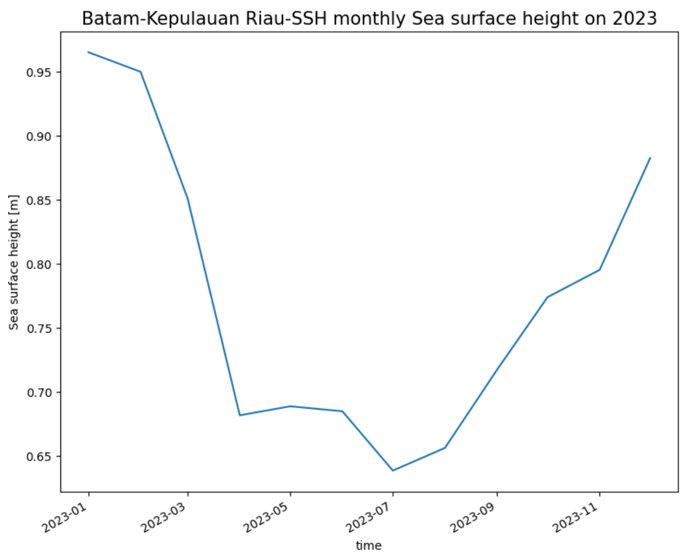
Numerous elements, including wind, seabed topography, and ocean currents, affect the distribution of SSH in the waters surrounding the Batam and Riau Islands. Low SSH values within the longitudinal coordinate range of 105°–103° and latitude -05°–1.8° (Fig. 6) indicate a reduced sea level in the area. Upwelling, or the flow of cooler seawater masses from the bottom levels to the sea surface, may be the cause of this condition[18-20]. This phenomenon usually happens when there is a strong sea breeze, which causes large amounts of cold water to rise to the surface of the sea. In the meantime, elevated SSH values in the latitude range of -1.0°–2.0° and longitudinal coordinate range of 105.1°–109° show a rise in sea level in the area. Large sea waves, rising tides, or the accumulation of water from multiple directions can all contribute to an increase in the SSH value. Seasons can also affect changes in the dominant SSH values throughout the course of the year[21]. In the Batam area, variations in temperature and wind speed can affect sea current patterns and the distribution of seawater masses.

3.3 Variability in sea surface height in the Indonesian Seas in 2023.

Altimetry satellite data from CMEMS in 2023 provided the sea surface height (SSH) (Fig. 7). These results indicate that the month of December has the highest SSH value. In December, with a value of 1.02 m, the distribution map yielded the lowest SSH value in July, measuring 0.63 m (Fig. 7a, 7b). The results of the distribution of SSH in Indonesian seas in 2023 show significant differences every month. Figure 7a displays the distribution of variability in SSH values in Indonesian seas in January, February, October, November, and December 2023.



(a)



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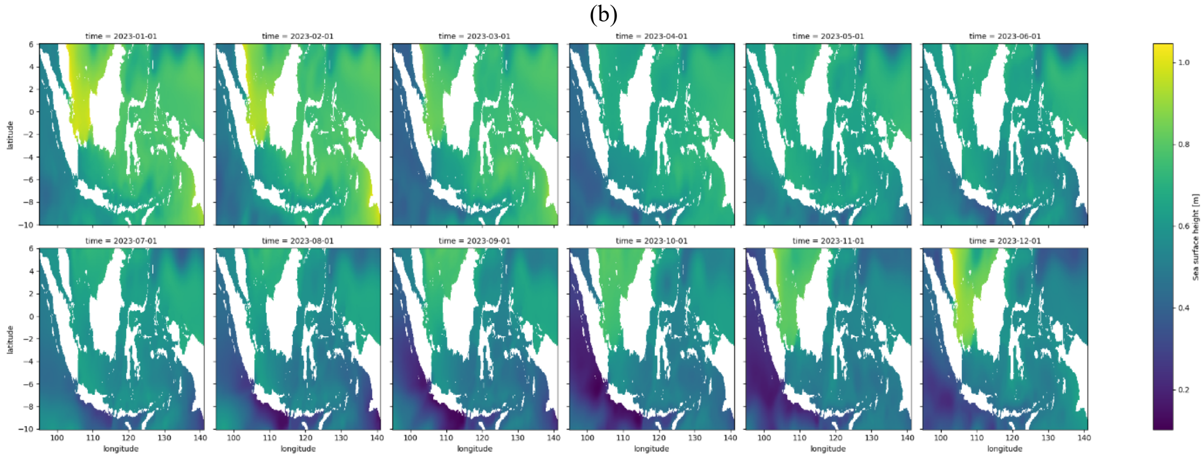


(c)

Fig. 7: Spatio-temporal results of sea surface height in the Indonesian Sea in 2023 in January, February, October, November, and December (a), graph of the value or trend line of SSH in Indonesian waters from January to December 2023 (b), and spatio-temporal of SSH values for 1 year in Indonesian seas (c).

SSH results in 2023 experienced a decreased trend starting from April to July; this is different from 2021. The one-year graph of the SSH value produced a trend line that showed a decrease beginning in April and ending in July. After the decrease in the SSH value ended in July, it increased from August to December; this was different in 2022 but was similar in 2021 (Fig. 7b). Figure 7c displays the distribution of SSH values for each year. These results indicate that variability with the colour scale results in 5 months scoring high in SSH. These months are January, February, October, November, and December. Meanwhile, SSH variability from March to September is still relatively low (Fig. 7c).

The decreasing trend in the SSH value that occurred from April to July 2023 shows that there were fluctuations in this value during that period. Various factors, such as changes in marine weather patterns, changes in ocean currents, or even geological activity on the sea floor, can cause this decline[22–25]. This indicates that there are complex dynamics in the marine system that significantly influence the SSH value. In addition, the increase in SSH values that occurred from August to December indicates changes in conditions that may be more stable or even other factors that influence this increase, such as global warming or overall climate change.

The distribution of SSH values for each year shown in Figure 7c shows a certain pattern in the variability of these values. Factors such as the rainy season, changes in sea surface temperature, or wind patterns typical of these months may influence the months that score high SSH values, namely January, February, October, November, and December. Meanwhile, the relatively low variability in SSH values from March to September indicates that there was a period where sea conditions tended to be stable or did not change significantly. The dry season or other atmospheric conditions can influence seawater movements and SSH values generally.

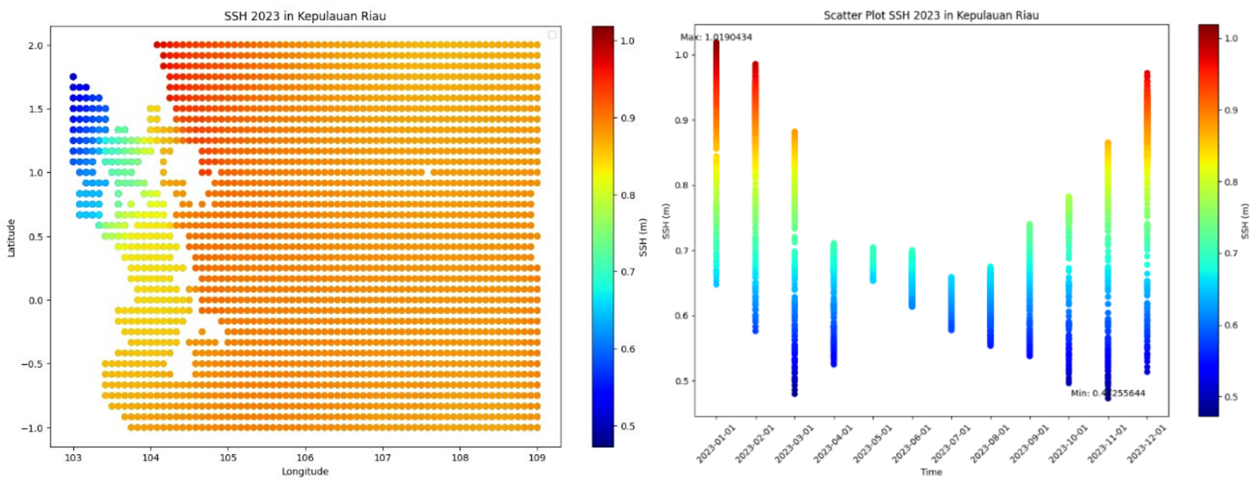


Fig. 8: Spatio-temporal SSH distribution showing the position (longitude and latitude) of SSH values and distribution of SSH values in time series every month in Batam Waters, Riau, in 2023.

Figure 8's data reveals significant variations in the distribution of SSH values in Batam waters, Riau Islands, based on latitude and longitude coordinates. The latitudinal coordinate range of 105.2°–103° records the lowest SSH values, while a different coordinate range, namely 105.3°–109°, shows the highest SSH values. Local geographic factors, such as ocean current patterns, seabed topography, or even interactions with surrounding atmospheric conditions, may cause these differences. This shows the importance of considering geographical factors in analysing the distribution of SSH values in certain water areas.

Apart from that, the differences in SSH values between certain months, such as November and January, are also interesting to observe. Seasonal factors or changes in natural cycles that occur every year can influence the lowest SSH value in November and the highest in January. For example, in January, there may be influences from the rainy season or changes in sea surface temperature that affect the overall SSH value. Further analysis of these factors can provide deeper insight into the dynamics of Batam waters and the factors that influence SSH values in the region.

The three years of sea surface height in the Indonesian Seas caused by tides—average high tide, average low tide, and average low tide—show the pattern of sea level rise. This fact bolsters the notion of calculating sea surface height through satellite measurement results, yet it also reveals that the quantitative value of these measurements may fluctuate depending on various factors like the measurement site, instrumentation, and other elements. Temperature variations in the sea can also have an impact because they can alter water density, which in turn can alter sea surface height[26)]. Changes in sea surface height can be an indicator of ongoing global warming. By regularly monitoring sea levels, we can see patterns of these changes and predict their impact on coastal and marine areas[27)]. In addition, we can use sea level height information to manage natural disasters like tidal floods or extreme tidal waves. By understanding patterns of changes in sea level height, we can take appropriate steps to mitigate disaster risks and protect people living in coastal areas.

Sea surface height measurements can also provide valuable information for understanding oceanographic dynamics and the effects of natural phenomena such as El Nino and La Nina[28)]. By combining sea level data with other data, we can gain a better understanding of the relationship between global climate change and ocean dynamics and how this may affect life on earth. Therefore, it is important for us to continue measuring and monitoring sea level height to gain a greater understanding of global climate change and its impact on our environment.

3.4 Sea Surface Height (SSH) RMSE Analysis, and Mean of SSH in 2021-2023

Figure 9 displays the results of the RMSE analysis from SSH data collected in the waters of Batam, Riau Islands, in 2021–2023. These results show that the data distribution patterns shown in blue, orange, and green have different rising and falling patterns. The results of this RMSE analysis produce a value of 0.11. These RMSE results were generated, with the lowest value in 2021 being in March with an SSH value of 0.50m and the highest in January with an SSH value of 1.04m. In 2022, it produces the lowest SSH value in February with an SSH value of 0.54m, with the highest SSH value of 1.04 m in December. In 2023, the lowest SSH value will be in November with a value of 0.47m, with the highest SSH value of 1.01m in January.

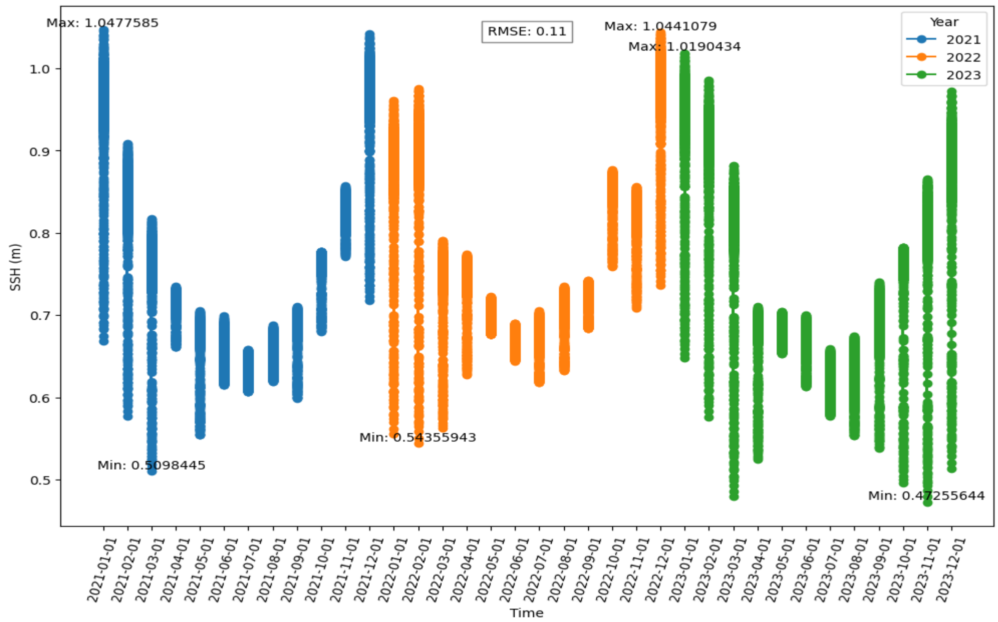
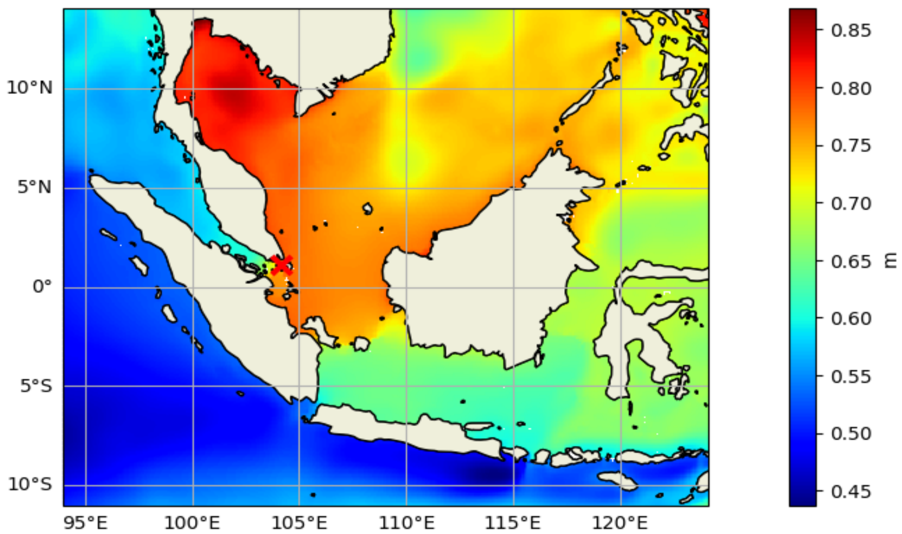
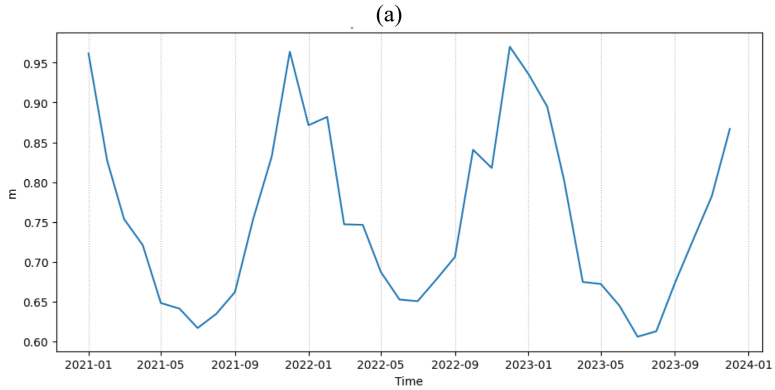


Fig. 9: RMSE analysis of SSH distribution in Batam waters, Riau Islands, in 2021–2023 (blue is 2021, orange is 2022, and green is 2023).



(a)



(b)

Fig. 10: Mean of SSH in 2021-2023, location of the sample of SSH analysis area (with X red color) in the map (a), graph of the monthly time series of SSH in the location of Batam waters, Riau Islands, in 2021-2023 (b).

Figure 9 displays the results of the RMSE analysis from SSH data collected in the waters of Batam, Riau Islands, in 2021–2023. These results show that the data distribution patterns shown in blue, orange, and green have different rising and falling patterns. The results of this RMSE analysis produce a value of 0.11. These RMSE results were generated, with the lowest value in 2021 being in March with an SSH value of 0.50m and the highest in January with an SSH value of 1.04m. In 2022, it produces the lowest SSH value in February with an SSH value of 0.54m, with the highest SSH value of 1.04 m in December. In 2023, the lowest SSH value will be in November with a value of 0.47m, with the highest SSH value of 1.01m in January.

An RMSE value of 0.11 indicates the average error level of the forecasting model on observational data. Differences in rising and falling patterns between these years may reflect variations in ocean dynamics influenced by various factors, such as climate change, ocean currents, or changes in seabed topography[29–31]. The context of SSH values in Batam waters from 2021 to 2023 reveals variations in the lowest and highest values that occur in specific months each year. For example, in 2021, the lowest SSH value occurred in March and the highest in January, while in 2022, the lowest SSH value occurred in February and the highest in December. This shows that there are seasonal patterns, or natural cycles, that influence fluctuations in SSH values in the region. Further analysis of the factors that influence variations in SSH values can provide a deeper understanding of the dynamics of Batam waters and the changes that occur from year to year. In addition, the comparison of SSH values between these years also provides an overview of the evolution of sea conditions in the region over time. An increase or decrease in SSH values in specific months each year can signal changes in sea conditions that require deeper understanding.

The Indonesian throughflow (ITF) and the monsoon trough are two important phenomena that influence the sea surface height (SSH) value in the Indonesian Sea region. The ITF, which flows from the Pacific Ocean to the Indian Ocean via the Indonesian Sea, carries masses of warm water, causing an increase in sea level (SSH) in the area. Meanwhile, the monsoon trough's seasonal wind pattern also influences ocean circulation and surface layers, resulting in variations in SSH values in the Indonesian region—increasing SSH in the west during the west monsoon season and decreasing SSH in the east during the east monsoon season. Therefore, the spatial and temporal variability of SSH values in the Indonesian Sea will reflect changes in the strength and pattern of the ITF and the monsoon trough.

Figure 10a shows the sample location, namely in the Batam waters area, showing the average SSH from 2021–2023. This result shows that the Batam Waters location is one of the areas that has a fairly high SSH value compared to other areas. These results yielded an average SSH value range of 0.65-0.78 m over a period of 3 years. Figure 10b shows the results of the time series graph, which shows the same pattern as Fig. 9. This shows that every month of January 2021, 2022, and 2023 has the highest value of SSH obtained.

From June to September (Southeast Monsoon) and Northwest Monsoon (December–February), there is a greater deviation in sea level height in the open sea. The phenomenon is a result of the interaction between the Indian Ocean currents and the effect of monsoon, which can propel a large volume of water towards the coastal regions[5]. From July to October, there is a larger occurrence of anomalies in the offshore area compared to the coastal areas. The presence of east winds results in the displacement of sea water towards the open seas[4].

The full moon exerts a substantial impact on sea tides, frequently leading to tidal floods in the northern region of Java Island. This phenomenon leads to an intensification of sea tides, resulting in elevated high tides and reduced low tides. The flat and sloping regions of the northern coastal portions of Java Island are susceptible to tidal floods when high tides occur as a result of the full moon.

Future sea surface height (SSH) increases on threatened beaches may necessitate the implementation of several strategic mitigation measures. First, it is necessary to build strong coastal infrastructure, such as embankments, seawalls, and breakwaters, to protect coastal areas from the threat of inundation and waves. Furthermore, conservation and restoration of coastal ecosystems, such as mangrove forests and coral reefs, can help reduce the impact of SSH. In the future, comprehensive implementation of these strategies can help reduce the risks and impacts of increased SSH on vulnerable beaches.

4. Conclusion

The analysis of sea surface height (SSH) data from 2021 to 2023 in the Indonesian Sea and Riau Islands reveals a trend of decreasing SSH values in specific months, with the lowest values occurring in certain months each year. There is a significant pattern of increasing and decreasing SSH values in the Indonesian seas and Batam waters, Riau Islands, which can have an impact on ocean currents and sea waves in the region. Additionally, the distribution of SSH values varies significantly each month, with certain months exhibiting high SSH values. This shows the importance of paying attention to geographical factors in analysing the distribution of SSH values in certain water areas.

Apart from that, there are different trends in decreasing and increasing SSH values from 2021 to 2023 in Indonesian waters, with different patterns each year. Despite monthly fluctuations in SSH values, certain patterns emerge, indicating a tendency for certain months to exhibit high SSH values. Various factors, such as ocean current patterns, seabed topography, and surrounding atmospheric conditions, influence the complexity of ocean dynamics in the region. The Root Mean Square Error (RMSE) analysis reveals that the distribution of SSH values varies annually. An RMSE value of 0.11 shows how far off the measured data is from the real trend.

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