Evaluation of altimetry satellite data products and sea level trends in the Indonesian maritime continent

J Lumban-Gaol*, S Vignudelli2, I W Nurjaya1, N M N Natih1, M E Sinurat1, R E Arhatin1 and E E Kusumaningrum1

1 Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University, Dramaga, Bogor 16680, West Java, Indonesia
2 Institute of Biophysics Operating Italian National Research Council (CNR), Pisa, Italy

*E-mail: jonsonlumban@apps.ipb.ac.id

Abstract. This study examines the accuracy of the sea surface height anomaly (SSHA) altimetry data products of Copernicus, Colorado University (CU), and X-TRACK-Centre for Topographic studies of the Ocean and Hydrosphere (X-TRACK-CTOH). The SSHA derived from altimetry accuracy was tested by comparison with tide gauge (TG) observations. Taking measurements along the IMC coast demonstrates the excellent agreement between the SSHA derived from altimetry and the TG observations, with an average root mean square deviation (RMSD) as low as 10 cm and a strong correlation. The study's findings revealed that the Copernicus data products could be used to monitor sea-level variability and trends in the IMC accurately. The 25-year time series data from SSHA demonstrated that the sea-level trend in the IMC is higher than the global trend.

Keywords: altimetry, Colorado University, Copernicus, tide gauge, sea level, X-TRACK-CTOH

1. Introduction

Indonesia is an archipelagic country consisting of more than 14,000 small islands with a coastline of 81,000 km and waters covering 5.8 million km² of its territory. Indonesia has a significant variation in sea level, and its increasing sea level is higher than the global trend [1, 2], making the country extremely vulnerable to increasing global sea levels. Many people live in coastal areas below the average high tide level, which is vulnerable to flooding by extreme sea levels. This rising level is likely to inundate some beaches and overflow many barrier islands that serve as natural protection against storm surge from tropical cyclones. It may also increase the risk of tidal flooding. In areas expected to increase rainfall, flash flooding and river flooding would also compound the flood risk associated with coastal waters.

Jakarta Post (18 January 2020) reported that rising sea levels had submerged two small islands in the province of South Sumatra, and four other nearby islands were on the brink of vanishing due to climate change. Therefore, continuous monitoring of sea-level rise and variability is an urgent issue in Indonesian waters. However, the distribution of the existing National Sea Level Monitoring Network, consisting of approximately 130 stations, is considered inadequate to provide a comprehensive understanding of tidal characteristics and changing sea levels along the coastline. Assuming one tidal station represents a tidal regime of approximately 100 km of coastline, the ideal number of permanent tidal stations for the whole country should consist of more than 500 stations.
Satellite radar altimetry has succeeded in providing ocean global data products for the last 25 years. Therefore, sea-level measurements from an altimeter can be used to monitor the sea level in the IMC. Some studies have shown that satellite altimetry provides high-quality SSHA data. These data have been successfully used to study ocean processes, such as trends and variability of sea level [3–5], Rossby waves [6, 7], eddy currents [8, 9], and geostrophic circulation on different spatial and temporal scales [10].

During the past 25 years, research institutions have used altimetry data products to study various aspects of the marine environment in the IMC. These studies including the Indonesian Throughflow [11], the effect of rapid fall of sea level on coral mortality [12], the effect of sea-level variability on bigeye tuna fishing grounds [13], the Kelvin current observed by altimetry [14], and the study of the impact of sea-level rise on coastal areas, etc. [15].

The satellite altimetry data products are often used for marine studies in the IMC, such as the Copernicus and Colorado University (CU) data products [13, 16]. Although these data are usually used for open ocean studies, some coastal altimetry data products have been produced for coastal applications by CTOH; the X-TRACK product, for example, has been used in the IMC [17]. Previously, evaluation of the Radar Altimeter Database System (RADS) products [18] and the Adaptive Leading Edge Sub-waveform (ALES) [19] have been conducted in several coastal areas in the IMC. However, Copernicus, CU, and CTOH altimetry products have never been used to evaluate the IMC. This paper evaluates the accuracy of the SSHA products provided by Copernicus, CU, and X-TRACK-CTOH to promote data usage, especially in the open-ocean and coastal waters of the IMC. Previous studies that calculated trends in sea level rise over different periods in various coastal areas were 2.3-2.8 mm/year for 1993-2009 [19], while in a period that were extended by six years, 1993-2015, the mean was 4.2 mm/year [2]. Satellite altimeter data over the past 25 years show the acceleration of the global rise in sea level driven by climate change [20]. The validation of altimeter data products is an essential contribution to studying sea levels in the IMC.

2. Materials and Methods

2.1. Tide gauge data
The tide gauge (TG) data from the University of Hawaii Sea Level Center (UHSLC) Fast-Delivery database is available here ftp://ftp.soest.hawaii.edu/uhslc/fast. We used daily sea-level records from eight tide gauges located along the IMC coast for the 2008-2018 period (Figure 1). For the Saumlaki and Ambon tide gauges, only data from 2009 to December 2018 are available due to data gaps.

Tidal data is corrected to avoid significant aliasing errors. We removed the pole tide and solid tide, while the geocentric tide was corrected using the harmonic analysis from the t-tide technique [21].

2.2. Altimetry data
Three data sets of SSHA altimeter products distributed by the Copernicus Marine Environment Monitoring Service (MEMS), CU, and X-TRACK-CTOH were used in the study. The SSHA ($h_{SLA}$) can be determined using the following equation:

$$h_{SLA} = H - R_{obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{SSB} - h_{DAC} - h_{tide} - h_{ms}$$  \hspace{1cm} (1)$$

Where in, $H$ is a satellite height above a reference ellipsoid determined by the precise satellite orbit determination, $R_{obs}$ is an observation range corrected by instrument errors, $\Delta h_{dry}$ and $\Delta h_{wet}$ are dry and wet tropospheric corrections, respectively, $\Delta h_{iono}$ is ionospheric correction, $\Delta h_{SSB}$ is sea state bias correction, and $h_{DAC}$ refers to dynamic atmospheric correction, $h_{tide}$ are tide corrections including ocean tide, load tide, solid earth tide, and pole tide, and $h_{ms}$ refers to the mean sea surface model.

The Multi-Mission Sea Level Thematic Center (SL-TAC) processed the Global Ocean Gridded L4 SSHA Copernicus products based on Jason-3, Sentinel-3A, HY-2A, Saral/Altika, CryoSat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, and the ERS1/2 altimeter data processing system. The horizontal sampling of SSHA is 1/4 degree. The description of the product is available here:
The SSHA CU products were processed by the Jet Propulsion Lab's Physical Oceanography Distributed Active Archive Center (PODAAC). The data were gridded by the kriging method and derived from TOPEX/Poseidon SSHA data, Jason-1, Jason-2, and Jason-3 as reference data from the level 2 swath data, plus ERS-1, ERS-2, Envisat, SARAL-Altika, and CryoSat-2. The horizontal sampling of SSHA is 1/6th degree. Data access is available here: https://ccar.colorado.edu/altimetry. Additional information is available at https://podaac.jpl.nasa.gov/dataset/SEA_SURFACE_HEIGHT_ALT_GRIDS_L4_2SATS_5DAY_6THDEG_V_JPL1609. X-TRACK, a new processing toolbox to derive improved coastal altimeter SSHA products developed by CTOH, is available here: http://ctoh.legos.obs-mip.fr/products/coastal-products/. The summary of the data used and the period is listed in Table 1.

| No. | Data Product       | Period  | Resolution | Interval |
|-----|-------------------|---------|------------|----------|
| 1   | Copernicus        | 1993-2018 | 0.25°    | 1 day    |
| 2   | Colorado U        | 1993-2018 | 0.06°    | 10 days  |
| 3   | X-TRAC-CTOH       | 2003-2010 | 350 m   | 35 days  |

Statistical analysis derived from SSHA altimetry with eight tide gauge stations was carried out by computing the correlation coefficient (r), and the root mean square deviation (RMSD), as given in the following equation, respectively [22]:

\[ r = \frac{c_{x,y}}{(S_x S_y)^{1/2}} \]  \hspace{1cm} (2)

\[ \text{RMSD} = \left( \frac{1}{N} \sum_{i=1}^{N} (x_i - y_i)^2 \right)^{1/2} \]  \hspace{1cm} (3)

where \( x \) and \( y \) are the SSHA of the altimetry products and the tide gauge, respectively, and \( N \) is the total number of samples. \( c_{x,y} \) is the covariance of variables \( x \) (i.e., SSHA of altimetry) and \( y \) (i.e., SSHA of tide gauge), and \( S_x \) and \( S_y \) are their standard deviations.

Fourier transform was used to analyze the variability of sea level as follows [22]:

\[ Y_k = \Delta t \sum_{n=1}^{N} Y_n e^{-i2\pi f_k n \Delta t} \]  \hspace{1cm} (4)

\[ Y_k = \Delta t \sum_{n=1}^{N} Y_n e^{-i2\pi f_k n / N} ; \quad f_k = \frac{k}{N \Delta t}, k = 0, \ldots, N \]  \hspace{1cm} (5)
The energy spectral density for sea level data time series is then:

\[ S_E(f_k) = |Y_k|^2 \quad k=0,\ldots, N - 1 \]  

where \( Y_k \) is the Fourier transform, \( \Delta t \) is the sampling interval, \( n = (1, 2, 3,\ldots, N) \), \( f_k \) is frequency

3. Result and Discussion

3.1. Comparison of offshore Altimetry and TG Observations

The SSHA Copernicus and CU data products are compared and evaluated on the SSHA of coastal tide gauge observations. The time series of the SSHA-derived TG records and the corresponding time series of the altimetry data of the Copernicus and CU products at the locations of the tide gauges are presented in Figures 2 and 3, respectively. The degree of consistency between the altimetry and tide gauge data is summarized in Table 1, which presents the correlation coefficient (r) of the time series and the RMSD between the records. The total mean value of the temporal correlation computed based on the eight cases is 0.93 and 0.86 for the Copernicus and CU products, respectively, classified as a very high correlation. A comparison with TG indicates that the correlation of the Copernicus SSHA product is superior to that of the CU product.

![Figure 2](image-url)
Figure 3. Sea surface height anomaly (cm) from the records at the A. Sabang, B. Sibolga, C. Cilacap, D. Prigi, E. Benoa, F. Saumlaki, G. Ambon, and H. Bitung tide gauges (black curves) and from the altimetry products of Colorado University to the locations of the tide gauges (red curves).

Table 2. Correlation coefficient (r) and RMSD between the altimetry products (Copernicus and CU) and the TG observations.

| TG    | Copernicus products | CU products |
|-------|---------------------|-------------|
|       | RMSD (cm) | r   | RMSD (cm) | r   |
| Sabang | 5         | 0.87 | 7         | 0.70 |
| Sibolga | 4         | 0.87 | 6         | 0.76 |
| Cilacap | 7         | 0.96 | 6         | 0.97 |
| Prigi   | 6         | 0.97 | 7         | 0.94 |
| Benoa   | 5         | 0.95 | 8         | 0.87 |
| Saumlaki | 3         | 0.95 | 4         | 0.92 |
| Ambon | 3         | 0.94 | 6         | 0.80 |
| Bitung | 3         | 0.92 | 4         | 0.89 |
| Mean   | 4.5       | 0.93 | 6.0       | 0.86 |
The data of SSHA along the IMC coast demonstrate the compatibility between coastal altimetry and the eight tide gauge measurements, with the RMSD as low as 7 cm at many stations. The RMSD indicates a significant difference between Copernicus and average CU products, with an average RMSD of 4.5 and 6.0 cm, respectively. The lowest RMSD between the TG and Copernicus altimetry data of about 3 cm is estimated at Saumlaki, Bitung and Ambon. However, using the CU product, the lowest RMSD of approximately 4 cm is found in Saumlaki and Bitung. The deviation between TG and satellite data ranges from 10-30% (Table 2).

3.2. Comparison of the coastal altimetry product and TG observations
The correlation coefficients between TG observations and coastal altimetry X-TRACK-CTOH, along the track, are robust (r>0.95), as shown in Table 3 and Figure 4 by the color of each marker. A correlation coefficient value > 0.95 indicates a perfect fit and therefore is a very reliable X-TRACK-CTOH coastal product for monitoring sea level in the coastal area of the IMC.

Table 3. Correlation coefficient (r) and RMSD between the altimetry products(X-TRACK-CTOH) and the TG observations.

| Station | Sibolga TG | Cilacap TG | Benoa TG | Saumlaki TG | Bitung TG |
|---------|------------|------------|----------|-------------|-----------|
| 1       | 0.98       | 0.97       | 0.98     | 0.99        | 0.93      |
| 2       | 0.97       | 0.97       | 0.97     | 0.99        | 0.97      |
| 3       | 0.98       | 0.98       | 0.98     | 0.99        | 0.98      |
| 4       | 0.97       | 0.98       | 0.97     | 0.99        | 0.97      |
| 5       | 0.97       | 0.99       | 0.97     | 0.99        | 0.96      |
| 6       | 0.95       | 0.99       | 0.96     | 0.99        | 0.97      |
| 7       | 0.94       | 0.99       | 0.96     | 0.99        | 0.99      |
| 8       | 0.96       | 0.99       | 0.97     | 0.99        | 0.99      |
| 9       | 0.98       | 0.99       | 0.89     | 0.99        | 0.99      |
| 10      | 0.97       | 0.99       | 0.91     | 0.99        | 0.99      |
| 11      | 0.98       | 0.99       | 0.92     | 0.99        | 0.99      |
| 12      | 0.94       | 0.99       | 0.90     | 0.99        | 0.99      |

Over Benoa-TG, the SSHA has a lower correlation than other tide gauges because Benoa-TG is located in complex coastal waters between the main path of Indonesian Throughflow (ITF) and Nusa Penida, a small island. Similarly, Sibolga-TG is located between Sumatra Island and Nias Island, with a lower correlation coefficient than Cilacap-TG, Saumlaki-TG, and Bitung-TG, which are directly related to open seas.

The analysis of X-TRACK data with five TG stations is conducted by computing the RMSD (Figure 5). Table 4 summarizes the mean temporal RMSD, along the track, of different TG stations. The lowest RMSDs are shown in bold. The lowest RMSD in Sibolga-TG is 4.8 cm, and the highest in Benoa-TG is 10.9 cm. The lowest mean RSMD of the five TGs is 8.2 cm.

Previously, coastal altimetry products have been evaluated using retracking of several waveforms in seas of Southeast Asia with a mean RMSD of 10 cm [23]. A study in the Gulf of San Matias (Argentina) shows that the RMSD between the X-TRACK product and the tide gauge observation is smaller than 10 cm [24]. Therefore, the X-TRACK product at several locations is better than the other coastal altimetry products.
Figure 4. The spatial plot of temporal correlation of SSHA along the tract of X-TRACK-CTOH products from different TG stations (a) Sibolga, (b) Cilacap, (c) Benoa, (d) Saumlaki, and (e) Bitung.

Figure 5. Root mean square differences between the SSHA CTOH product along with the track and tide gauge stations in (a) Sibolga, (b) Cilacap, (c) Benoa, (d) Saumlaki, and (e) Bitung.
Table 4. The RMSD between X-Track-CTOH altimetry products and TG observations.

| Station | Sibolga TG | Cilacap TG | Benoa TG | Saumlaki TG | Bitung TG |
|---------|------------|------------|----------|-------------|-----------|
| 1       | 5.7        | 11.6       | **11.9** | 7.4         | 19.0      |
| 2       | 6.3        | 9.5        | 12.8     | 6.5         | 17.3      |
| 3       | **4.8**    | 8.2        | 13.2     | 6.4         | 17.6      |
| 4       | 5.9        | 9.2        | 15.4     | 6.1         | 18.6      |
| 5       | 6.4        | 7.4        | 15.1     | 8.2         | 18.1      |
| 6       | 7.2        | **6.8**    | 16.5     | 8.0         | 15.6      |
| 7       | 8.0        | 9.0        | 17.3     | 7.2         | 14.3      |
| 8       | 7.0        | 9.7        | 14.2     | **6.3**     | 11.5      |
| 9       | 6.4        | 10.8       | 22.5     | 7.8         | 14.2      |
| 10      | 6.1        | 11.6       | 20.6     | 6.6         | 14.0      |
| 11      | 4.9        | 10.2       | 20.2     | 21.7        | 11.7      |
| 12      | 7.8        | 8.7        | 20.8     | 27.1        | **11.2**  |
| Mean    | 6.4        | 9.4        | 16.7     | 9.9         | 15.3      |

3.3. Variability and trends of sea surface height anomaly

Figure 6 shows the temporal variability and trends of SSHA during the period 1993–2018. The power spectral density function of SSHA shows dominant signals corresponding to the semi-annual, annual and inter-annual variability. One is the oscillation around 0.5 to 1 year, and the other is around 3 years (Figure 7).

The monsoon system drives the annual cycle, which blows from the east from May to September (Southeast Monsoon) and from the west from November to March (Northwest Monsoon). During the southeast monsoon season, the sea level in the eastern Indian Ocean is lower than during the northeast monsoon. This drop is well known to be driven by southeast solid monsoon winds resulting in coastal upwelling in the eastern Indian Ocean [25]. The interannual variability of the SSHA in the EIO is dominated by the Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO). During the El Niño (1994, 1997-98, 2002-03, 2004-05, 2006-07, 2009-10, 2014-16 and 2018-19) and IOD positive phase (1994, 1997, 2006, 2009 dan 2019), upwelling is more intense and causes the sea level to be lower than upwelling in normal conditions [13].

The sea-level trends in the 1993–2018 period are positive almost everywhere in the IMC (Figure 6). The mean increase in sea level in IMC waters was 4.3 mm/year, mainly appearing in the southern Java coast, such as Prigi and Cilacap. Internal climate variability, such as El Niño, can contribute significantly to regional sea levels on shorter time scales. It is best to consider sea-level variability when planning efforts to mitigate the effects of future sea-level change [26].

The study focuses on the Eastern Indian Ocean of IMC, characterized as an open sea with a depth of > 200 meters (Figure 1). An analysis of the altimetry data with TG observations showed that the mean RMSD of Copernicus, CU, and X-TRACK products was 4.5 cm, 6.0 cm, and 8.2 cm, respectively. Recent evaluations of coastal altimetry data products at 8 TGs in the shallow waters (< 75 m) of IMC, such as the Java Sea and South China Sea areas, have been conducted where the mean RMSD was 10.32 cm [24], higher than that of our study. The altimetric signals in shallow and complex waters are high noise compared to those in the open and deep ocean [27].

Different data processing methods can cause the RMSD of Copernicus and CU products to be smaller than X-TRACK. Copernicus and CU products are gridded and merged products, while X-TRACK products are along a track. Compared to altimetry data along the path, the merged products provide the smoothest variability in both time and space [28]. The mean temporal correlations between Copernicus (0.93), CU (0.86), and X-TRACK (0.98) data products and TG observations are classified as robust correlations that showed the altimetry products agree with the tide gauge observations. The RMSD and
correlation indications showed that the Copernicus product is slightly more accurate than the other products in the IMC.

Figure 6. Anomaly and trends of sea surface height in (A) Sabang, (B) Sibolga, (C) Cilacap, (D) Prigi, (E) Benoa, (F) Ambon, (G) Saumlaki, (H) Bitung, (I) Java, (J) Makassar Strait, (K) Banda Sea and (L) North Papua.
Figure 7. Power spectral density shows the annual and interannual variability of SSHA in the IMC.

The trends of sea-level rise from satellite altimetry in the IMC for the 1993–2018 period in all TG stations increased by an average of 4.4 mm/year, which was higher than previous studies [2, 18]. The sea-level rise trends in the IMC are also higher than global trends (3.2 mm/year) (Figure 8). Satellite sea level data is vital for monitoring sea levels in the IMC because TG observation sea level data are not continuous, and time is short [18]. The TG sea-level observation data on the IMC can also be biased due to the influence of the instability of the reference level being affected by vertical solid land movements resulting from seismic events and land subsidence [18, 29]. Therefore, sea-level data from satellite altimetry is beneficial for monitoring sea-level variability and trends in the IMC.

The main cities and settlements in the IMC are generally located on the coast, such as Jakarta, Semarang, and Surabaya. They are very vulnerable to increases in sea level because their populations are pretty dense. According to the World Economic Forum (2018), Jakarta is one of the fastest-sinking cities globally due to rising sea levels and land subsidence [30] that cause over-extraction of groundwater. Observations of the continuous rise of the sea level in the IMC are needed to anticipate coastal flood disasters. Therefore, the availability of accurate and reliable satellite altimetry data over long periods could help overcome the lack of TG-observation data in the IMC.

Figure 8. Multi-missions sea level trends, period: Sep-1992-Jan 2018 (EU Copernicus Marine Service/CNES/LEGOS/CLS, 2018).
4. Conclusions
The three altimetry data products show excellent performance for sea-level monitoring at the IMC. In general, the Copernicus product is slightly better than the other products. The sea level shows the annual and inter-annual variations in the IMC influenced by the monsoon system, El-Niño, and IOD. The regional mean rise in sea level (4.3 mm/year) has shown a significant increase, indicating that the rise in IMC is higher than the global mean rise in sea level (3.2 mm/year) based on 25 years of altimetry data.

Acknowledgments
The authors would like to thank the Copernicus MEMS, Colorado University, X-TRAKC-CTOH for producing and distributing Altimetry data, the University of Hawaii Sea Level Center for distribution tide gauge data observation. This work was supported by the Ministry of Research Technology and Higher Education through the competitive Magister research under grant [No 1/E1/KP.PTNBH/2020 & 1/AMD/E1/KP.PTNBH/2020].

References
[1] Heliani L S, Ateya I L, Fukuda Y and Takomoto S 2002 Mean Sea Level and Sea Surface Variability of Indonesian Waters from TOPEX/Poseidon International Association of Geodesy Symposia (Berlin: Springer) pp 259–63
[2] Handoko E Y, Fernandes M J and Lázaro C 2017 Assessment of altimetric range and geophysical corrections and mean sea surface models-Impacts on sea-level variability around the Indonesian seas Remote Sens. 9 1–32
[3] Nerem R S, Tapley B D and Shum C K 1990 Determination of the ocean circulation using Geosat altimetry J. Geophys. Res. 95 3163–79
[4] Nerem R S, Chambers D P, Choe C and Mitchum G T 2010 Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions Mar. Geod. 33 435–46
[5] Melet A, Gourdeau L and Verron J 2010 Variability in Solomon Sea circulation derived from altimeter sea level data Ocean Dyn. 60 883–900
[6] Hughes C W 1995 Rossby waves in the southern ocean: A comparison of TOPEX/POSEIDON altimetry with model predictions J. Geophys. Res. 100 15,933-15,950
[7] Cipollini P, Cromwell D, Challenor P G and Raffaglio S 2001 Rossby waves detected in global ocean colour data Geophys. Res. Lett. 28 323–6
[8] Chaigneau A, Gizolme A and Grados C 2008 Mesoscale eddies off Peru in altimeter records: Identification algorithms and eddy spatio-temporal patterns Prog. Oceanogr. 79 106–19
[9] Fu L L, Chelton D B, Le Traon P Y and Morrow R 2010 Eddy dynamics from satellite altimetry Oceanography 23 15–25
[10] Poulin P M, Menna M and Mauri E 2012 Surface geostrophic circulation of the mediterranean sea derived from drifter and satellite altimeter data J. Phys. Oceanogr. 42 973–90
[11] Susanto R D and Song Y T 2015 Indonesian throughflow proxy from satellite altimeters and gravimeters J. Geophys. Res. Ocean. 120 2844–55
[12] Elvan Ampou E, Johan O, Menkes C E, Niño F, Birol F, Ouillon S and Andrefouet S 2017 Coral mortality induced by the 2015-2016 El-Niño in Indonesia: The effect of rapid sea level fall Biogeosciences 18 817–26
[13] Lumban-Gaal J, Leben R R, Vignudelli S, Mahapatra K, Okada Y, Nababan B, Mei-Ling M, Amri K, Arhatin R E and Syahdan M 2015 Variability of satellite-derived sea surface height anomaly, and its relationship with Bigeye tuna (Thunnus obesus) catch in the Eastern Indian Ocean Eur. J. Remote Sens. 48 465–77
[14] Syamsudin F, Kaneko A and Haidvogel D B 2004 Numerical and observational estimates of Indian Ocean Kelvin wave intrusion into Lombok Strait Geophys. Res. Lett. 31 1–4
[15] Takagi H, Esteban M, Mikami T and Fujii D 2016 Projection of coastal floods in 2050 Jakarta Urban Clim. 17 135–45
[16] Saputra J, Lumban-Gaol J, Panjaitan J P and Atmadipoera A S 2019 Spatial pattern and temporal variability of sea level anomaly and geostrophic current in the eastern Indian ocean from satellite altimetry Pertanika J. Sci. Technol. 274 2281–304

[17] Lumban-Gaol J, Adrian D, Vignudelli S, Leben R R, Wayan Nurjaya I, Osawa T, Manurung P and Arhatin R E 2018 An assessment of a coastal altimetry data product in the Indonesian Waters IOP Conference Series: Earth and Environmental Science 176 1–10

[18] Nurmuaila S L, Fenoglio-Marc L and Becker M 2010 Long term sea level change from satellite altimetry and tide gauges in the Indonesian Region EGU Gen. Assem. 12 1–7

[19] Passaro M, Dinardo S, Quartly G D, Snaith H M, Benveniste J, Cipollini P and Lucas B 2016 Cross-calibrating ALES Envisat and CryoSat-2 Delay-Doppler: A coastal altimetry study in the Indonesian Seas Adv. Sp. Res. 58 289–303

[20] Nerem R S, Beckley B D, Fasullo J T, Hamlington B D, Masters D and Mitchum G T 2018 Climate-change–driven accelerated sea-level rise detected in the altimeter era Proc. Natl. Acad. Sci. U. S. A. 115 2022–5

[21] Pawłowicz R, Beardsley B, and Lentz S 2002 Classical tidal harmonic analysis including error estimates in MATLAB Using T_TIDE Comput. & Geosci. 28: 929–937

[22] Emery W J and Thomson R E 2001 Data Analysis Methods in Physical Oceanography (Elsevier) pp 371–567

[23] Idris N H 2020 Regional validation of the Coastal Altimetry Waveform Retracking Expert System (CAWRES) over the largest archipelago in Southeast Asian seas Int. J. Remote Sens. 41 5680–94

[24] Birol F, Fuller N, Lyard F, Cancet M, Niño F, Delebecque C, Fleury S, Toublanc F, Melet A, Saraceno M and Léger F 2017 Coastal applications from nadir altimetry: Example of the XTRACK regional products Adv. Sp. Res. 59 936–53

[25] Susanto R D, Gordon A L and Zheng Q 2001 Upwelling along the coasts of Java and Sumatra and its relation to ENSO Geophys. Res. Lett. 28 1599–602

[26] Hamlington B D, Strassburg M W, Leben R R, Han W, Nerem R S and Kim K Y 2014 Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean Nat. Clim. Chang. 4 782–5

[27] Gommenginger C, Thibaut P, Fenoglio-Marc L, Quartly G, Deng X, Gomez-Enri J, Challenger P and Gao Y G 2011 Retracking altimeter waveforms near the coasts Coastal Altimetry ed S Vignudelli, A Kostianoy, P Cipollini and J Benveniste (Berlin: Springer) pp 61–101

[28] Yildiz H, Andersen O B, Simav M, Aktug B and Ozdemir S 2013 Estimates of vertical land motion along the southwestern coasts of Turkey from coastal altimetry and tide gauge data Adv. Sp. Res. 51 1572–80

[29] Fenoglio-Marc L, Schön T, Illigner J, Becker M, Manurung P and Khafid 2012 Sea Level Change and Vertical Motion from Satellite Altimetry, Tide Gauges and GPS in the Indonesian Region Mar. Geod. 35 137–50

[30] Abidin H Z, Andreas H, Gumpil I, Fukuda Y, Pohan Y E and Deguchi T 2011 Land subsidence of Jakarta (Indonesia) and its relation with urban development Nat. Hazards 1–19