Internal solitary waves in the Northwest Sumatra Sea-Indonesia: from observation and modeling

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Abstract. The southern Andaman waters has been well known as one of the strongest generating and propagating area of internal solitary waves (ISWs), generated by semidiurnal barotropic tidal currents that impinge submarine ridge offshore western Weh. This study aims to investigate sea surface features of internal tides and tidal current around the submarine ridge and adjacent Weh-Aceh waters, derived from satellite imagery datasets (January-May 2018) and CROCO model-output datasets. The results show that sea surface signatures of ISWs are characterized by a strong radar signal backscattering of a dense ripple package in the generating area and two groups of ISWs arch in the propagating area, where the distance of the package groups and wavelengths vary 60-80 km and 9-163 km, respectively. Observed ISWs in March 2018 was 31. The satellite and model datasets suggest that generating area of internal waves is confined over the Breuh ridge. Here, the very strong semidiurnal (M2) barotropic tidal currents of 0.5-5.0 m/s are observed. During high-tide, amplified barotropic tidal currents acrossing the ridge flow partly southeastward into the Weh-Breuh passage. The model suggests that generating internal tidal waves over the ridge are manifested by strong vertical perturbation of isopycnal and current stratifications in the lee-waves area.

Keywords: internal tides, ocean circulation model, Sentinel-1A SAR, satellite imagery, solitons, Weh-Sumatra Sea

1. Introduction

Weh island is part of North Aceh waters, Indonesia, where its ocean dynamics is influenced significantly by the Nicobar-Andaman Sea, the Malacca Strait, and the Indian Ocean. The Nicobar-Andaman Sea, located in the northeast of the Indian Ocean, is a deep water with average depth of 1100 m, and is bordered by Myanmar, Thailand, Malaysia and Indonesia countries [1]. The Nicobar-Andaman Sea connects to the southwest of Aceh Sumatra with a shallow seabed topography consisting ridges and seamounts that are ideal for generating the internal waves (Figure 1) [2].

An internal wave is an oceanographic phenomenon that occurs below the sea surface. This wave is formed due to stratification disturbances between seawater density layers, generated by wind or tides [3]. Barotropic tidal currents crossing the shallow ridges of the Nicobar Islands and northwest Sumatra can generate the internal waves [4]. These tidal currents drive layers of seawater bodies across barriers on the seabed such as sills or ridges, causing disturbances that generate internal waves [5]. The general characteristics of internal waves in the ocean have wavelengths of hundreds of meters to tens of kilometers and periods of tens of minutes to hours [2].
The presence of internal waves associated with sea surface currents can modulate sea surface roughness. Satellite with radar sensor technology-synthetic aperture radar (SAR) is the most effective technology for detecting and monitoring internal waves in the ocean, because it has the ability to detect small changes in the roughness of the sea surface. The higher the roughness, the higher the backscatter received by the radar and the intensity of the image brightness also increases [6]. The internal waves captured by the radar are in the form of a series of alternating light and dark linear or curved lines that represent peaks and valleys [6]. Radar satellite imagery has a limitation that is only able to observe the surface. Therefore, it is necessary to support numerical modelling methods to observe the dynamics of the water column on which there are several internal solitary waves in the radar imageries.

[7, 34] observed internal waves from Terra/Aqua MODIS and Sentinel-1A SAR satellites from 2013-2015 imagery to see the spatial-temporal distribution in the Andaman Sea. [2] observed the formation of secondary internal waves due to the underwater bank using ERS-2 SAR imagery and numerical modelling to study the dynamics of the water column, thus observing the interaction between barotropic tidal currents and the seabed topography. [8] observed this phenomenon in the Andaman Sea by making a section from the generation location until it disappeared to analyze the difference in backscattering characteristics between mode-1 and mode-2 of internal waves. [9] used a three-dimensional non-hydrostatic numerical modelling method to observe the evolution of internal wave propagation in the Andaman Sea from an oceanic basin to shallow waters, where concave and convex fragments due to internal wave refraction were seen.

Internal waves activities in the Andaman Sea threaten building structures at sea, such as oil and gas drilling activities on the high seas or other facilities near shore. In one documented incident in the North Andaman Sea where internal waves passed, an oil drill tilt of about 3° was seen [6]. Strong currents and shear joining the soliton can also put extreme stress on the drill pipe during offshore operations [10]. Internal waves also play an important role in biological processes in the ocean and coastal area, for example, internal waves breaking in shallow water will release nutrients carried from the deep layers so that the waters become much fertile, and also internal waves bring food for marine biota that live on coral reefs [11].

This study aims to investigate characteristics and dynamics of internal waves in the Weh-Breuh waters within the southern Nicobar-Andaman Sea region. Previous studies [e.g., 4, 6, 8] documented satellite derived solitary waves in the northeastern region of Nicobar-Andaman region, where generating area of internal waves over the Sumatera ridge still needs to be explored. The data used in this study are acquired from the Sentinel-1A SAR satellite imagery between January and May 2018 in which the occurrence of internal waves are the most frequent [34], and in accordance with the high damage of floating net cages arrays by the natural factors in southern coast of Weh Island. The characteristics of internal waves and their spatial distribution on the sea surface is analyzed from the Sentinel datasets, complemented by the results of ocean circulation modelling with the hydrostatic coastal regional ocean circulation modelling (CROCO) system to demonstrate barotropic tidal currents vectors and fluctuation of density of the seawater column around the internal tidal waves generation area. The results of the study are expected to provide information on the number of internal wave events and internal wave characteristics, such as waves packet, wavelength, current speed, spots where internal waves are generated, which can be used as input in building offshore facilities, such as oil refineries, floating fisheries net cages safety, and ocean and coastal spots with high primary productivity.

2. Materials and methods
The study area is located in the Weh waters and its adjacent seas, as shown in Figure 1a. The model domain of the ocean circulation model experiment is limited to geographic coordinates of 94.5°E-96°E and 5.25°N-6.25°N. The seabed topography in the study area is characterized by the existence of a seabed ridge extending from Breuh Island and Weh Island to the northwest direction, where a deep-sea canal is formed parallel to the ridge (Figure 1b).

The datasets in this study are obtained from the Sentinel-1A level-1 ground range detected (GRD) satellite image data with interferometric wide mode between January-May 2018, which were downloaded from the alaska satellite facility (ASF) web (asf.alaska.edu) and remote sensing application centre (RSAC) LAPAN. The input model forcing dataset were obtained from world databases [12],
including wind stress from the QuikSCAT scatterometer satellite (https://podaac.jpl.nasa.gov/QuikSCAT), sea surface temperature from AVHRR-Pathfinder (https://www.ncei.noaa.gov/access/AVHRR_Pathfinder-NCEI-L3C-v5.3), global bathymetry from GEBCO-30" (https://www.gebco.net/data_and_products/gridded_bathymetry_data/), atmospheric flux (heat flux, air-sea parameters, freshwater flux) from COADS05 (https://iridl.ldeo.columbia.edu/SOURCES/.COADS/), global tides from TPXO7 (https://www.tpxo.net/global), and seawater properties from WOA2009 (https://www.nodc.noaa.gov/OC5/WOA09).

Figure 1. Map of study area in Weh waters-northwest Sumatra and its adjacent seas. (a) red rectangles denote satellite imagery coverage. Yellow rectangle denotes model domain for CROCO configuration; (b) 3-dimension seafloor topographic map in the study area around the ridge of Breueh and Weh islands. Arrows denote schematic barotropic tidal current direction during floods and ebbs tide conditions.

3.1. Sentinel-1 satellite imagery
The Sentinel-1 is a satellite launched by the European Space Agency (ESA) and Copernicus. The Sentinel-1A satellite was the first mission launched on April 3, 2014, followed by a second mission, namely the Sentinel-1B satellite on April 25, 2016. Each satellite has a temporal resolution of 12 days and 175 orbits per cycle. The two satellites are placed in the same orbit so that their temporal resolution is 6 days globally. Sentinel-1 satellite uses C-band SAR which operates at a center frequency of 5405 GHz and an angle of incidence of 200-450. This satellite is designed to have a minimum active period of 7 years in its orbit [13].

The Sentinel-1 satellite can operate in four modes, including: interferometric wide mode, wave mode, strip map mode, and extra wide-swath mode (Table 1). Level-1 image data is divided into two types, namely Single Look Complex (SLC) and Ground Range Detected (GRD). SLC data is a focused SAR image that uses orbital and altitude data from satellites to geo-reference and view geometric slopes [14]. GRD data is a focused, multi-looked SAR image, and an earth ellipsoid model for the projection of a certain area. Multi-look is a SAR image processing technique to reduce speckle in the image. Polarimetric data Sentinel-1 is limited only by the combination (Horizontal Horizontal-Vertical Horizontal) and (Vertical-Vertical-Vertical-Horizontal) [15, 16, 30].
The Sentinel-1A satellite has a temporal resolution of 12 days to traverse the same region. This can be seen in Table 3 where after the satellite took pictures on January 19, 2018 it recorded again on January 31, 2018 at the same time. The satellite imagery used has an ascending (towards the north pole) and descending (towards the south pole) recording orbit. The average ascending orbit image is recorded by the satellite at approximately 11:51:00 UTC, while the descending type image is recorded at approximately 23:28:00 UTC. Ascending and descending images record the research area with different coverage areas.

Table 1. Sentinel-1 satellite operational products [30].

| Acquisition Mode          | Resolution Class | Resolution (Rz x Az) (m) | Pixel Space (Rz x Az) (m) | ENL   | Swath (km) |
|----------------------------|------------------|--------------------------|--------------------------|-------|------------|
| Strip map mode             |                  |                          |                          | 3.9   | 80         |
| Interferometric wide swath | HR               | 23 x 23                  | 10 x 10                  | 34.4  | 80         |
|                            | MR               | 84 x 84                  | 40 x 40                  | 464.7 | 80         |
| Interferometric wide swath |                  |                          |                          |       |            |
|                            | MR               | 88 x 89                  | 40 x 40                  | 105.7 | 250        |
| Extended interferometric   | MR               | 50 x 50                  | 25 x 25                  | 3     | 400        |
|                            |                  |                          |                          |       |            |

Note: Az (azimuth), ENL (equivalent number looks), FR (full resolution), HR (high resolution), Rz (range).

3.2. Internal wave detection mechanism from radar satellite

Surface features of internal waves can be detected by satellites and radar planes indirectly from variations in sea surface roughness. Internal waves are associated with surface current variables that modulate sea surface roughness. The theory that describes the modulation of small-scale sea surface roughness with surface current variables was developed within the framework of the weak interaction theory of hydrodynamics by [6, 17, 31]. When using this theory together with the Bragg scattering theory which relates the spectral values of the waves at sea level to the normalized radar cross section (NRCS), the relationship between NRCS and the surface pressure gradient \( \frac{dU_x}{dx} \) can be approximated by:

\[
\sigma = \sigma_0 \left(1 - A \frac{dU_x}{dx}\right)
\] 

(1)

The \( \sigma \) symbol is the total NRCS, \( \sigma_0 \) is the NRCS in the background, \( x \) is the look direction coordinate of the SAR antenna projected into the horizontal plane, and \( A \) is a constant determined by the radar wavelength, incidence angle, and relaxation rate. The bigger the internal wave amplitude, the bigger \( \frac{dU_x}{dx} \). Equation (2.5) and Figure 2(a) show that the NRCS value increases in the convergent flow zone \( \frac{dU_x}{dx} < 0 \) and decreases in the divergent zone \( \frac{dU_x}{dx} > 0 \), resulting in bands with the addition of and the reduction of the image intensity relative to the background, respectively [6, 16, 32].

Generally, the appearance of internal waves captured by radar images is non-linear and appears in the form of wave packets. The amplitude of the solitons in the wave packet decreases from the front to the back (Figure 2b). The formation of these solitons is associated with depression of the pycnocline layer and then associated with a convergent surface current region (increased Bragg wave amplitude). While behind it there is a divergent surface current region (decreased Bragg wave amplitude). Consequently, the intensity of the radar image increases at the front and decreases at the rear (Figure 2b). Therefore, the internal soliton of the pycnocline depression can be described by the SAR consisting of a bright sub-band at the front followed by a dark sub-band [2].
3.3. Satellite image processing

Image processing is carried out in several stages, namely pre-processing, post-processing, and lay outing. The pre-processing stage includes radiometric correction, geometric correction, filtering speckles on the image and eliminating land areas so that the extraction process only focuses on ocean areas. The post-processing stage includes digitizing wave crests, calculating wave parameters (length, direction of propagation, number of peaks, length of the first crest), and backscattering values. The lay outing stage is carried out to combine the digitized results of wave crests with a water bathymetry map. This image processing uses the sentinel application platform (SNAP) program and ArcGIS 10.4. Calculation of propagation angle using python syntax in ArcGIS with reference angle to the north.

Determination of the direction of propagation of internal wave packets from satellite imagery is done by making several auxiliary lines as in Figure 3a, following the method described by [14]. The first step is to digitize the wave crest in the form of an arc and draw a line to connect the two ends (lines A-B). Furthermore, from the centre point of the line A-B drawn a straight line to the north (N) as the initial angle (0 degrees). The last is to make a perpendicular line (C) with lines A-B and get the propagation angle of the internal wave packet (α).

The presence of internal waves in the seawater column can be detected by radar satellites from sea surface features seen from the backscatter value. Figure 3b shows the presence of internal wave packets (dark colour lines) in the satellite image with different shapes. The wave packets are digitized using the SNAP program and saved in shapefile format. The results of the extraction with the shapefile format are then opened in the ArcGIS program and superimposed on a bathymetric map so that the relationship between the presence or generation of internal waves with the topography of the seabed can be interpreted.
Figure 3. (a) Sketch of the estimated direction of internal wave propagation and (b) Sketch of the extraction of the internal wave crest from the Sentinel-1A satellite imagery.

3.4. Hydrostatic ocean general circulation model and model configuration
The CROCO modelling system uses a primitive equation defined in Cartesian coordinates, where the momentum balance is expressed in terms of the x and y axes, as described in detail in [12], as follows.

\[
\begin{align*}
\frac{\partial u}{\partial t} + \vec{u} \cdot \nabla u - f v &= - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + \nabla_h (K_{Mh} \cdot \nabla_h u) + \frac{\partial}{\partial z} (K_{Mv} \frac{\partial u}{\partial z}) \\
\frac{\partial v}{\partial t} + \vec{u} \cdot \nabla v - f u &= - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + \nabla_h (K_{Mh} \cdot \nabla_h v) + \frac{\partial}{\partial z} (K_{Mv} \frac{\partial v}{\partial z})
\end{align*}
\]

(2)

(3)

where \( u \) and \( v \) are 2-dimension velocity fields; \( \vec{u} \cdot \nabla u \) and \( \vec{u} \cdot \nabla v \) are advection forms, \( f \) is Coriolis parameter, \( \rho_0 \) is density, \( P \) is total pressure, \( h \) is mixed layer depth, \( K_{Mh} \) is horizontal mixing coefficient and \( K_{Mv} \) is vertical mixing coefficient. The equation of sea state is expressed as:

\[
\rho = \rho(S, T, P)
\]

(4)

where \( S \) is salinity and \( T \) represents temperature. Based on the hydrostatic approach it is assumed that the vertical pressure gradient will balance the buoyancy forces:

\[
0 = -\frac{\partial p}{\partial z} - \rho g
\]

(5)

where \( P \) is the total pressure and \( g \) is the acceleration due to gravity. The final equation expresses the continuity equation for an incompressible flow as follows:

\[
0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}
\]

(6)

Changes in temperature and salinity with time are calculated based on:

\[
\begin{align*}
\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T &= \nabla_h (K_{T_h} \cdot \nabla_h T) + \frac{\partial}{\partial z} (K_{Tv} \frac{\partial T}{\partial z}) \\
\frac{\partial S}{\partial t} + \vec{u} \cdot \nabla S &= \nabla_h (K_{S_h} \cdot \nabla_h S) + \frac{\partial}{\partial z} (K_{Sv} \frac{\partial S}{\partial z})
\end{align*}
\]

(7)

(8)

where \( u \cdot \nabla T \) and \( u \cdot \nabla S \) are advection, \( K_{T_h} \) is horizontal mixing for temperature and \( K_{Tv} \) is vertical mixing coefficient for temperature.

The model configuration consists of several steps, including pre-processing the data, compiling the model, running the model, and visualizing the output of the model. The pre-processing stage is an activity to enter global input data (such as bathymetry, sea surface temperature, wind stress, tides, seawater properties, and atmospheric flux) and set the general parameters of the model configuration (Table 2). The model domain is bordered by geographical coordinates of 94.5°E-96°E and 5.25°N-6.25°N with a resolution of 1/90° (1.23 km) which is set in the crocotools_param.h file. After adjusting the parameters used, then a grid model is created using the make_grid command.
The next step is to process variables as model inputs such as atmospheric forcing, surface temperature, climatological conditions, initial and lateral open boundary conditions. Variable processing of global data for model input using commands like make_forcing, make_tides, pathfinder_sst, make_clim, make_bry, make_ini. Then, set the forcing model in the cppdefs.h file and adjust the grid in the crocotools_param.h file with param.h. Next is the compilation stage which aims to combine the input data that has been arranged in the data pre-processing stage. Model compilation is done with the jobcomp command using the gfortran compiler. Before running the model, it is necessary to configure several parameters such as time step, number of barotropic, and number of average time step (Table 2). The next stage is to running the model according to the specified configuration. The length of the model simulation is three months (January-March) with spin up one month. The model output dataset are saved for the averaged data every half hour. The model output is visualized using MATLAB with the croco_gui command.

### 3.5. Tidal ellipse of tidal current

The tidal data used to generate the tidal ellipse are obtained from the TPXO7 tidal data prediction, which are entered into the model to generate tidal currents in the form of a tidal ellipse parameter. Tidal currents are periodic so that they can be separated into basic harmonic components with the least square fit method. The velocity components are represented by the average current and the sum of the harmonic components of the current as follows [18]:

\[
\mathbf{u}(r, t) = \langle \mathbf{u}, \mathbf{b} \rangle + \sum_{i=1}^{N} \frac{a_i(t) \cos(\omega_i t)}{2}\left(\cos(\phi_i r) \mathbf{i} + \sin(\phi_i r) \mathbf{j}\right) + \frac{b_i(t) \sin(\omega_i t)}{2}\left(-\sin(\phi_i r) \mathbf{i} + \cos(\phi_i r) \mathbf{j}\right)
\]

where, \(\mathbf{u}(r, t)\) is the averaged current, \(\phi_i\) is the position vector, \(a_i\) and \(b_i\) are the amplitude, \(t\) is the time, \(\omega_i\) is the frequency of the tidal component, and \(N\) is the sum of the tidal components. Before being executed by least square fit, the data is multiplied by the Gaussian weighting function with the following equation:

\[
\phi(r, r_j) \sim \exp\left\{-\frac{(x-x_j)^2}{\sigma_x^2} - \frac{(y-y_j)^2}{\sigma_y^2}\right\}
\]

where, \(\phi(r, r_j)\) are knot points positions, \(\sigma_x\) and \(\sigma_y\) are decay parameters that control the shape of the Gaussian curve. Tidal currents are generated from 10 tidal components extracted from TPXO7 data, including principal lunar (M2), principal solar (S2), larger lunar elliptic (K2), luni solar (N2), luni solar (K1), principal lunar (O1), principal solar (P1), lunar fortnightly (Mf), lunar monthly (Mm), and solar semiannual (Ssa). The results of tidal current extraction are described in the form of a tidal ellipse parameter.
parameter consisting of a semi-major and semi-minor axis representing the maximum and minimum current velocity, the inclination is the anticlockwise angle between the east and the semi-major axis [19].

3.6. Model validation
The model outputs need to be validated with observational data to determine the level of model accuracy, by calculating the correlation value between the two datasets. Validation is carried out through correlation analysis between sea level predictions from the Geospatial Information Agency (BIG) predictions with the model output dataset. The predictive value of BIG was used because of the limited observational data at the study site. The value of the correlation coefficient was determined by following the equation of [18, 20]. In addition, the root mean square error (RMSE) value is also calculated to determine the difference between the sea level height value from the model and the datasets of the BIG, following [18].

The correlation between the sea level of the model output and the prediction data from the BIG (Figure 4) revealed a correlation coefficient value of around 0.90. This shows a significant correlation between the two datasets, so the model output can be used for further analysis. The calculation result of the RMSE value is 0.08, so the model output is quite good in describing the conditions in the field. Prediction data point retrieval and model output are adjusted to the location of the real time tidal measurement station in Sabang port-Weh island.

3. Results and discussion
3.1. Internal waves characteristics from Sentinel-1A imagery
The presence of internal waves detected from SAR (Synthetic Aperture Radar) satellite imagery is in the form of light and dark lines indicating variations in sea level roughness [17]. Variations in sea level roughness can be caused by the presence of convergent and divergent current patterns which are influenced by internal wave activity in the lower layers [21]. High sea level roughness due to surface waves reflects more electromagnetic wave energy than calm sea levels. This makes the rough sea face look like a light colored line, while the calm sea level looks like a dark line in the image [14].

The Sentinel-1A image on January 31, 2018 (Figure 5a) shows the presence of an internal waves packet that displays a propagation direction to the southeast with an angle of 104°. The position of the internal wave packet is in the area between the ridge extending from Breuh and Weh islands (Figure 5b). The pixel intensity profile was extracted from the radar backscatter ($\sigma_0$) value (Figure 5c). These internal wave packets have an arc-like type of shape, hence the name arc-like type internal waves. In the wave packet there are 9 solitons, if you draw a line plot (AA') it will produce a backscatter value which has 9 wave crests (red line). The backscatter value in the wave packet is the largest for the first soliton. The average wavelength between solitons is 2,099 km and the length of the first peak/soliton is 35,671 km. The satellite on May 31, 2018 (Figure 6a and 6b) captured a wave packet that was in the same position as January 31, 2018 but only had 6 solitons. The package has a propagation direction to the southeast at an angle of 104,509 degrees. The average wavelength between solitons is 2.51 km and the
length of the peak/first soliton is 25,019 km. Figure 6c is a backscatter profile along the line AA’ which has a high value at the soliton location.

Figure 5. (a) Sentinel-1A imagery acquired on January 31, 2018. (b) Extracted soliton superimposed on the bathymetric map. (c) Pixel intensity profile along the line plot AA’.

Figure 6. (a) Sentinel-1A imagery acquired on May 31, 2018. (b) Extracted soliton superimposed on the bathymetric map. (c) Pixel intensity profile along the line plot AA’.
Figure 7. (a) Image of Sentinel-1A acquired on April 14, 2018 when the crescent phase is shrinking. (b) The extracted soliton is superimposed on the bathymetric map. (c), (d), (e) Pixel intensity profile along the line plot AA’, BB’, CC’.

Sentinel-1A image on April 14, 2018 (Figure 7a) shows the presence of three internal wave packets where all three have a direction of propagation to the southeast with angles from the first to the third packet are 97.653°, 98.53°, and 96.024°. The position of the first wave packet is farthest from the ridge and the third packet is closest to the ridge (Figure 7b). The pixel intensity profile was extracted from the radar backscatter ($\sigma_0$) value. The backscatter value in the third package (Figure 7c) is greater because it is near the generation region. Meanwhile, the backscatter values of the second (Figure 7d) and first (Figure 7e) packets are smaller because they are far from the ridge. The further away from the generating area, the energy of the internal wave will decrease and gradually evolve into a solitary-like wave [22], so that the backscatter value is smaller. The first and second wave packets have arc-like internal waves, while the third packet has irregular internal waves. The first wave packet has 3 solitons, the second package has 1 soliton, and the third package has 17 solitons. The average wavelength between solitons in the first and third packets is 8,998 km and 1,056 km, respectively. The lengths of the first peaks/solitons in the first to third packages are 91.96 km, 51,203 km and 29,383 km, respectively.

3.2. Spatial-temporal distribution and direction of internal waves propagation
The spatial-temporal distribution of internal waves in Weh waters from 12 Sentinel-1A imageries between January and May 2018, overlaid with bathymetric maps to show the effect of seabed topography changes (Figure 8). The distribution of internal waves is divided into three areas: the generating area over the ridge, propagating area in the northeast and far-east of Weh island, and very far from the ridge and Weh island. In addition, the wave packets far from the ridge have a longer crest/soliton length than the wave packets near the ridge (Figure 8).

The ascending image records from the waters of Weh Island to the far east, while the descending image records from the west to the eastern waters of Weh Island. This causes the ascending image to record more internal wave packets than the descending image.

The internal wave packet with the largest average wavelength occurred on April 14 2018, which is around 8,9985 km. The image on March 21, 2018 with the length of the first peak and the number of solitons is 163,355 km and 31 solitons, respectively, where the two values are the largest of all existing images. These results are in good agreement with the study of [34] which stated that the most internal waves in the Andaman Sea were found in March, February and April. The highest occurrence of the
soliton waves in March-April in eastern boundary of Andaman Sea is perhaps associated with an interaction of very strong semidiurnal barotropic tidal current over the Breuh ridge, a relaxation of the monsoonal winds that create much stronger stratification of seawater temperature, and a modulation of the arrival of semiannually remotely forced downwelling Kelvin waves from the Equatorial Indian Ocean along the eastern boundary of Andaman Sea [35]. However, this hypothesis needs to be further investigated in the near-future works. There are 3 wave packets spread over three locations with different numbers of solitons (Figure 8). The wave packet that is near the generation region (ridge) has 9 solitons with a propagation direction of 96°. The second wave packet has 16 solitons with a propagation direction of 98°. According to [23], increasing depth can cause an increase in the number of solitons and a change in the direction of the wave packet.

![Figure 8](image)

**Figure 8.** The cumulative spatial-temporal distribution of internal waves, from the Sentinel-1A image in January - May 2018 overlaid with a bathymetric map.

| Wave packet | Date     | Time (UTC) | Average Wavelength (km) | Number of Soliton | First Peak Length (km) | Direction (°) |
|-------------|----------|------------|-------------------------|-------------------|------------------------|---------------|
| 1           | 19/1/2018 | 23:27:49   | 1.7                     | 8                 | 26.3                   | 76            |
| 1           | 31/1/2018 | 23:27:49   | 2.1                     | 9                 | 35.7                   | 104           |
| 1           | 1         | 1.8        | 9                       | 25.2              |                        | 109           |
| 2           | 1/2/2018  | 11:51:01   | 4.1                     | 14                | 78.4                   | 95            |
| 1           | 20/3/2018 | 23:27:49   | 1.2                     | 15                | 14.2                   | 78            |
| 1           | 1         | 1.7        | 9                       | 13.3              |                        | 96            |
| 2           | 21/3/2018 | 11:51:01   | 3.2                     | 16                | 69.6                   | 98            |
| 3           | 3         | 3.9        | 6                       | 163.4             |                        | 96            |
| 1           | 01/4/2018 | 23:27:49   | 1.7                     | 8                 | 28.4                   | 103           |
| 1           | 02/4/2018 | 11:51:01   | 1.0                     | 12                | 21.0                   | 109           |
| 1           | 13/4/2018 | 23:27:50   | 1.1                     | 6                 | 42.1                   | 107           |
| 1           |           | 1.1        | 17                      | 29.4              |                        | 96            |
| 2           | 14/4/2018 | 11:51:02   | -                       | 1                 | 51.2                   | 99            |
| 3           | 3         | 9.0        | 3                       | 92.0              |                        | 98            |
| 1           | 19/5/2018 | 23:27:51   | 1.5                     | 6                 | 34.7                   | 65            |
| 2           | 20/5/2018 | 11:51:04   | 5.0                     | 2                 | 13.3                   | 99            |
| 1           | 31/5/2018 | 23:27:52   | 2.5                     | 6                 | 25.0                   | 105           |

Mean & stdev 3.0 (±2.3) 8.2 (±4.8) 49.2 (±38.8) 96.1 (±11.5)
3.3. Model amplitude and ellipse of diurnal (K1) and semidiurnal (M2) tidal components.

The tidal ellipses were obtained by processing the amplitude and phase values of the zonal (u) and meridional (v) current components (Figure 9). The figures are only the amplitude and ellipse for the K1 (diurnal) and M2 (semidiurnal) components which are the most dominant components. Figure 9a shows small tidal ellipses in the ridge region and around the narrow passage between Breuh island and Sumatra mainland. The magnitude of the amplitude of the K1 component in the area within the box ranges from 0.08-0.12 m. Overall, the amplitude in the model area is highest in the Malacca Strait (0.16 m), while the lowest in the Indian Ocean (0.08 m).

Figure 9b also shows large tidal ellipses in the region of the narrow ridge and crevice. The amplitude of the M2 component in the inner region of the box ranges from 0.3-0.55 m. In the model area, the highest amplitude is also in the Malacca Strait (0.65 m) while the lowest is in the Indian Ocean (0.15 m). The tidal ellipses are seen more clearly in the waters of Weh to the north of Sumatra and around the Malacca Strait. The tidal ellipse's amplitude gets smaller as it enters the Andaman Sea and the Indian Ocean.

The tidal ellipses shape indicate that the direction of the tidal currents moves predominantly following its longest diameter which is called the semi-major axis. In addition, the tidal type in Weh waters tends predominantly semidiurnal because the amplitude of the M2 component (semidiurnal) is larger than the K1 component (diurnal). According to study by [24] and [1] the tidal pattern in Aceh waters is semidiurnal and mixed tide predominantly semidiurnal.

![Figure 9](image1.png)

**Figure 9.** (a) The shape of the tidal ellipse and the amplitude of the K1 (diurnal) tidal component in the model region. The red box is the study area; (b) The shape of the tidal ellipse and the amplitude of the M2 (semidiurnal) tidal component in the model region. The red box is the study area.

3.4. Circulation of tidal current

The circulation pattern on the tidal time-scale at a depth of 40 meters in the area around the ridge varies according to the tidal conditions. Tidal forcing from the Indian Ocean, Bay of Bengal, and Andaman Sea controls the tidal dynamics of Weh waters [1]. During high tide conditions (Figure 10a), the tidal current flows northeastward and eastward at velocity of 4-7 m/s. The same thing also happened during high tide conditions (Figure 10b), the direction of current movement tends to these directions but the speed was reduced to about 4-6 m/s. On the other hand, during low tide conditions (Figure 10c) and low tide towards high tide (Figure 10d), the direction of current movement changes to be southwestward and westward. Current velocity during low tide conditions ranges from 4-6 m/s and at low tide to high tide conditions ranges from 2-5 m/s. The dominant direction of current in the ridge area moves back and forth, namely the southwestward and northeastward flow directions.
The movement of alternating currents is due to changes in bathymetry and sea level elevation [25]. When barotropic tidal currents flow over coarse topographic features, some of their energy will be used for local mixing and some will be converted into baroclinic energy through internal tidal generation [3]. According to [26] the M2 tidal wave component at the study are propagates from the Andaman Sea to the Natuna Sea through the Malacca Strait.

The highest current velocity during high tide conditions (Figure 11b) and low tide towards high tide (Figure 11d) is right above the ridge with a value of 5-5.5 m/s. Current velocity is lower during high tide (Figure 11a) and low tide (Figure 11c) to 4.5-5 m/s. A column of water that has a high current
velocity during high and low tides from the surface to a depth of 100 m (end of the ridge). The value of the current velocity can be maximum at high tide conditions towards the lowest ebb and also at low tide towards the highest tide [27].

3.5. Seawater density distribution and vertical velocity

The cross-section of seawater density profile from the west (left) to east (right) ridge at different tidal conditions reveals stratification changes. The mass density of water in the area ranges from 1,022-1,032 kg/m³, where from the surface to the bottom layer the density is getting bigger. During high tide (Figure 12a) and low tide (Figure 12b), there is a pycnocline depression/reduction in the eastern (right) ridge. On the other hand, during low tide (Figure 12c) and low tide (Figure 12d) the pycnocline depression/decrease was found in the west (left) ridge. The decrease in pycnocline during high tide conditions occurs to a depth of 500 m and then increases when high tide conditions go down to a depth of 900 m.

The uplifted pycnocline that occurs during low tide conditions to a depth of 400 m and deepened during low tide conditions to 900 m take place because of the interaction of current with the ridge. According to [2] internal waves can be formed due to disturbances which are generally caused by tidal currents that push layers of water mass across obstacles on the seabed such as seamounts and ridges. The decrease in the pycnocline is related to the internal wave characteristics detected by the radar satellite imagery.

The vertical velocity cross-section is extracted in the specific area, based on the generating location and internal wave propagation captured by the Sentinel-1A satellite imagery (Figure 13a). The vertical velocity in the ridge area or generating area that extends from Breueh to Weh islands waters has a negative value range of 0.3-0.5 m/s. While in the propagation area, it has a positive value range of 0-0.1 m/s. When viewed cross-section in Figure 13b, there are two ridges that have a strong negative vertical velocity at the top up to -0.5 m/s.

According to [28] the negative vertical velocity value represents the movement of the current vertically against the direction of gravity (upwards). The interaction between barotropic tides and seabed topography is one of the main sources of internal wave generation in the ocean. Barotropic tidal currents that cross the topographical slope of the seabed and produce a vertical velocity component that displaces water mass particles, thereby generating internal waves [29].
4. Conclusion

The internal waves detected by radar satellites are expressed by wave packets consisting of number solitons. The spatial distribution of internal waves, based on the results of radar imagery analysis, is grouped into three areas, namely generating area around the ridge, propagating area off the northeast coast and far east of Weh waters. The backscatter value of the radar signal is strongest around the ridge (generating area) and weakens further away from it. The distance between wave packets varies between 60-80 km, the estimated wavelength ranges from 9-163 km, and the maximum number of internal waves of 31 solitons was observed on March 21, 2018. The main forcing of internal waves along the ridge by barotropic tidal currents from the semidiurnal component (M2) with the orientation of the M2 ellipse semi-major axis to the northeast (flood tide) and to the southwest (ebbs tide) with amplitude of sea level elevation and tidal current magnitude are 0.5 m and 5 m/s, respectively. The passage of the tidal current at flood tide from the Indian Ocean that impinges the seabed ridge experiences a very drastic amplification, some of which flows into the passage waters between Weh-Breueh and Sumatra mainland, and partly flows in the north side of Weh island to the east and is deflected to the southeast. The direction of flood tide (ebb tide) is northeastward (southwestward). The cross-section seawater density profile controls stratification changes due to a shallow in the pycnocline as the current moves across the ridge. The cross-section vertical velocity profile also shows a strong upward current movement over the ridge. Those are cause the formation of internal waves in the Weh waters, especially around the seabed ridge that extends from Breuh to Weh islands, so that they are detected clearly from radar satellite imagery.

Further study is needed to complement phase parameters of internal wave velocity from radar imagery and extend the imagery dataset for one year in order to observe number of solitons during different monsoon period. It is also needed to configure non-hydrostatic numerical modelling experiment, so that the vertical density and pressure fluctuation profiles are more clearly visible.
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