Article

Internal solitary waves observation and feature extraction based on wavelet transform by Sentinel-1A in Lombok Strait, Indonesia

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Abstract

Lombok Strait is an essential pathway in trans-oceanic water mass transport. The water mass transport flowing over Indonesian waters, known as Indonesian Throughflow (ITF), transfers warm water mass from the Pacific to the Indian Ocean annually. Lombok Strait has intensive characteristics of the internal waves (IWs) generation due to the strong current that passes through the complex bathymetry along the strait area. IWs with large amplitude and nonlinear properties are known as Internal Solitary Waves (ISW) that can be detected by Synthetic Aperture Radar (SAR) images. A Wavelet Transform method for ISW feature extraction was applied to SAR images by Sentinel-1A (C-band). ISW packet characteristics can be distinguished from other phenomena based on their geometrical structure and shape. ISW packet pattern consists of light and dark lines which intensity decrease from front to rear. SAR observation detected 5 parameters, including phase speed, soliton numbers, wavelength, first crest length, and propagation direction. The arc-like ISW in the Lombok Strait propagated to the North of the sill with the average phase speeds of about 2.13 m/s and was frequently detected during the northwest monsoon (NWM). The detected soliton number was less than 6 solitons per packet with a wavelength of about 1 – 4 km, and the first crest length varies from about 12.16 km to more than 100 km. ISW detected in Sentinel-1A images were located at the bathymetry of about 800 meters, around the Lombok Strait area.

Keywords: *internal solitary waves; Lombok Strait; Sentinel-1; Wavelet*

1. Introduction

Internal waves (IWs) are waves that propagate within the interior of fluid (Alpers, 2014). When the fluid is stratified, these waves can generate both in the ocean and atmosphere. In the ocean, fluid stratification is usually occured due to solar radiation on the surface layer. In order to generate IWs, the interface between the layers must be disturbed. The disturbance is usually caused by the tidal current, which flows over rough bathymetry (Apel, 1988). IWs propagate on the interface between the two layers of different densities as the surface waves propagate on the interface between water and air. IWs in the oceans are usually non-sinusoidal and non-linear, with complex shapes of solitary waves which often identify as solitary waves or soliton. IWs with non-linear properties are called Internal Solitary Wave (ISW). ISW generate in stratified oceans as a group or packet wave, with the number of waves varying from low to high frequency, depending on the period and distance from the generating site.

IWs are different from surface waves. IWs are not related to the elevation of sea surface but related to a variable surface of current that modulates the sea surface roughness (Alpers, 2014). Synthetic Aperture Radar (SAR) can detect slight changes that occur on rough sea surfaces, with wavelengths of several centimeters to decimeters. This instrument can capture the IWs with the roughness patterns. SAR is the most commonly used instrument for monitoring IWs from space. It enables the operation in all-weather conditions, day and night, and has a wide range of up to 250 km. Sentinel-1 is an advanced mission instrument C-band operation of the satellites European Remote Sensing (ERS) 1/2 that have a better temporal resolution than previous missions. The rapid development of SAR technologies and the exponential increase of SAR data prompted us to find a faster and more automated method to automatically filtering IWs information on SAR images and extracting IWs features. Several wavelet analysis applications have been applied to various satellite images and demonstrated the ability of this method for coastal monitoring (Liu et al., 1997). He et al. (2006) proposed an internal wave feature extraction algorithm based on stationary wavelet transform in SAR oceanic surface images. The algorithm incorporates a morphological thinning algorithm and threshold technique. This refinement step enhances the accuracy of the detected internal waves in SAR images.

Lombok Strait is an essential pathway in trans-oceanic water mass transport. The current that crosses Indonesian waters is known as Indonesian Throughflow (ITF), which plays a role in the transfer of warm water masses from the Pacific Ocean to the Indian Ocean annually. In shallow waters between the Nusa Penida and Lombok islands, there is a sill with depth of less than 350 meters. With a large tidal current, Lombok Strait has intensive characteristics of the ISW generation. ISW in the Lombok Strait is generated in stratified water by tidal flows over the sill area (Susanto et al., 2005). The appearance distribution of ISW in SAR images over a long period can be used to estimate the characteristics and dynamics of ISWs in the Lombok Strait.

Lombok Strait has an intensive characteristic of the ISW generation due to the strait water stratification, rough bathymetry, and strong tidal flows. The ISW generation and propagation are controlled by the background flow related to the ITF, water stratification, and tidal conditions in this area. Characteristics and dynamical parameters of IWs in the Lombok Strait have been identified using SAR images (Karang et al., 2012, 2019; Matthews et al., 2011; Mitnik et al., 2000; Mitnik, 2008). ISW packets in this area have been observed using SAR images from ERS-1/2 and showed that the nonlinear solitary waves are generated by tidal flows over the irregular sill area. Propagation speeds estimation about 1.8–1.9 m/s (Mitnik et al., 2000). ISW generated in the Lombok Strait propagates in three different directions: southward only, northward, and in both directions (Visser, 2004). Investigation of the ISW characteristics in Lombok strait concerning the dominant monsoon seasonality using satellite imagery and numerical modeling then introduced two fundamental wave types identified in Lombok Strait, which are often called arc-like ISW that spread to the northern part of the strait and the ISW irregular spread in the southern part of the strait (Matthews et al., 2011).

This study applies the wavelet transform for images using Sentinel-1A images in Lombok Strait to extract ISW features (Chonnaniyah et al., 2019). The wavelet transform is expected to make the ISW feature extraction processing time more efficient. The result of ISW feature extraction on Sentinel-1A imagery is expected to provide an overview of ISW spatial-temporal distributions and estimate the parameters at Lombok Strait. Temporal distribution was observed for three years (2015-2017) to analyze the seasonal effect on the detection of the ISW.

2. Materials and Methods

2.1 Research Location

Sentinel-1 is a radar imaging mission that provides continuous weather imaging throughout the day and operates at a central frequency of 5.405 GHz and an angle of 200 – 450 (ESA Team, 2013). The Sentinel-1 mission operated with C-bands imaging (wavelength 3.8 - 7.5 cm) has four imaging modes with different resolutions (reaching 5 m) and coverage (up to 400 km), provides dual-polarization capability, improvement of the revisit times, and rapid product delivery. Sentinel-1 provides improvement data from the previous C-band SAR Earth Observation of ESA's, i.e., ERS-1, ERS-2, ENVISAT, Canada's

ADARSAT-1, and RADARSAT-2. Precise measurements of spacecraft position and attitude are available for each observation data.

Interferometric Wide swath mode used in this study acquired data with a 250 km swath at 5 m by 20 m spatial resolution. Interferometric Wide mode records the target in three sub-swaths using Terrain Observation with Progressive Scans SAR (TOPSAR). This technique can produce a homogeneous image throughout the swath. The suitable swath range for the ISW monitoring over the Lombok Strait area (114.96° – 117.43°E and 7.53° – 9.16°S) is shown in Figure 1.

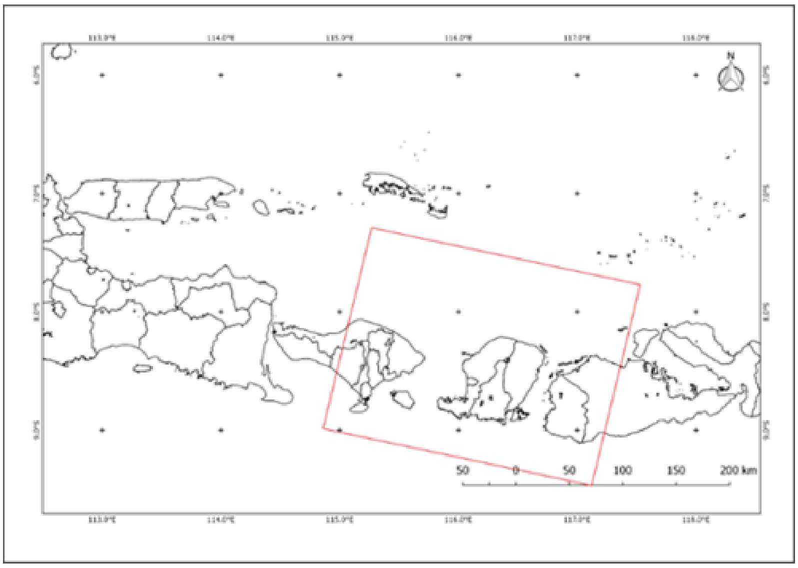

Figure 1. Research location

The Sentinel-1 images can be downloaded from the Copernicus website (https://scihub.copernicus.eu/). This study used descending orbit data during the sensing period of 2015 – 2017. The polarization used is VV on GRD product type and IW sensor mode. Fifty-four images were downloaded during the period of 2015-2017. All these images were then scanned to select an image with an ISW pattern. Only 16 images were chosen because they have an obvious ISW pattern. These 16 images were then processed for feature extraction. General Bathymetric Chart of the Oceans (GEBCO) data were used to show the variation of ISWs feature extraction to the bathymetric contours. Tidal elevation prediction was downloaded from the Online Tidal Prediction of Badan Informasi Geospatial (BIG) website at the sill area (115.7351° E and 8.7762° S).

2.2 ISW feature extraction

The stationary wavelet transform was used to isolate detected ISW features on Sentinel-1A imagery in the Lombok Strait area. The ISW feature extraction process in this research was divided into three steps. The first step is pre-processing, the initial stage for SAR image processing. The pre-processing step includes radiometric calibration, geometric correction, speckle filter. Land-sea mask was also used to dispose of land data so that the extraction process focuses only on the oceans. The next stage is the de-noising step that was processed after transforming the image using wavelet transform. The fundamental steps of the stationary wavelet transformation for image feature extraction include selecting a wavelet filter, decomposing the image into approximation, and detail coefficients at various scales and orientations, choosing coefficients that capture the desired features, extracting those selected features, and potentially reconstructing an approximation of the original image. The stationary wavelet transform used wavelet filters to analyze and extract features from images. The result of this de-noising process will be used as the input image at the ISW feature extraction next step. The ISW feature extraction process uses a gradient operator to detect changes in the pixel value of the image. The final step of the extraction process was a mathematical morphological process that separated ISW line features with extracted small objects. The ISW feature extraction method is described in Figure 2.

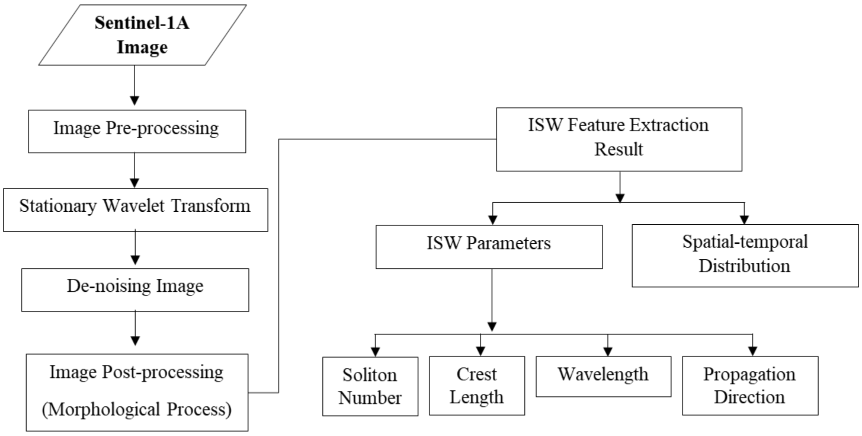

Figure 2. Research scheme

2.3 Parameters estimation

Studies of the ISWs propagation is an important mechanism to determine the hydrodynamics of the Lombok Strait. SAR images can be used to estimate several parameters related to ISW characteristics. These parameters are the phase speed, soliton numbers, wavelength, first crest length, and propagation direction. A wave packet is defined as a set of some of the soliton with the brightest intensity on the front and is reduced to the rear.

Soliton number is the number of bright lines detected in SAR images. Soliton number was estimated by calculating the extracted line representing a bright band. The ISW wavelength was estimated by calculating the distance between two adjacent lines in one packet. The first crest (leading soliton) was the soliton at the front in one package and had the brightest intensity of the other solitons. The length of the first crest was measured by the distance between the two brightest ends of the soliton. Phase speeds of ISW were defined as the group velocity of a wave packet when propagating. Phase speeds were estimated by the spatial difference between the two wave crests in one image divided by period. The time difference between the two packets of IWs in the Lombok strait area was in the period of the dominant tide, specifically semidiurnal (M2) which has a period of 12.42 hours.

The propagation direction is defined as the direction of propagation angle of the packet wave towards the North. ISW propagation direction in the Lombok strait seems to be spreading northward and southward of the sill location, but when this wave is on the outside of the strait, there is a wave deflection at a certain angle. The extraction method of the propagation direction of ISW from the significant wave crest of packets using a simple method has been introduced (Gao et al., 2018). To get the propagation direction, in Figure 3, curve AB is the wave crest, point C is the midpoint of the straight line AB, transect line CD is perpendicular to line AB, and angle" a" is the angle between the propagation direction and the North direction.

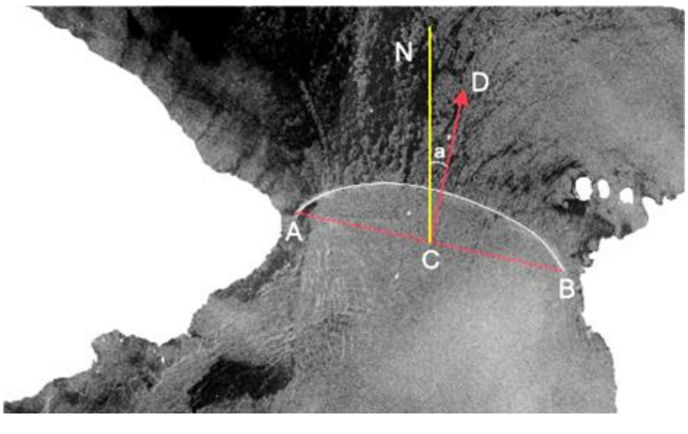

Figure 3. The ISW propagation direction extraction sketch

3. Results

The Sentinel-1A level 1 GRD interferometric wide mode images show that the significant signatures of ISW were observed in the Lombok Strait during the study period. The most apparent Manifestation of ISW in Lombok Strait propagates from the generation site to the northward and southward found in Sentinel-1A images. Figure 4 recorded by Sentinel-1A on April 8, 2016, at 18:41 (local time), shows two packets of ISW propagating north into the Flores Sea and south into the Indian Ocean. The observed ISW was assumed to be generated by the interaction between the consecutive tidal currents and the shallow sill.

a) b)

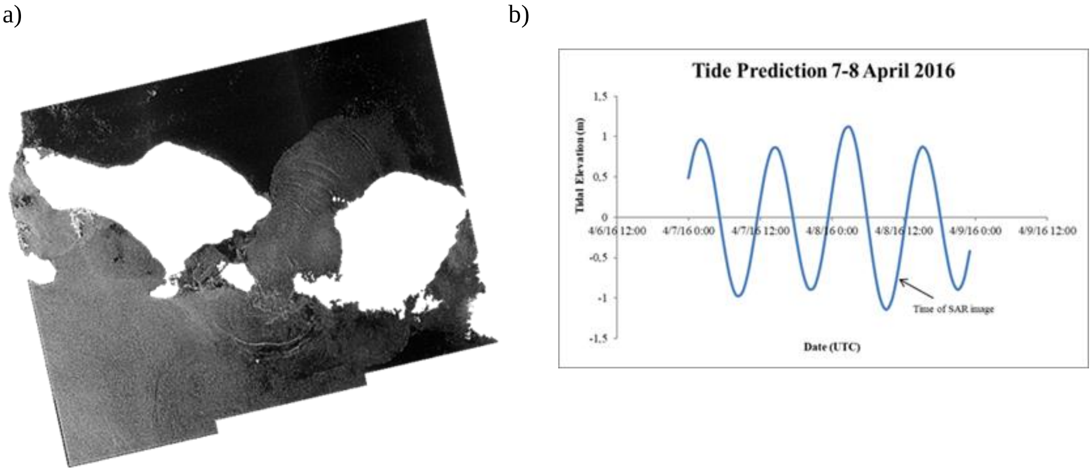

Figure 4. (*a*) Sentinel-1A imagery of the Lombok Strait recorded on April 8, 2016, at 10:41 (local time); (*b*) Tide prediction at sill area in Lombok Strait.

The spatial-temporal distribution map was created by placing all the ISW feature extraction results at their corresponding locations overlapped with bathymetric contours of Lombok Strait from GEBCO, shown in Figure 5. The observation results show that the ISW packet propagation is distributed northward and southward of the ISW generation areas sill in the southern part of the strait. The ISW feature extraction results by Sentinel-1A showed that ISW was detected more in areas between Bali and Lombok Islands; only few wave packages were detected in the northern part of the strait into the shallow waters around Kangean Island.

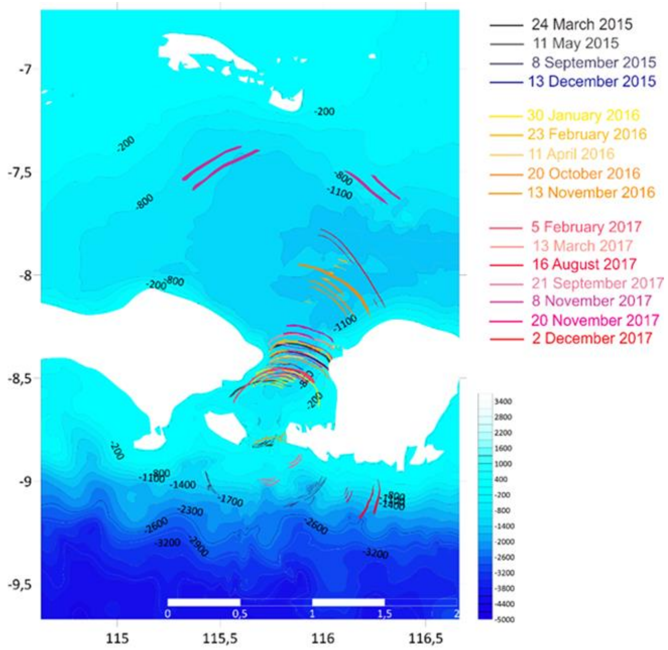

Figure 5. Spatial-temporal distributions map of ISWs extraction results in the study area by Sentinel-1A images during 2015 – 2017 overlapped with bathymetric contours from GEBCO.

The soliton number extracted in this study is less than equal to six solitons. The results of Sentinel-1A image extraction in this study mostly only have one wave packet per image. The wavelength in a packet around the strait was about 1-2 km and increases about 3-5 km in open waters (Flores Sea). The first crest detected in the enclosed strait area is about 30-40 km long and was enlarged to more than 100 km from open waters to shallow waters near Kangean island. The dynamical parameters of these ISWs based on 16 Sentinel-1A images are summarized in Table 1.

Table 1. Dynamical parameters of northward and southward propagating ISWs in the Lombok strait, estimated using Sentinel-1A images

Date	Internal Solitary Waves Parameter					
	Monsoon / Period	Soliton Number	Wavelength (km)	First Crest Length (km)	Propagation Direction (degree)	Bathymetric Location (m)
Northward-propagation						
March 24 2015	NWM	1	-	32.27	12.15	800
December 13 2015	NWM	4	4.65	34.04	15.24	800
January 30 2016	NWM	6	2.44	33.60	25.76	800
February 23 2016	NWM	4	5.28	33.46	8.47	1200
February 05 2017	NWM	3	2.02	43.54	-13.56	800
March 13 2017	NWM	3	4.76	37.18	4.81	800
November 20 2017	NWM	6	4.19	34.22	18.64	1200
December 02 2017	NWM	2	3.20	60.27	50.38	1350
Average			**3.79**		**18.63**	
October 20 2016	SNT	5	3.29	34.21	18.27	800
November 13 2016	SNT	4	4.34	-	35.53	1350
November 08 2017	SNT	2	5.92	113.74	6.17	1200
Average			**4.52**		**19.99**	
May 11 2015	NST	3	1.14	32.63	-14.62	600
April 11 2016	NST	2	3.53	35.02	19.98	800
Average			**2.34**		**17.30**	
Southward-propagation						
September 08 2015	SEM	6	1.05	-	145.9	1650
August 16 2017	SEM	5	3.23	-	94.12	1050
September 21 2017	SEM	3	1.71	12.16	149.07	1050
Average			**2.00**		**129.70**	

4. Discussion

The radar signature of ISW detected in Figure 4. a) is shown as an arc-like shape in both directions. About six crests are seen on the SAR image in Figure 4. a) spread northward, and about three crests spread southward of the sill. The southward-propagating ISW have brighter radar signatures than those propagating northward. The first crest location can be seen clearly in this image. The propagation packet to the south is assumed to generate at the same time as the second north propagation packet; the packet that propagates to the south is half the speed of the packet northward. The speed difference is due to differences in the stratification of waters between the two oceans.

The extracted wave type is arc-like, a characteristic of ISW in the Lombok Strait. The extracted feature is an ISW feature that has a strong radar signature. Temporally, ISW features are frequently extracted during the northwest monsoon (NWM) when the southward current of the ITF is not strong. These results are consistent with the numerical simulation and SAR imagery from ERS 1/2 and PALSAR (Matthews et al., 2011). The ISW that propagates to the southern part of the sill will be deflected following the bathymetric contours of Indian Ocean waters. ISW propagates to the south and occurs during the southeast monsoon (SEM) when the southward throughflow is intermittent. ISW detection dates are sorted into four seasonal categories. SEM from May 15 to October 15, southeast to northwest transition (SNT), NWM from November 15 to March 31, and northwest to southeast transition (NST) (Matthews et al., 2011).

The propagation direction angles of 16 images are listed in Table 1. In the northern part of the sill, generated ISW almost all toward the North with an average propagation direction angle of about 18.34°. The extracted ISW is located more at the bathymetric contours, about 800 meters when the ISW is still around Lombok Strait. Figure 6. (a) is an image with two ISW packets detected. Compared with the tidal prediction in Figure 6. (b), the Sentinel-1A image is taken after the full spring tide. Packet 1 is assumed to generate from the tidal interaction before the image recording time. Based on the current measurements using moorings placed near the sill window, tidal flow is predominantly semidiurnal (Murray et al., 1990). Therefore, the intermediate phase speed can be calculated by calculating the distance between consecutive wave packets. The distance between packets on the image taken on March 13, 2017, is 95.08 km. Thus, the average phase speeds of 2.13 m/s were estimated from the $V = \Delta L/T$ equation, where $T = 12.42$ hours is the semidiurnal tidal period. This observation result agrees well with previous studies' investigation (Ningsih et al., 2008; Susanto et al., 2005).

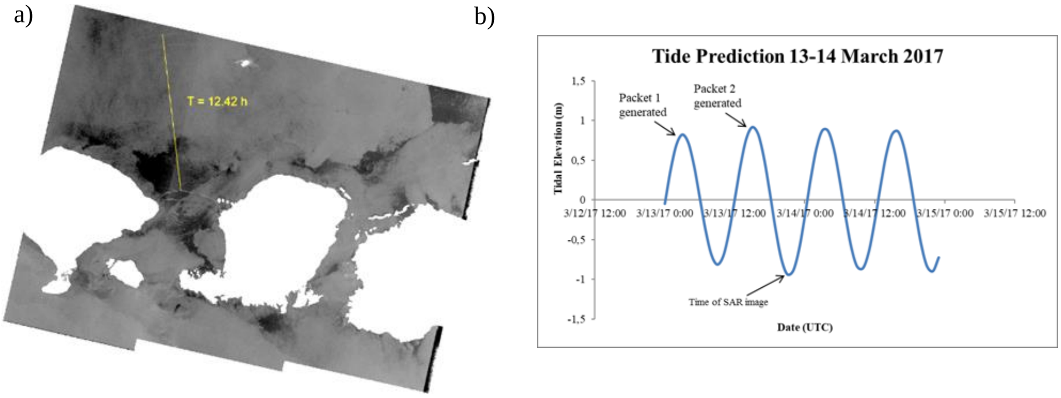

Figure 6. (a) Sentinel-1A imagery of the Lombok Strait recorded on March 13, 2017, at 21:52 UTC, which is used to calculate the phase speeds; (b) Tide prediction at sill area in Lombok Strait

5. Conclusions

Wavelet transform shows an effective method for Internal Solitary Waves (ISW) feature extraction and five parameters (soliton numbers, first crest length, wavelength, propagation direction, and phase speeds) by Sentinel-1A in Lombok Strait during 2015 – 2017. Sentinel-1A observation results show that the arc-like type of ISW in the Lombok Strait propagated to the North of the sill with an intermediate phase speed of about 2.13 m/s and was frequently detected during the Northwest monsoon (NWM) when the southward current of the ITF is not strong. The detected soliton number is less than 6 solitons per packet with a wavelength of about 1 – 4 km, and the first crest length varies from about 12.16 km to more than 100 km when it is reached near Kangean Island. The extracted ISW is located more at the bathymetric contours, about 800 meters, when the ISW is still in the Lombok Strait area. The exact relationship between the southward current and the number of solitons and internal waves is highly complex and depends on various interacting factors. The interaction of currents with other oceanic features, such as density gradients, topography, and tidal forces, plays a significant role in determining the occurrence, intensity, and behavior of solitons and internal waves within a southward current.

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Access Hub (https://scihub.copernicus.eu/dhus/#/home), processed by European Space Agency (ESA). Online Tidal Prediction *Badan Informasi Geospatial* (BIG) website (https://realtides.big.go.id/prediksi) for the tidal prediction accessed in August 2018.

Conflicts of Interest

The authors declare no conflict of interest.

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