Tide-Generated Internal Solitons in Bay of Bengal Excite Coastal Seiches in Trincomalee Bay

By

Edwin Alfonso-Sosa, Ph. D.

Ocean Physics Education, Inc.

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Abstract

MODIS/Terra/Aqua sensors allowed us to obtain 250-m resolution true-color images of internal solitary waves during sun glint conditions. These internal solitons packets were generated at 8° 50.9' N and 92° 49.3' E, about 4 km Northwest off Batti Malv Island of the Nicobar Archipelago in the Andaman Sea during a 3-day period of strong semidiurnal surface tides. About 20 km from the origin, the packet consists of 6 to 7 internal solitary waves, but 100 km farther from the origin position the number of waves in each packet doubled. The waves were ranked in amplitude order and their intra wave distance decreased from 7 km to 2.5 km. These packets moved West (270°) and crossed 1270 km in about 5.4 days to reach the entrance of Trincomalee Bay, Sri Lanka. The average inter packet distance is 122 km, suggesting that the packets were phase locked with the internal tide. Offshore of Trincomalee Bay entrance a nonlinear internal wave field was observed. The intra wave distance was 2.5 to 5 km. A nonlinear internal wave can excite a 42-minute coastal seiche in the Bay with an amplitude of 7 cm. Using a novel approach called *seichelogía* we estimated that the amplitude of the nonlinear internal wave was 8 m.

Introduction

The first scientific evidence of coastal seiche excitation by tide-generated internal solitary waves was found after the analysis of 13 years of tide gauge records from Magueyes Island, located in Puerto Rico (Giese et al., 1982; Giese et al., 1990). The internal solitons generated at Aves Ridge during spring-perigean tides travel 540 km across the Caribbean Sea in 3.6-5.1 days to impinge on the SW slopes of Puerto Rico (Alfonso-Sosa, 2012). Later, it was found that the coastal seiches recorded in Puerto Princesa, Palawan Island, were excited too by tide-generated internal solitary waves that cross the Sulu Sea in 2.3-2.5 days (Giese et. al., 1998). A successful theoretical model to explain the generation of surface coastal seiches by deep-sea internal solitary waves was developed (Chapman and Giese, 1990). The internal soliton impinges on the submarine slopes near the shelf break generating a horizontal current impulse. The current impulse at the shelf break excites a natural period standing oscillation in the shelf waters, with maximum amplitude near the coast. About 30 years later, more evidence of coastal seiche excitation by internal waves was found at Trincomalee Bay, Sri Lanka (Wijeratne et. al., 2010). Wijeratne proposed the hypothesis that internal waves generated at the Andaman Sea during spring tides travel 1200 km across the Bay of Bengal in 6-8 days to reach Trincomalee Bay. But they did not provide any evidence of the internal waves by means of direct ship measurements or satellite imagery.

In the last eight years, 250-m resolution MODIS images acquired by the Earth Observing System Terra and Aqua Satellites during sunglint conditions allowed us to survey high-frequency nonlinear internal solitary wave occurrences on a near-global scale (Christopher Jackson, 2007). It is possible to detect internal solitons packets leaving the generation area during fortuitous conditions: minimum cloud cover, near-specular reflectance pattern of sunlight off the ocean surface (sunglint) and strong oceanic stratification. The origin and speed of Aves Ridge Solitons in the Caribbean Sea and Ceará Solitons in the Atlantic Ocean had been determined by analysis of MODIS images (Alfonso-Sosa, 2012; Alfonso-Sosa, 2013).

Recently, it was possible to extract information of the deep water internal solitons from the coastal seiche signal. *Seichelogía* is a novel approach to study the nonlinear –nonstationary seiche signal based on the relationship between the seiche's instantaneous frequencies and the ocean's stratification near the shelf break (Alfonso-Sosa, 2013). Seichelogía enables us to estimate the amplitude of the internal soliton responsible for the coastal seiche excitation.

The focus of this paper is to provide direct evidence that internal waves generated at the Nicobar Archipelago are responsible for exciting seiches in Trincomalee Bay, Sri Lanka. Using MODIS imagery and *seichelogía* will provide the necessary evidence to prove the hypothesis of Wijeratne and its collaborators.

Methodology

On March 2013-14, on the inter monsoon period, we acquired MODIS Aqua/Terra images from the Bay of Bengal and Andaman Sea during fortuitous conditions. A total of 5 images show clear surface patterns associated with internal solitary waves departing West from the Nicobar Archipelago. This area is subject to strong semidiurnal barotropic tides (M2). The images KML files in Google Earth™ allowed us to measure and characterize these internal solitons. The ratio between the distance separating the solitons and the semidiurnal M2 period (12.42 hrs= 44712 s) allowed us to estimate their speeds (Christopher Jackson, 2007; Alfonso-Sosa, 2012).

We performed seichelogía analysis of the water level signal recorded by the tide gauge at Trinconmalee. Details of the seichelogía method used in this study can be followed in the article titled: *Seichelogía: Una técnica novel para detectar remotamente cambios en el interior del océano* (Alfonso-Sosa, 2013).

Results and Discussion

MODIS/Aqua/Terra images revealed the points of origin of the internal soliton packets crossing the Bay of Bengal. Figure 1 and 2 are MODIS images separated by one year interval, both images show internal soliton packets generated north and south of Car Nicobar Island and travelled west into the Bay of Bengal. The second image taken on March 19 2014 allowed us to pinpoint the exact location of generation for a nascent soliton packet. It was located at 8° 50.921'N and 92° 49.337'E, about 4 km (2.16 nautical miles) offshore the NW coast of Batti Malv Island and 29.9 km (16.15 nautical miles) from the south coast of Car Nicobar Island. The image shows the bipolar nature of the generation area, because some packets are shed into the Andaman Sea and others into the Bay of Bengal. About 20 km from the origin, the packet consists of 6 to 7 internal solitary waves, but 100 km farther from the origin position the number of waves in each packet is doubled. The waves were ranked in amplitude order and their intra wave distance decreased from 7 km to 2.5 km. Another generation area was located mid channel between the islands of Batti Malv and Chaura. The specific coordinates are: 8° 36.953'N and 92° 55.610'E. Figure 1 and 2 shows another generation area in the passage separating Little Andaman Island and Car Nicobar Island. A careful inspection of the images reveals that the wave fronts in the packages generated north and south of Car Nicobar I. travelled parallel to each other. Figure 3 shows the scarped submarine topography around the Nicobar Archipelago. The generation areas are situated in the shallower sills separating the islands. The distance separation between the packets (~90-100 km) suggests that the semidiurnal tidal currents impinging on the sills are responsible for their generation. Figure 4 shows four solitons packets generated North of Car Nicobar Island crossing the Bay of Bengal on 14-MAR-2013. Since each package is generated every 12.4 hours, we can assume that the first package was shed on 12-MAR-2013. The packets are almost equally spaced. The average inter packet distance is 122 km. Since this distance equals the semidiurnal internal tide wavelength (mode 1), is probable that the nonlinear packets are phase locked with the linear internal tide wave. The lead packet is located mid distance between Nicobar Islands and Sri Lanka (Figure 5). The exact location is 550 km (297 nautical miles) ENE (74°) of Trincomalee Bay. Three days later, on 17-MAR-2013, the packets arrived to the NE waters of Sri Lanka. Based on these images, each soliton package took 5 to 6 days to cross the Bay of Bengal. If the distance between each package is 122,000 m and we divide this number by a semidiurnal period (44712 s), we obtain a nonlinear speed of 2.72 m/s. These relative fast solitons can cover the whole distance between Car Nicobar Island and Trincomalee Bay (1270 km) in about 5.4 days. Both soliton packets generated north or south of Car Nicobar Island can reach Trincomalee Bay as shown in Figure 5. Deep submarine canyons with depths of 3000 m extend outward of the bay entrance (Figure 6). Internal waves can travel keeping their deep water speed until they reach the shelf inside the embayment. The Trincomalee's shelf extends approximately 7.7 km (Figure 6, bottom). A nonlinear internal wave field was detected outside of Trincomalee Bay on March 29 2007 by MODIS, the same date when Wijeratne demonstrated the occurrence of large amplitude coastal seiches in the Bay (Figure 7). On March 25 2014, 6 days after the solitons departed from the Nicobar Islands (Figure 2), a nonlinear internal wave field was detected offshore Trincomalee Bay by MODIS (Figure 8). The intra wave distance was 2.5 to 5 km. To determine the amplitude of these solitons we applied *seichelogía* analysis to the water level data recorded by Trincomalee's tide gauge. The data was taken on April 15 2008 and March 22 2013. The tide gauge's location is shown in Figure 6. From the analysis of the April 15 data we obtained that the coastal seiche events are intermittent and separated by 6.7 hours (Figure 9). In addition the seiche signal shows intra frequency modulation, the instantaneous frequency can go from 20 CPD to 40 CPD in less than one cycle of oscillation. A linear regression of the instantaneous frequency (IF) for the second IMF between 20:02 and 20:38 on April 15 2008 (Figure 10) allowed us to calculate the ocean's stratification near the shelf break.This information was input into the analytical model of Chapman and Giese (1990) to calculate the amplitude of the KdV soliton capable of excite a shelf response equal to the observed one. To excite a coastal seiche with an amplitude of 7.3 cm it is necessary a KdV soliton amplitude of 8.4 m (Figure 11). The table below summarizes the findings. We assumed a two-layer model, with an upper layer depth of 100 m and a total depth of 4000 m.

Start	**End**	**Maximum Seiche Amplitude (cm)**	**KdV Soliton Amplitude[2,3] (m) (NHT, KdV, 1481)**	**Maximum Cross Shelf Current[2,3] (cm/s) (NHT, KdV, 1481)**
4/15/2008 20:05	4/15/2008 20:39	7.3	8.4	2.3
3/22/2013 4:59	3/22/2013 5:23	3.5	3.5	1.0
3/22/2013 6:15	3/22/2013 6:44	3.2	2.3	0.6

[2] Based on the analytical model of Chapman and Giese 1990, J. Phys. Oceanogr., **20**, 1459–1467.

[3] Gaussian Pulse was substitued by KdV soliton.

Conclusion

Due to the large surface vertical stratification in the Bay of Bengal, relative small amplitude internal solitons can easily excite coastal seiches in Trincomalee Bay. An internal soliton with a amplitude of 8 m is capable of exciting a surface coastal seiche with an amplitude of 7 cm. The large surface stratification in the Bay of Bengal allows that solitons generated in the Nicobar Islands can easily cross westward 1270 km upon reaching the eastern coast of Sri Lanka in 5.4 days. This is the longest travel distance of an internal soliton capable of exciting coastal seiches.

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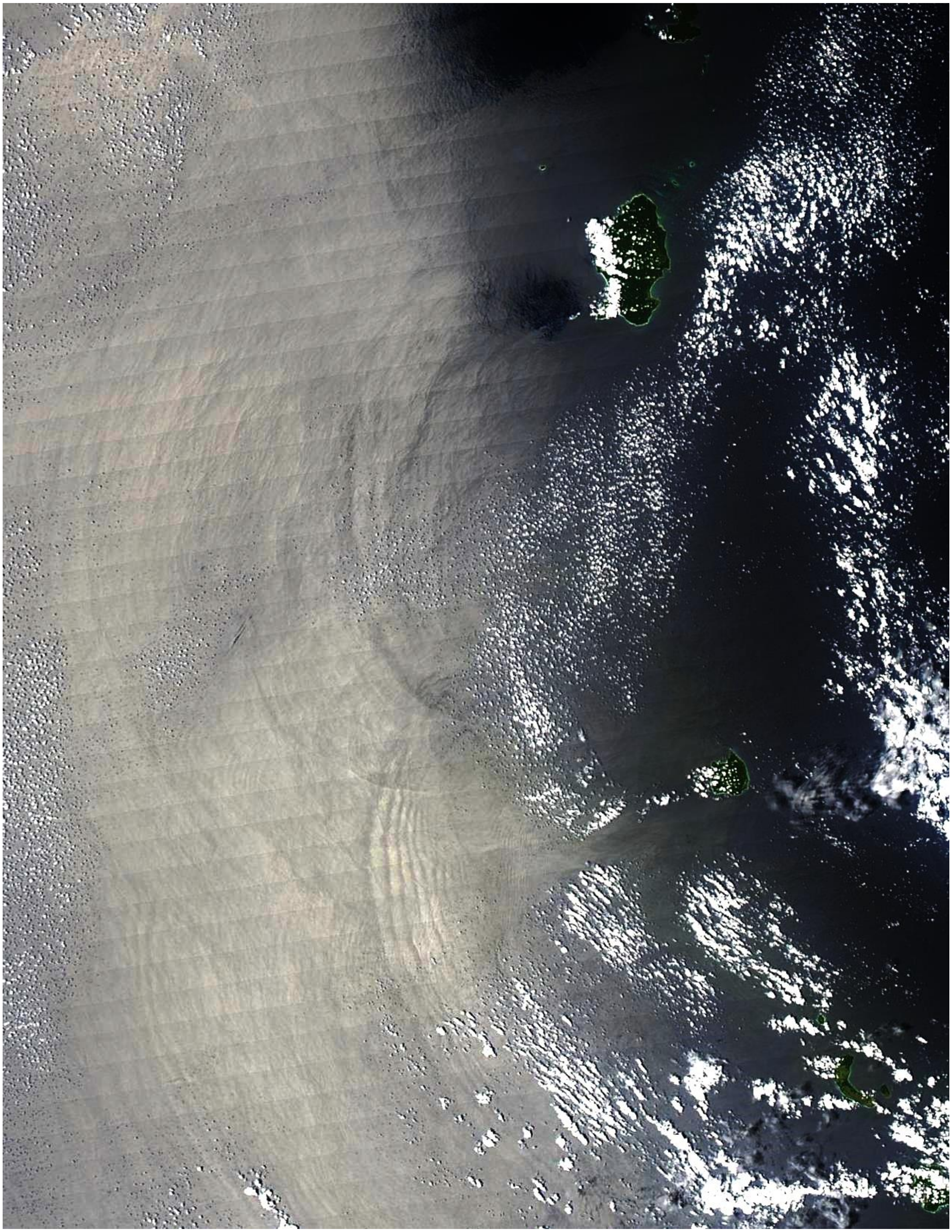

Figure 1. Internal Solitons packets generated north and south of Car Nicobar Island (middle of the image); all travel west into the Bay of Bengal. MODIS image was taken on 16-MAR-2013.

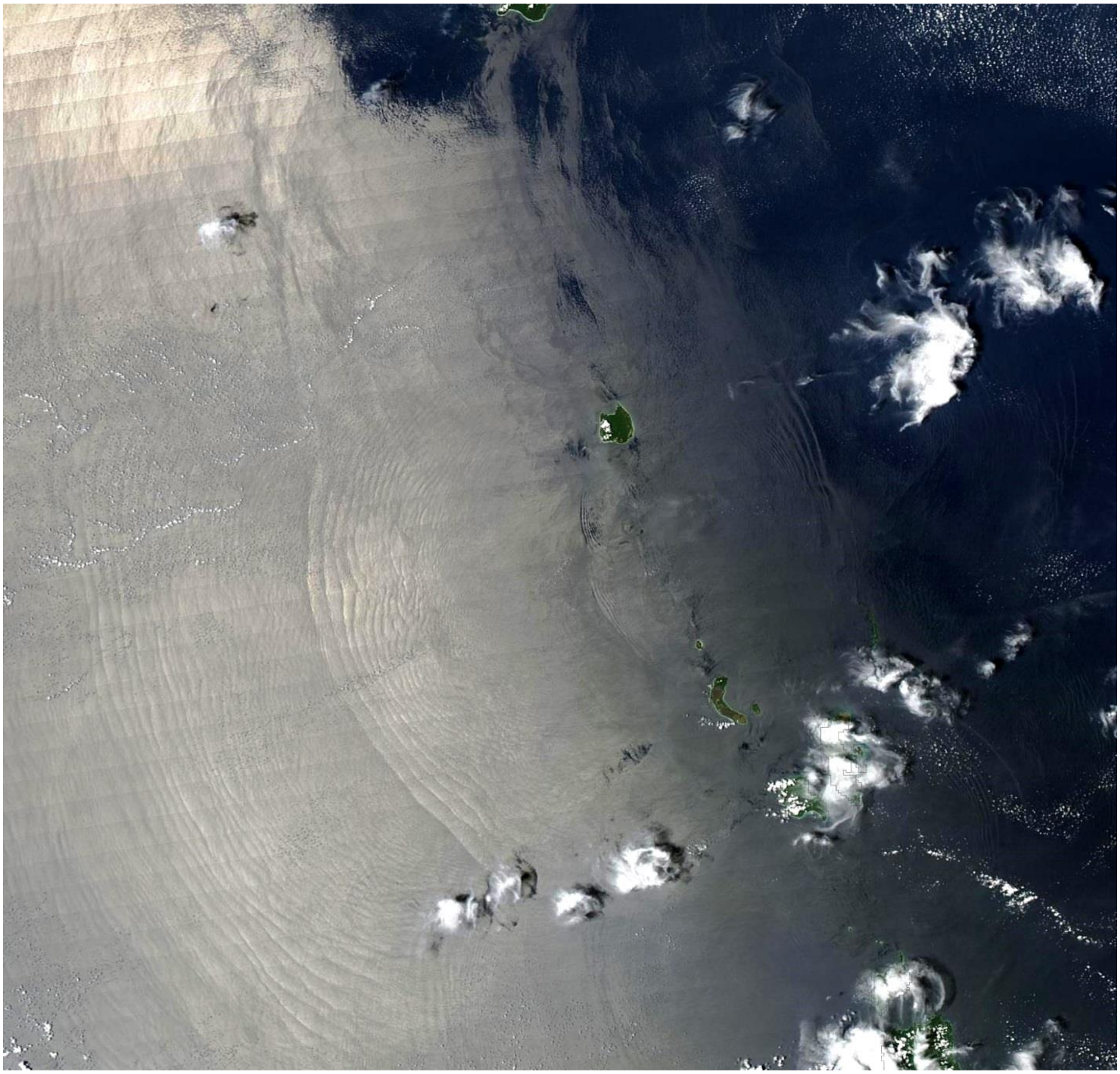

Figure 2. MODIS image on 19-MAR-2014 showing two large soliton packets, generated south of Car Nicobar Island, moving west into the Bay of Bengal. Another 2 packets are moving east into the Andaman Sea.

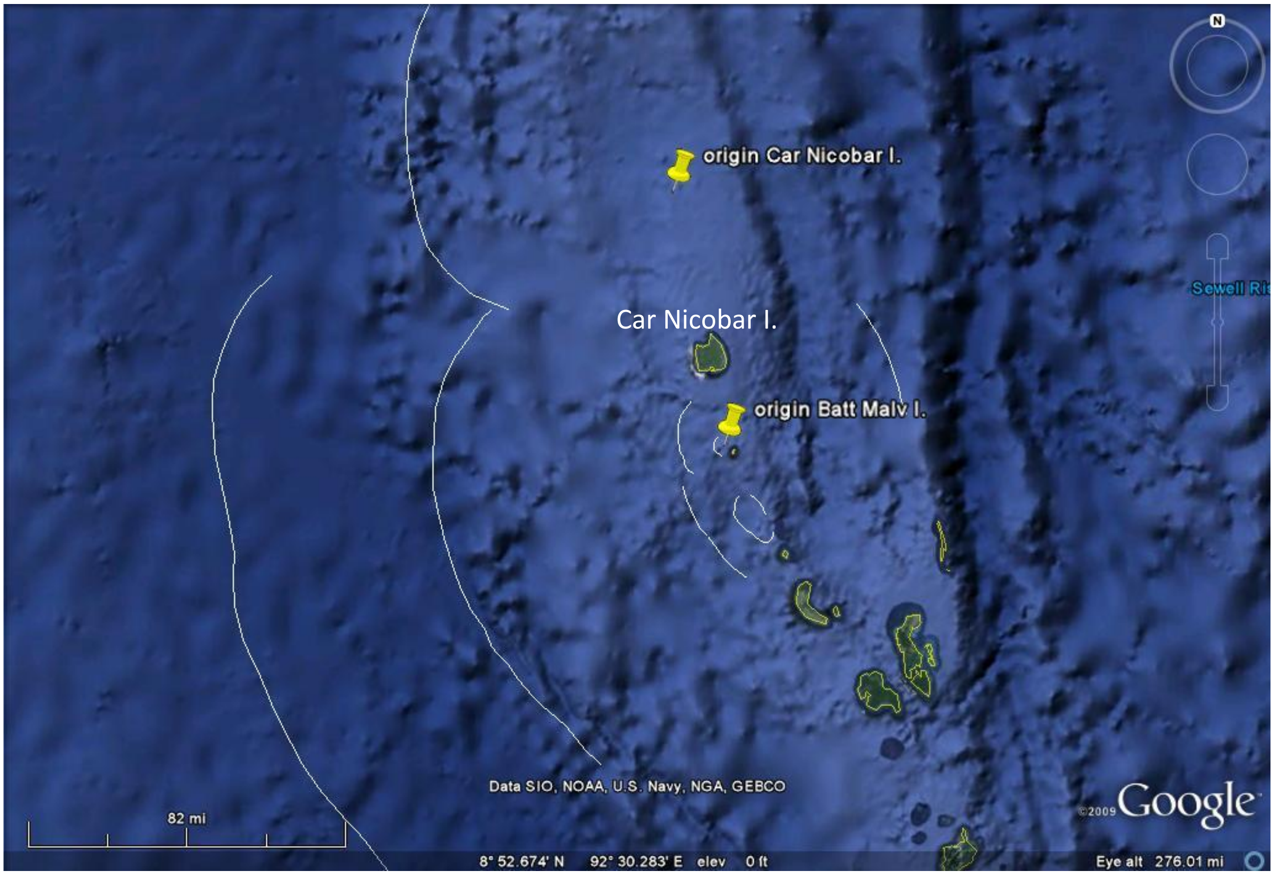

Figure 3. The bathymetric map of the Nicobar Archipelago reveals the scarped submarine topography around the islands. White lines trace the wavefronts of the internal solitons shown in the previous figure; only the leader of the soliton packet is shown. Separation between the leading waves of the packs is about 90 km. The two yellow pins indicate origin areas of internal solitons packets, located in the sills separating the Nicobar Islands.

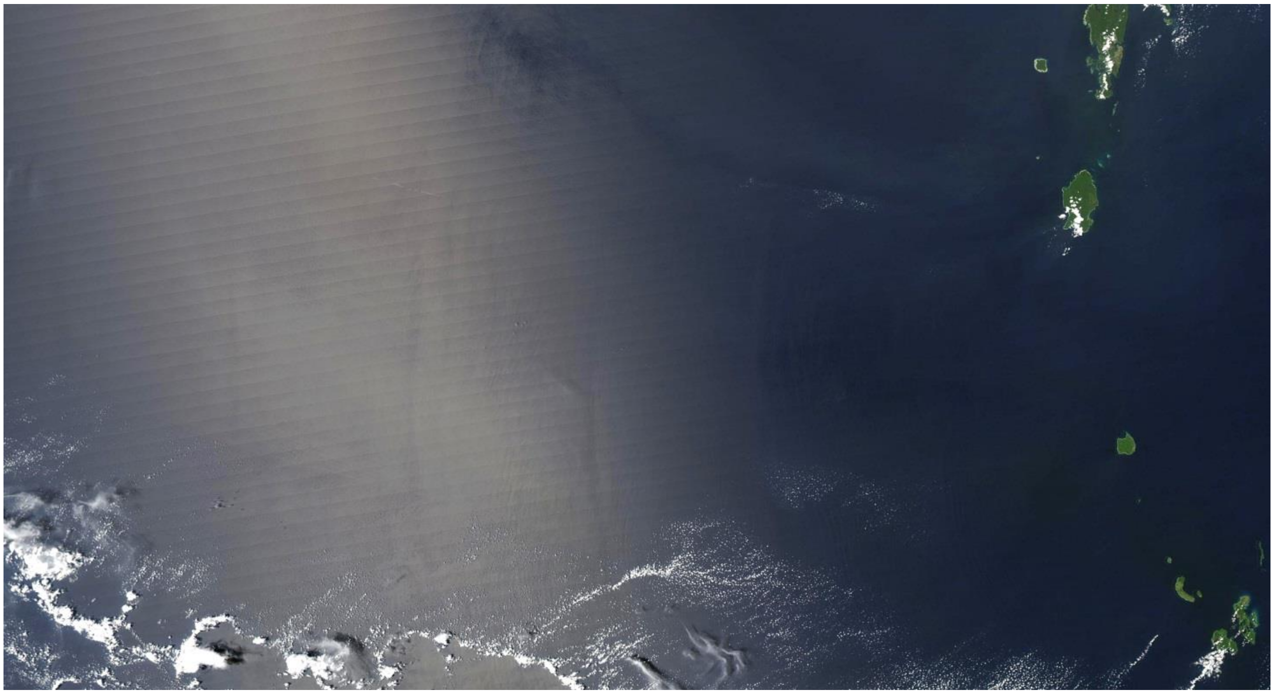

Figure 4. Four solitons packets generated North of Car Nicobar Island are crossing the Bay of Bengal. The average inter packet separation is 122 km. MODIS image taken on 14-MAR-2013.

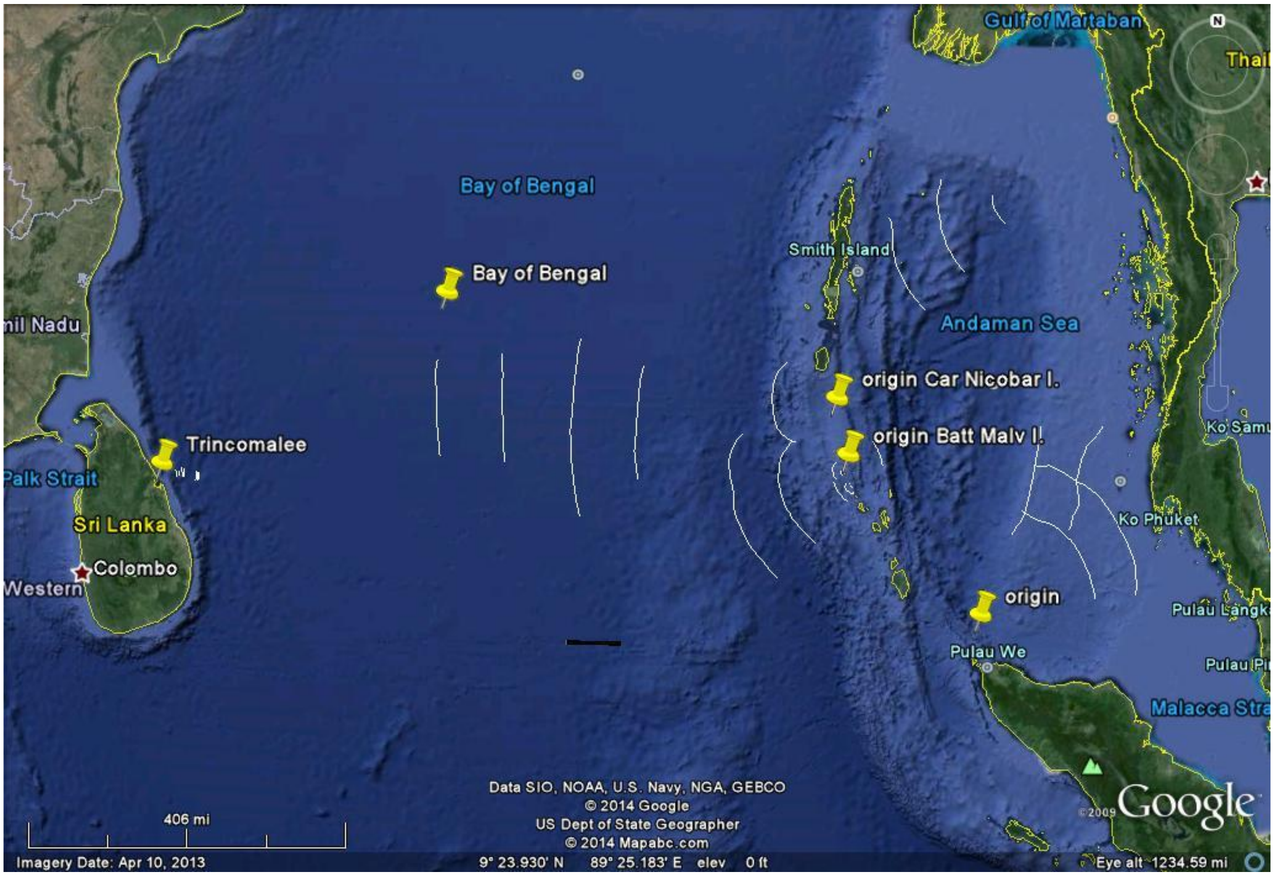

Figure 5. The leader solitons travel west and cross the Bay of Bengal. The space between them is about 122 km. The two yellow pins indicate origin areas of internal solitons packets in the Nicobar Islands. The solitons (white lines) shown are from previous Figures 1 to 4. The packet lines offshore Trincomalee represents the nonlinear internal wave field shown in Figure 8.

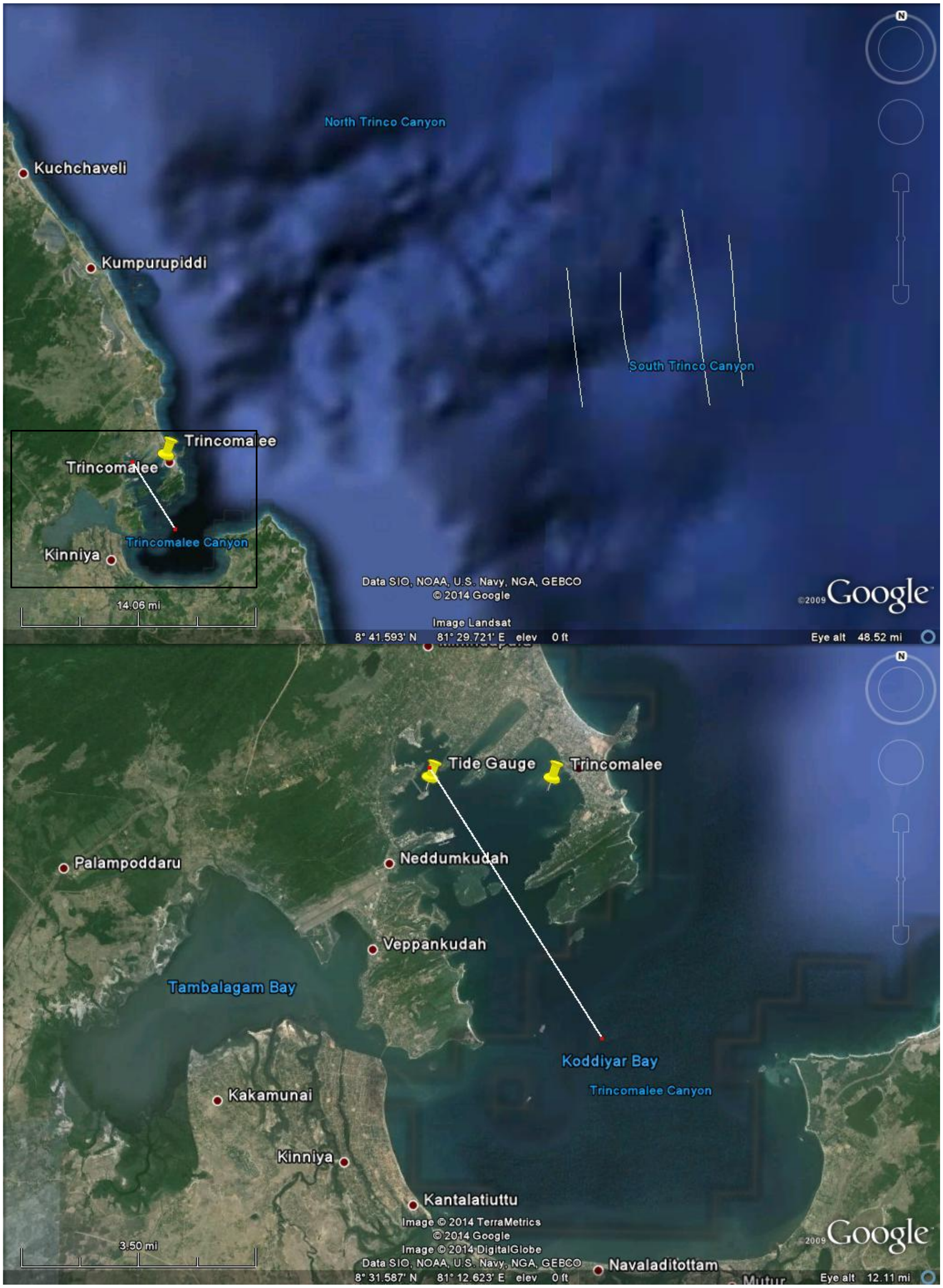

Figure 6. Top. View of Trincomalee Bay and surrounding deep submarine canyons. White lines represent the actual location of wave fronts of internal waves approaching the Bay. Bottom. A zoom view of Trincomalee Bay showing the location of the tide gauge station. The white line represents the length of the shelf, is about 7.7 km.

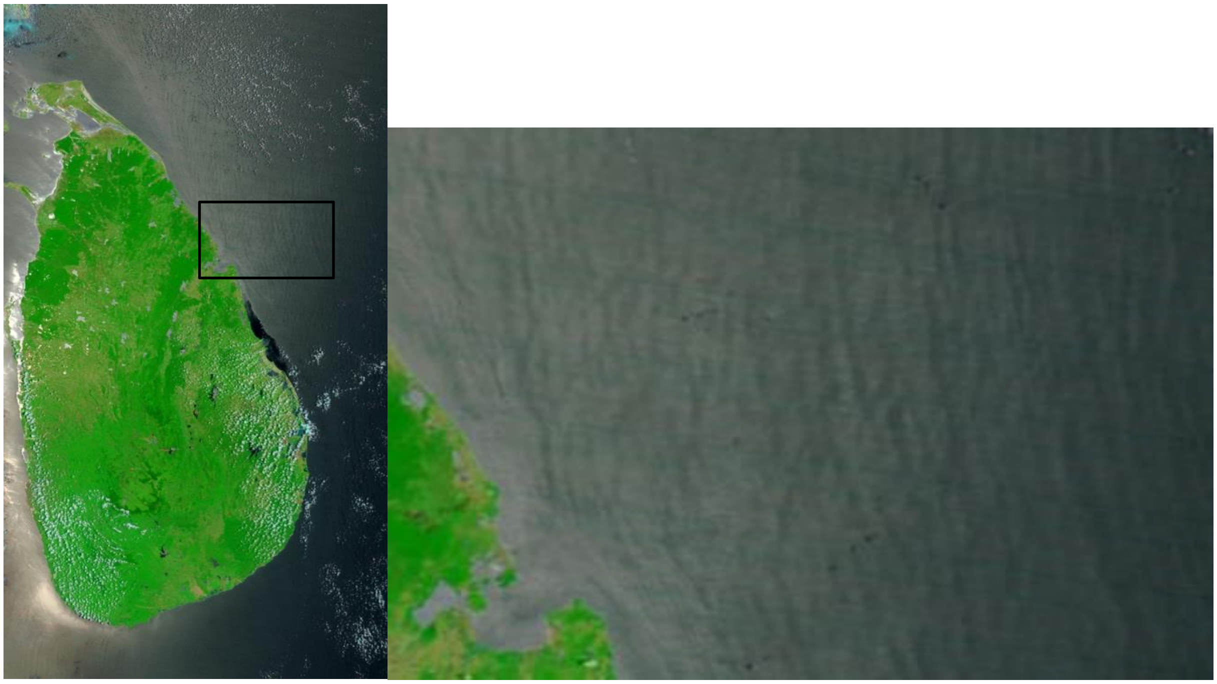

Figure 7. Left. 250m-resolution MODIS image of Sri Lanka Island (Channels 7-2-1) taken on 29-MAR-2007. The black box outlines the Bay of Trincomalee and its offshore waters. A zoom image is shown at right. It shows an extensive internal wave field just offshore of Trincomalee’s bay.

Figure 8. It shows an extensive internal wave field just offshore of Trincomalee Wave on 25-MAR-2014. MODIS image. The intra wave distance was 2.5 to 5 km.

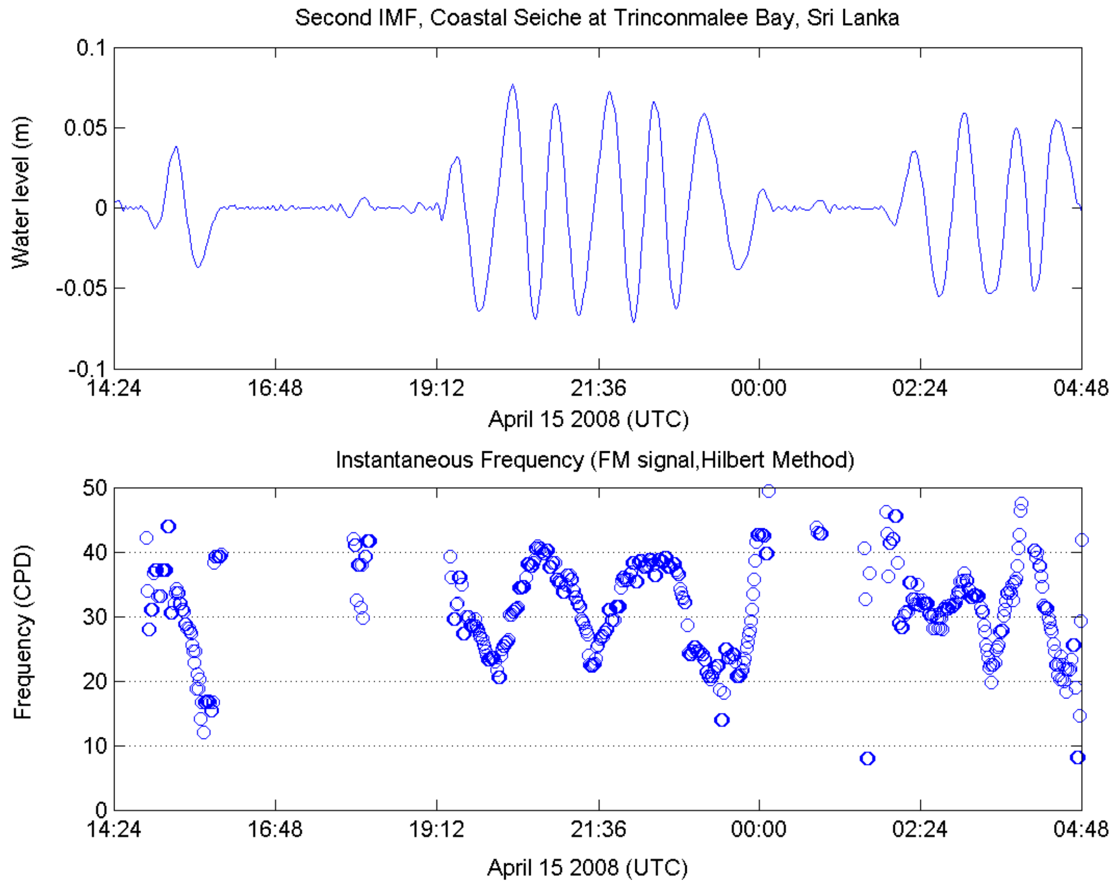

Figure 9. Second intrinsic mode function (IMF) derived from Empirical Mode Decomposition (EMD) of the water level signal at Trincomalee Bay. It represents the coastal seiche signal. Below. The graph shows the instantaneous frequency (IF) of the above IMF.

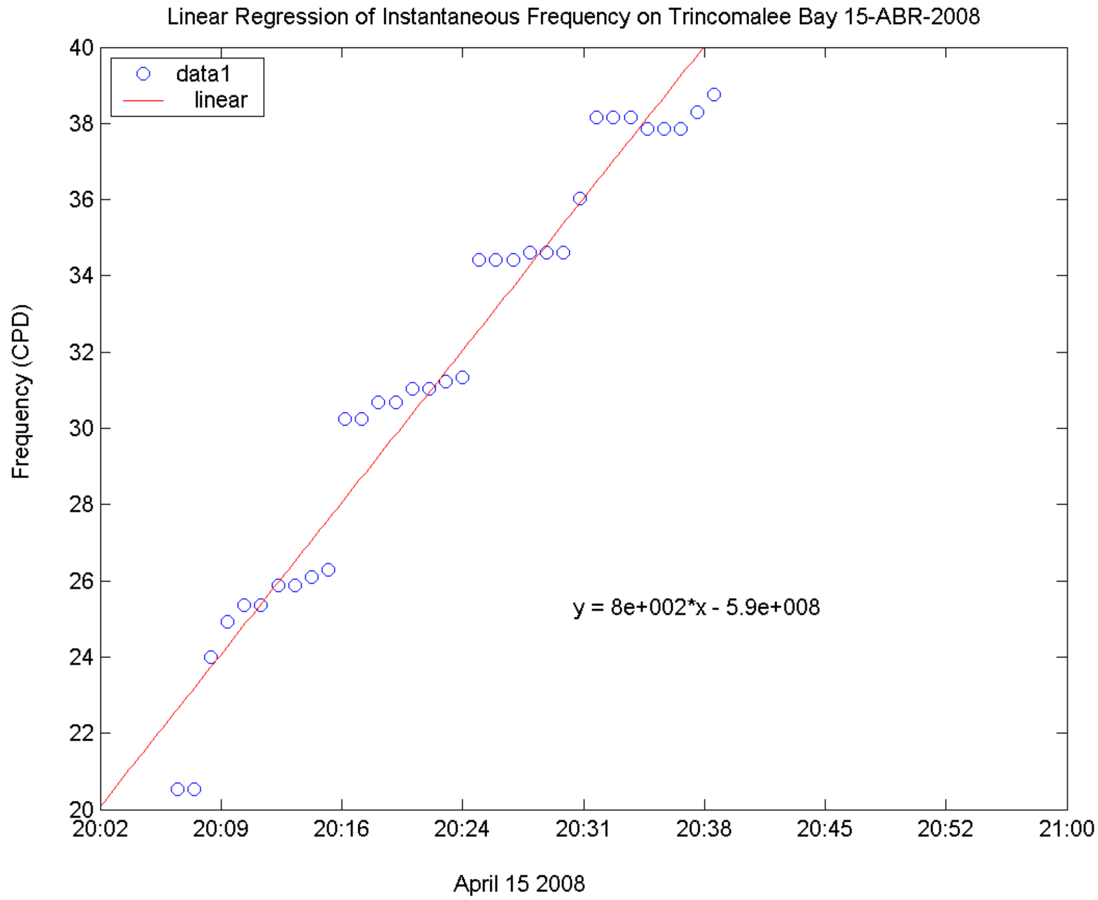

Figure 10. A linear regression of the instantaneous frequency (IF) for the second IMF between 20:02 and 20:38 on April 15 2008.

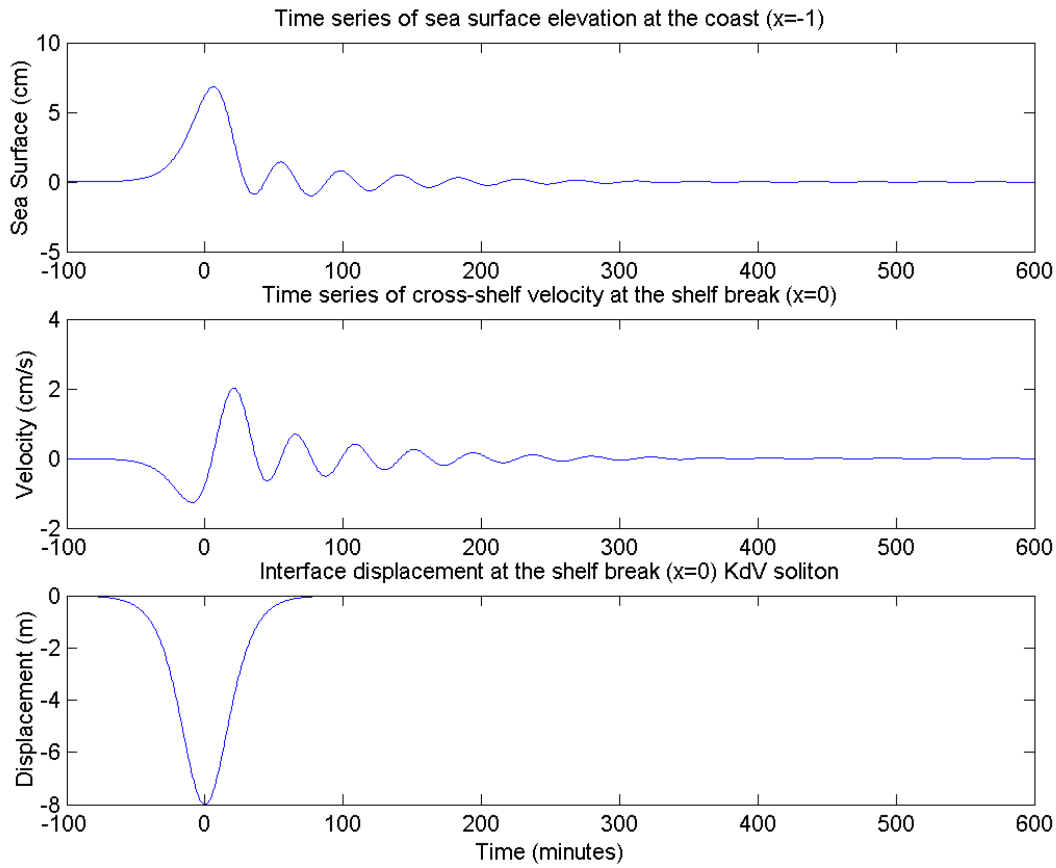

Figure 11. Top. The shelf water's response at the coast. Middle. The cross-shelf velocity at the shelf break. Bottom. KdV internal soliton amplitude at the shelf break.