Tide-Generated Internal Solitary Waves in the Nicobar Islands Passages excite Coastal Seiches in the Maldives Islands

After the ISWs crossed 2420 kilometers of the Indian Ocean in 10.5 days

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July 27 2016

Abstract

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 in the Indian Ocean. These images clearly show packets of internal solitary waves (ISWs) generated in the Nicobar Islands passages during the extraordinary coincidence of the following astronomical factors: perigee, syzygy, zero lunar declination, spring equinox, longitude of the lunar node equal to 180°. The relatively fast ISWs packets (2.7 m/s) propagated southwest (245°) and crossed **2420 km** of Indian Ocean in about **10.5 days** to excite coastal seiches in the waters of the Addu Atoll - the southernmost atoll of the Maldives Islands - located near the Equator. Satellite images and sea level data evidence the concurrence of these two physical phenomena. Our finding sustains that ISWs can travel very long distances and impinge on distant archipelagos far from their generation region.

Introduction

The first scientific evidence of coastal seiche excitation by tide-generated internal solitary waves (ISWs) 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 ISWs 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. Four years later, satellite images detected packets of ISW's crossing the Bay of Bengal (Alfonso-Sosa, 2014). 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 was 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.

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 solitary wave 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's ISWs in the Caribbean Sea and Ceará ISWs in the Atlantic Ocean had been determined by analysis of MODIS images (Alfonso-Sosa, 2012; Alfonso-Sosa, 2013).

The focus of this paper is to provide direct evidence that internal waves generated at the Nicobar Archipelago are responsible for exciting seiches in Gan, Addu Atoll, Maldives Archipelago. Both archipelagos separated by a distance of 2420 km.

Coastal Seiches in Gan, Addu Atoll

Harbor oscillations (coastal seiches) are a specific type of seiche motion that occur in partially enclosed basins (gulfs, bays, fjords, inlets, ports, and harbors) that are connected through one or more openings to the sea (Rabinovich, 2009). Long waves entering through the open boundary (harbor entrance) from the open sea are responsible for generating the harbor oscillations. In addition, the harbor seiche losses energy when radiates it through the mouth of the harbor. The fundamental mode of the harbor oscillation is called the Helmholtz mode. The periods of the Helmholtz mode (n=0) and the other harbor modes (n=1, 2, 3…) can be approximately estimated by the following formula (Rabinovich, 2009):

$$T_n = \frac{4L}{(2n+1)\sqrt{gH}}$$

where L is the length of the water body and H is the depth. Both are expressed in meters. The periods are expressed in seconds. The following table details the period of the harbor oscillation for each natural mode. The periods are expressed in minutes. The Addu Atoll's lagoon general depths vary from 37 m to 46 m but the reefs encircling the lagoon are in depths from 13 m to 18 m. An average depth of 28.5 meters was calculated. The lagoon width was measured using Google Earth images and its value was about 13 km. The first row shows the period of the Helmholtz mode (n=0).

Merian's Formula for the periods (natural) of a rectangular basin with uniform depth			
Addu Atoll, Maldives Islands			
Open-ended basin		n	T_n (minutes)
L (m)	H (m)	0	51.8
13000	28.5	1	17.3
		2	10.4
		3	7.4
		4	5.8

Methodology

On February-April 2015, we acquired MODIS Aqua/Terra images from the Bay of Bengal and Equatorial Indian Ocean during fortuitous conditions. A total of 3 images show clear surface patterns associated with internal solitary waves departing southwest from the Nicobar Archipelago (Figures 2-4). 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, 2014; 2012).

A record of one-minute water levels was obtained from the Sea Level Station Monitoring Facility at Gan, Maldives Island. Outliers and spikes were removed from the record. The station is maintained by the Maldives Meteorological Department. http://www.ioc-sealevelmonitoring.org/station.php?code=ganm

Water Level Data Analysis

The 1-minute water level data recorded at Gan sea level station was subjected to the Empirical Mode Decomposition (EMD), a novel method to analyze nonstationary and nonlinear signals (Huang et al. 1998). This adaptive method has been applied to the analysis nonlinear water waves (Huang et al. 1999). From EMD we obtain intrinsic mode functions (IMF) components that have a physical interpretation. Well known nonlinear systems such as the Duffing equation has been subject to Hilbert Huang Transform (HHT) analysis and each component have a physical meaning. Using Normalized Hilbert

Transform (NHT) we found the instantaneous frequencies of each IMF component obtained by EMD. The concept of instantaneous frequency has been well explained by Huang et al. (2009).

This analysis was performed in Matlab, using the m-files provided by: 中央大學數據分析中 Research Center for Adaptive Data Analysis. Chungli,Taiwan http://rcada.ncu.edu.tw/intro.html

Results and Discussion

MODIS/Aqua/Terra images revealed the points of origin of the internal soliton packets crossing the Indian Ocean. Figures 2-4 are MODIS images that show internal soliton packets generated south of Car Nicobar Island and travelled southwest into the Bay of Bengal. The first generation point was located at these coordinates: 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 (Alfonso-Sosa, 2014). A second generation area was located mid channel between the islands of Batti Malv and Chaura (See Figures 3-4). The specific coordinates are: 8° 36.953'N and 92° 55.610'E. The generation areas are situated in the shallower sills separating the islands. The distance separation between the packets (~ 100 km) suggests that the semidiurnal tidal currents impinging on the sills are responsible for their generation.

Figures 5-6 show the same ISWs packet propagating southwest on two consecutive days: the 23rd and 24th of February 2015. This packet was generated on February 19, 2015 (Figure 2). Based on the distant covered (230,000 m) and the time period between the two images (78240 s) we calculated that the speed of the lead wave was 2.9 m/s. After 5 days of travel, the ISWs packets missed Sri Lanka and continue their journey to the Maldives Archipelago. Figure 1 show a mosaic constructed from thirty MODIS images – with positive detection of ISWs – that revealed a southwest (245° T) propagation path. In Figure 4, from the JPO article of Maarten C. Buijsman and collaborators (2016), one semidiurnal internal tide beam shows a similar propagation direction; it propagates away from the Nicobar Islands and reaches the Maldives. Both evidence support that the ISWs and semidiurnal tides follow the same path across the Indian Ocean.

Figure 8 shows five ISWs packets generated South of Car Nicobar Island crossing the Indian Ocean on 25-FEB-2015. Each package was generated every 12.4 hours by the semidiurnal internal tide. The packets are almost equally spaced. The average inter packet distance is 120 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. 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 large distance of 2420 km between Batt Malv Island (Nicobar Is.) and Addu Atoll (Maldives Is.) in about 10.5 days (Figure 1). Internal waves can travel keeping their deep water speed until they reach the Addu Atoll, the southernmost atoll of the Maldives Archipelago. Gan sea level station is located at the following coordinates: LAT-0.6867°, LON 73.1517°; meaning that the ISWs packets – that excited seiches in Gan – crossed south of the Equator at the Indian Sea. Similarly, in the Atlantic Ocean ISWs generated by strong semidiurnal currents in the upper slope off the Amazonian

Shelf can travel long distances; some can propagate 1300 km to the Northeast (see post of 14-SEP-2014 in https://www.facebook.com/OceanPhysicsEducation/).

The first ISWs packet was expected to arrive at Addu Atoll on March 2 2015, since it was generated on February 19 2015 at Nicobar Is., but bad images (high cloud cover, no-sunglint) did not allowed the satellite sensor to detect the ISWs; meanwhile seiche activity increased on March 2, 2015 (see Figure 18). A nonlinear internal wave field was detected 275 km East of Addu Atoll on March 3, 2015. A total of seven MODIS images show clearly the internal wave field around the Maldives responsible of the seiche activity in the subsequent days (Figures 9-16, ordered in chronological order). Some of these images show the scale of the wavelength for the high frequency internal waves. East of the Addu Atoll most of the wavelengths run between 2 km to 4 km; south of the entrance of Gan Channel the wavelengths are reduced to about 1 km (Figure 10). Figure 14 shows internal solitary waves with a wavelength of 6.6 km passing south of the atoll and a second packet of ISWs lagging the first one by a distance of 82 km.

Figures 12-13 show two packets of internal solitary waves entering and exiting the 1.5 Degree Channel separating the Huvadhoo Atoll and the Hadhdhunmathee Atoll, the larger wavelengths run from 7.6 km to 15 km. The ISWs packets crossed the 1.5 Degree Channel without major dissipation and continued their west propagation leaving behind the Maldives.

Figure 17 shows the results from the Empirical Mode Decomposition (EMD) analysis of water levels at Gan tide station from February 21 2015 to April 7, 2015. The figure shows only the first five IMF components. The fifth component is the semidiurnal tide and the fourth component represents the 50-60-minutes coastal seiche. A closer look to the 50-60-minutes seiche record revealed that consecutive sudden increases in activity are separated by an interval of 15 days (Figure 18). The first one occurred on March 02 2015 and the second one on March 17 2015. The first period of increased seiche activity lasted about 8 days but the second period was more active and lasted till the end of the time series. Maximum amplitude reaches up to 0.03 m on March 30th 2015 and in April 2nd 2015. MODIS images presented on Figures 12-13 and 14 show the internal waves responsible for the excitation of those seiche events. Figures 19 to 21 show specific days when coastal seiche activity increases and at the same time concurrent MODIS images show internal waves impinging on the Maldives Archipelago. The seiche is intermittent and show increases in amplitude every 11.6 hours (Figure 19) but sometimes this period shortens to 9 hours (Figure 21).

It is important to point that 2015 was an extraordinary year for semidiurnal tidal forcing. If the perigee coincides with syzygy, equinox and the longitude of the lunar node, **N** equals 180 degrees (Minimizing Lunar Declination) all these factors will maximize the semidiurnal form of the tides. N crossed 180° (i.e., lunar declination reached minima) on October 2015. In the whole year 2015, the position in the 18.6 Nodal Cycle was favorable for the generation of strong semidiurnal tides and ISWs. On Feb 19 and March 19 2015 the perigee and syzygy were separated by less than 13 hours; March 19 was one day before the spring equinox and a total solar eclipse. All these factors contributed to an exceptional generation of semidiurnal internal tides. This fact can explain why after March 17 2015 the internal wave activity and the seiche activity lasted longer than after March 2 2015.

Conclusion

ISWs generated during strong semidiurnal tidal currents in the Nicobar Islands sills can travel 2420 km in about 10.5 days to excite coastal seiches in the waters of Addu Atoll (Maldives Islands) located in the Equatorial Indian Ocean. Satellite images and sea level data evidence the concurrence of these two physical phenomena. Extraordinary astronomical conditions increased the semidiurnal tidal forcing that was responsible for the increased internal wave activity and subsequent coastal seiche activity.

Acknowledgements

We acknowledge the use of Rapid Response imagery from the Land Atmosphere Near-real time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS) with funding provided by NASA/HQ. The image browsing and downloading was facilitated by NASA Worldview site.

Gan Station data was kindly provided by Maldives Meteorological Department (Maldives) and the UNESCO/IOC Sea Level Website. http://www.ioc-sealevelmonitoring.org/index.php

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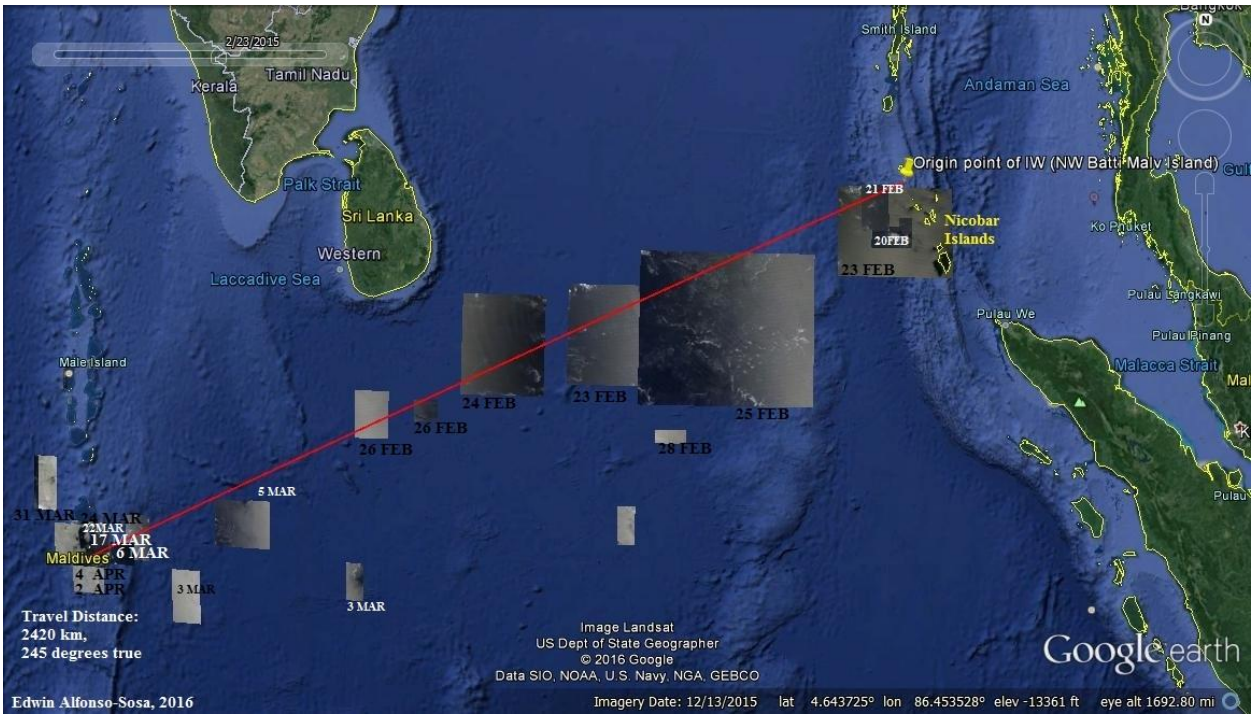

Figure 1. Mosaic of MODIS images showing the position and dates of the detected internal waves.

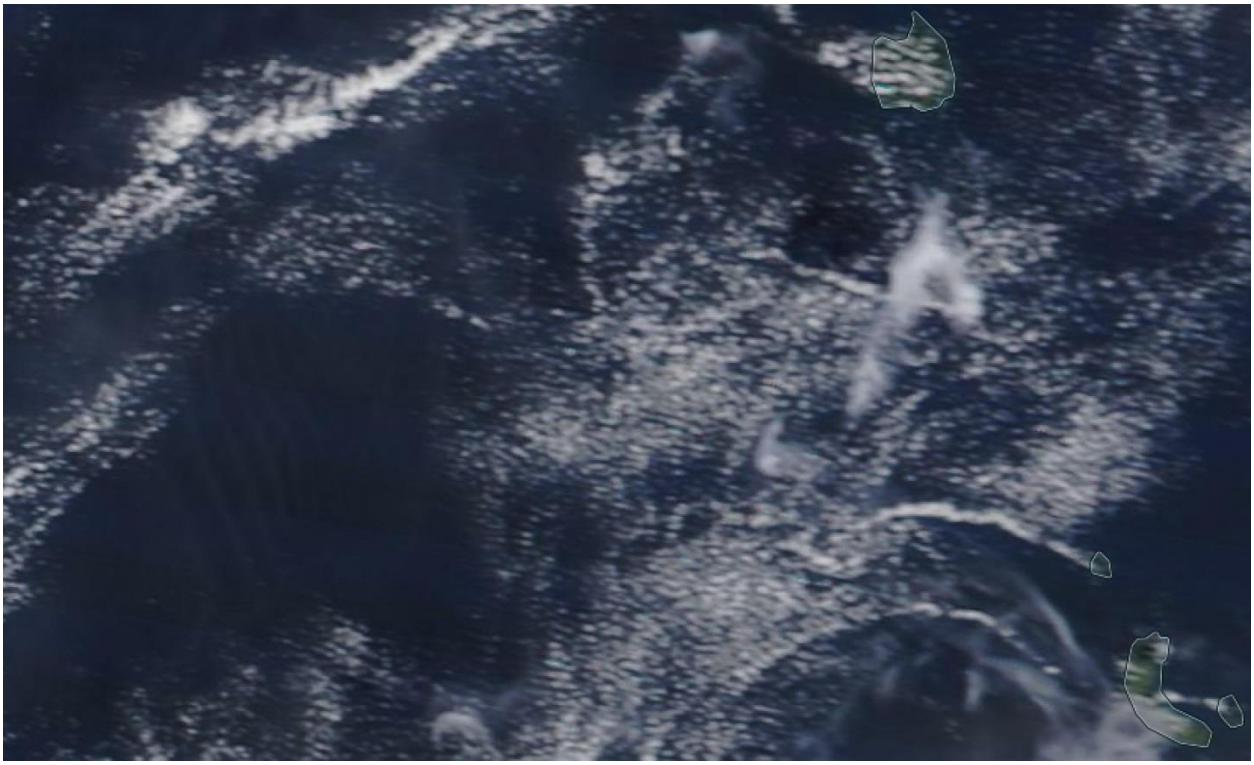

Figure 2. 19 February 2015. MODIS/Terra. First packet of ISWs detected by MODIS/Terra.

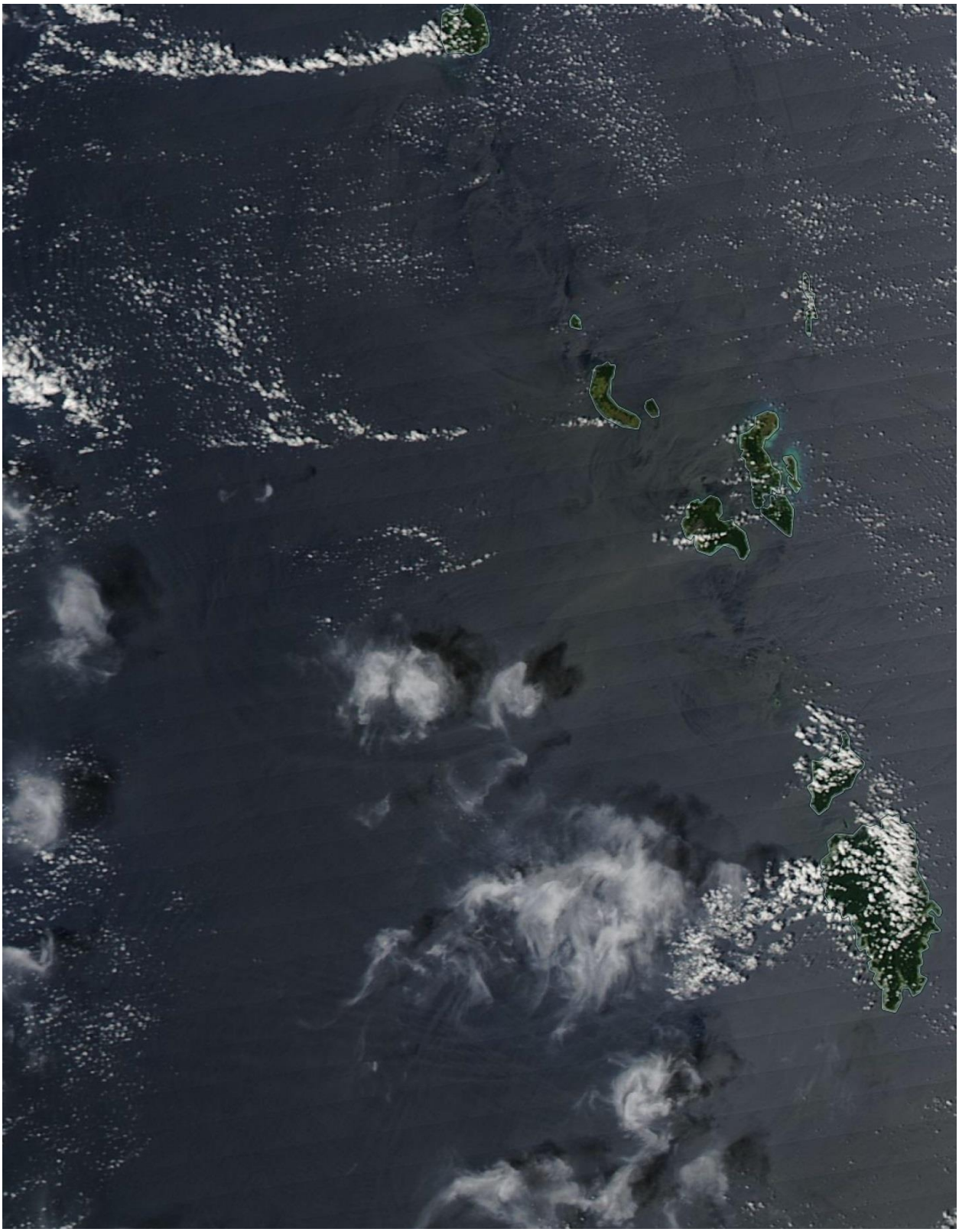

Figure 3. 20 February 2015. MODIS/Aqua. Two Packets of ISWs generated at the Nicobar Islands passages propagating to the southwest.

Figure 4. 23 February 2015. Nicobar Archipelago passages are the generation area of the internal waves.

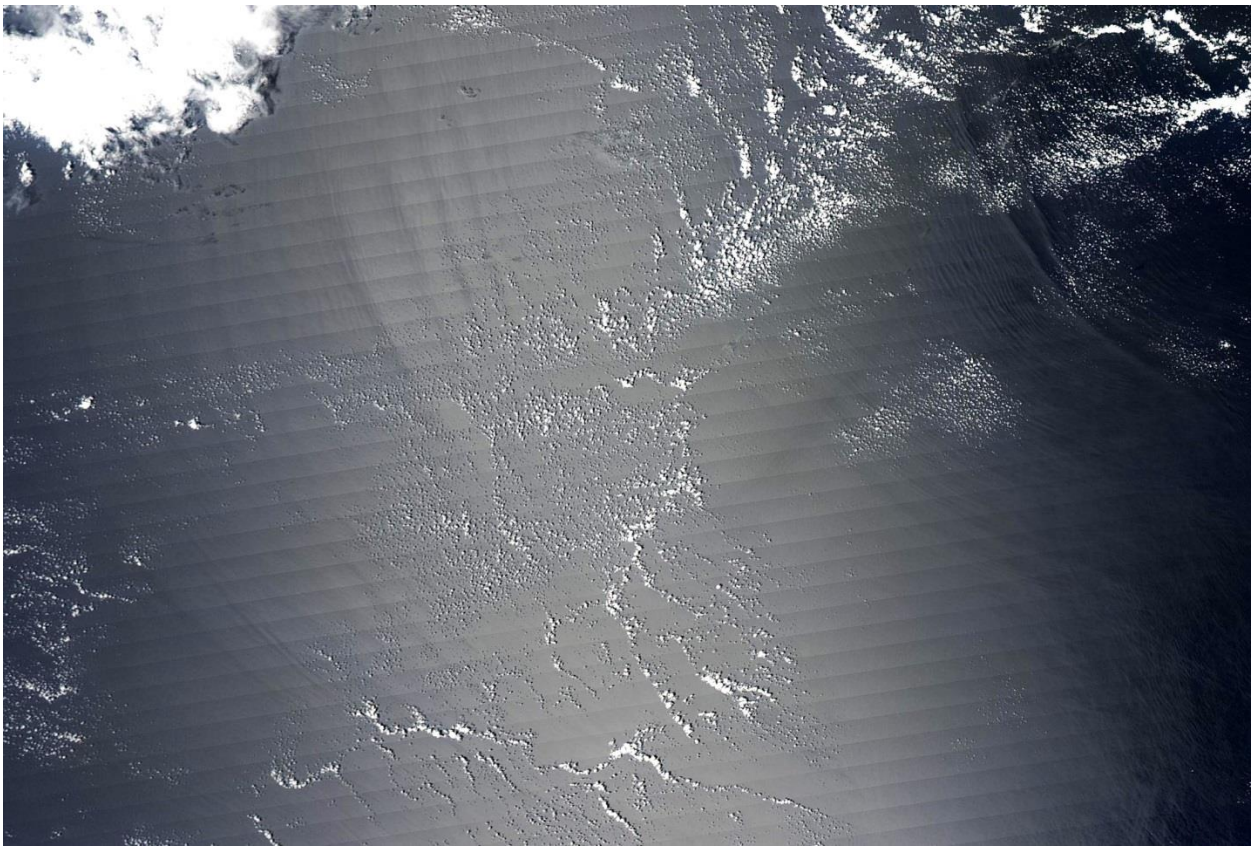

Figure 5. 23 February 2015. MODIS/Aqua.

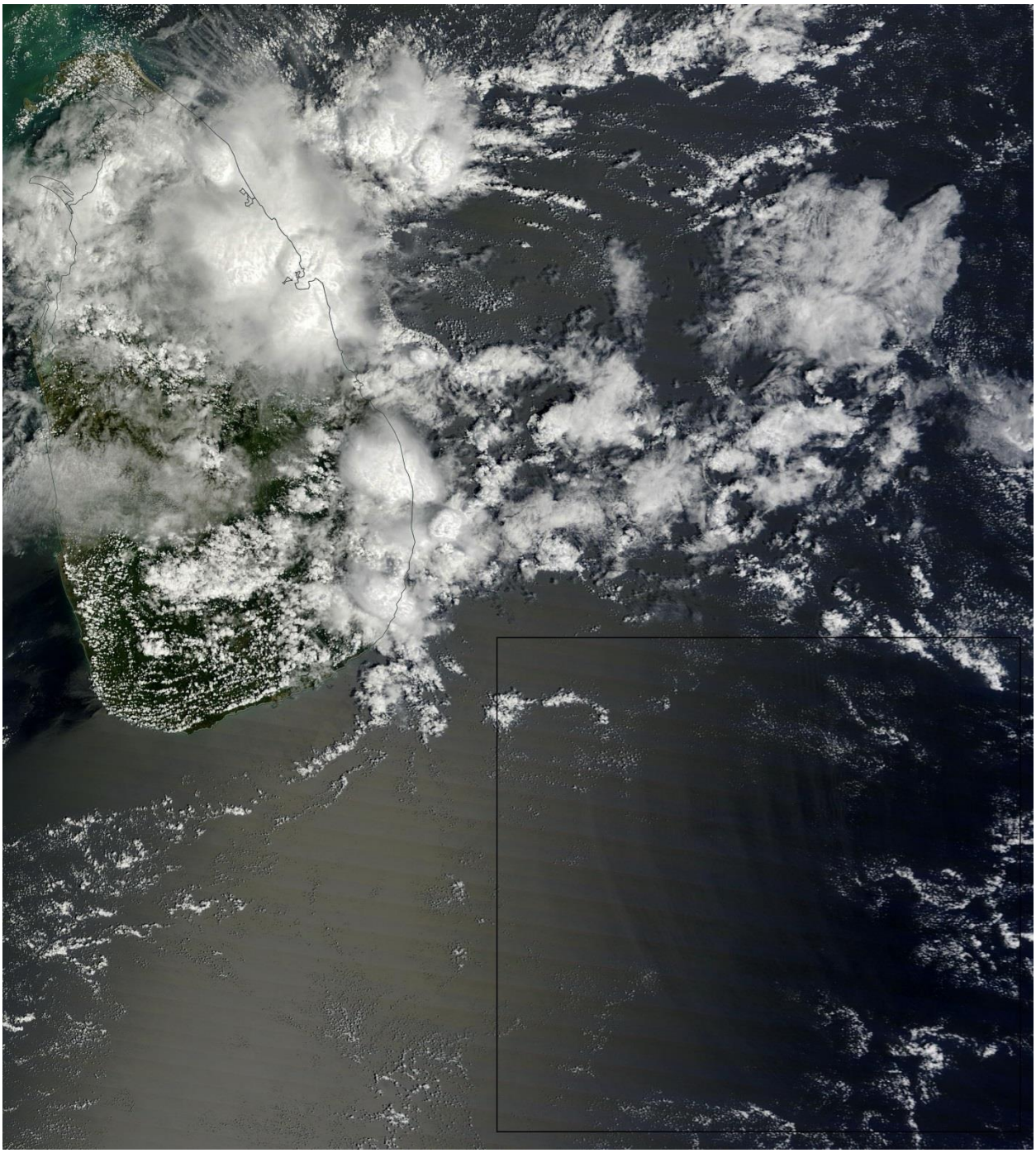

Figure 6. 24 February 2015. MODIS/Terra.

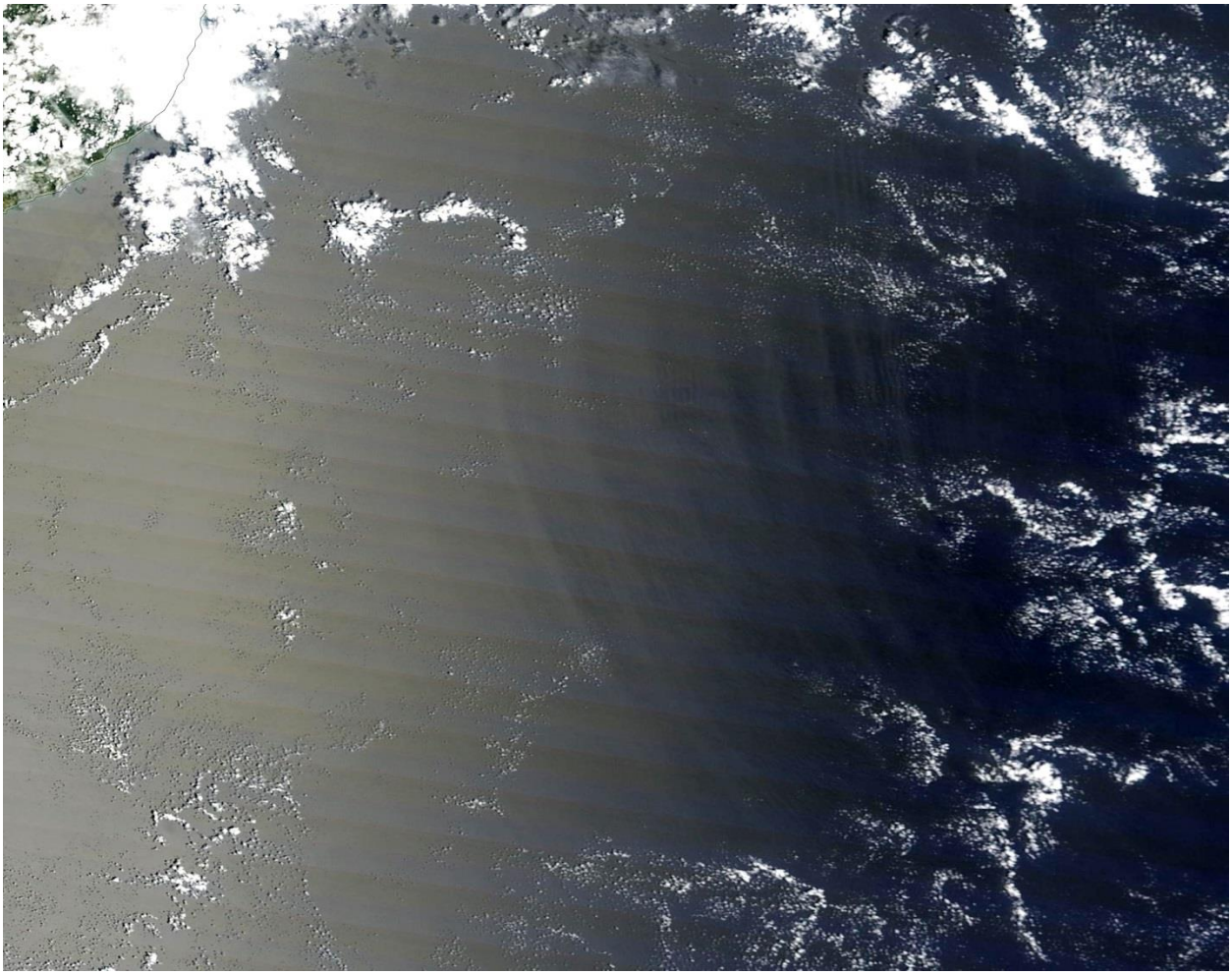

Figure 7. 24 February 2015. MODIS/Terra. Zoom of black rectangle in previous figure.

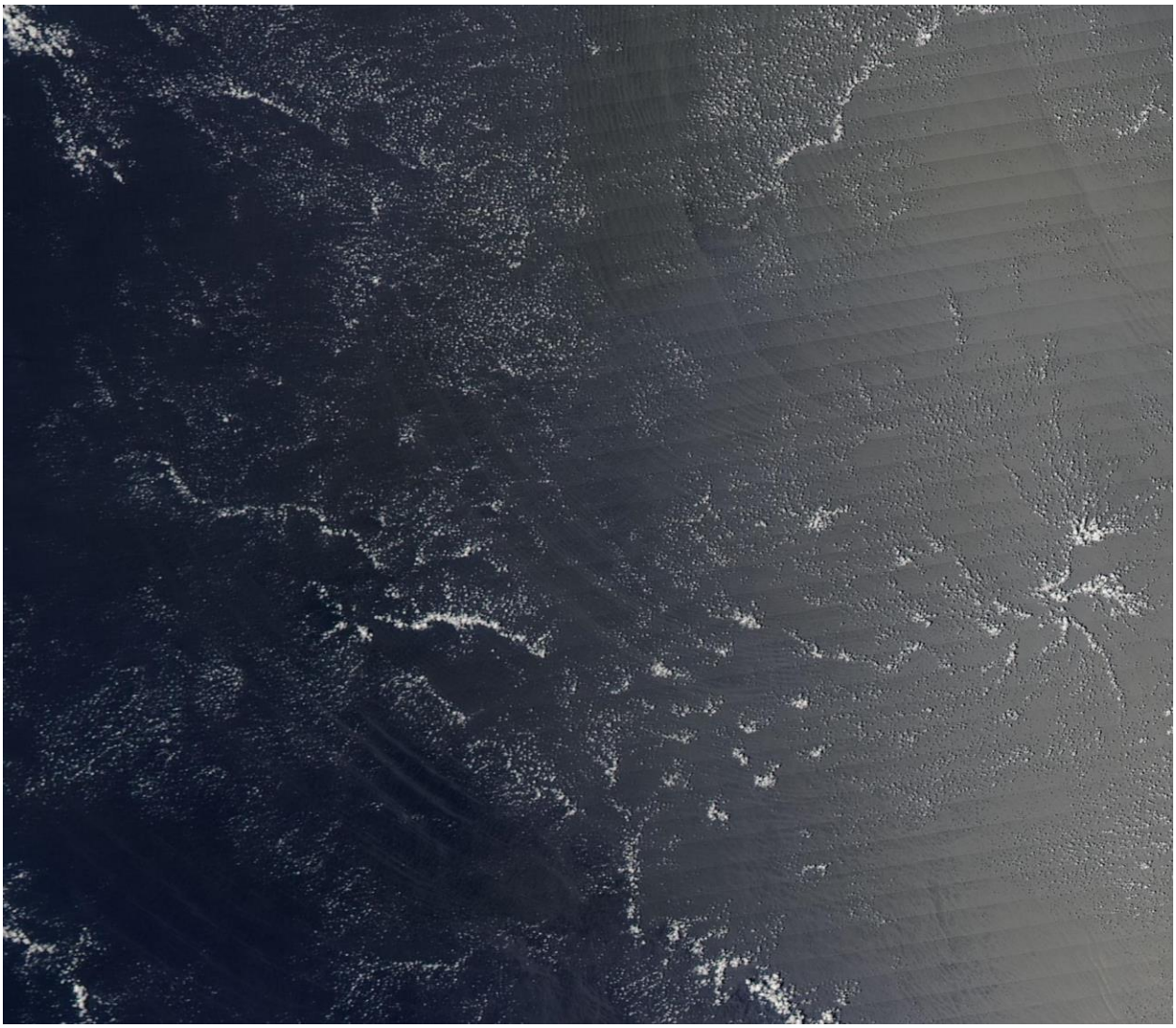

Figure 8. 25 February 2015. MODIS/Aqua. Five packets of ISWs propagating Southwest (246° T). Speeds and Indian Ocean crossing times are shown in the table below.

	Date	Satellite	Time Interval (s)	Distance between ISWs Packets (m)	Speed (m/s)	Indian Ocean Crossing Time (days)
1	2/24/2015 5:19	Terra				
2	2/23/2015 7:35	Aqua	78240	230000	**2.9**	**9.5**
1	2/25/2015 7:22	Aqua	44712	118000	2.6	
2	2/25/2015 7:22	Aqua	44712	101000	2.3	
3	2/25/2015 7:22	Aqua	44712	122000	2.7	
4	2/25/2015 7:22	Aqua	44712	138000	3.1	
				Mean	**2.7**	**10.5**

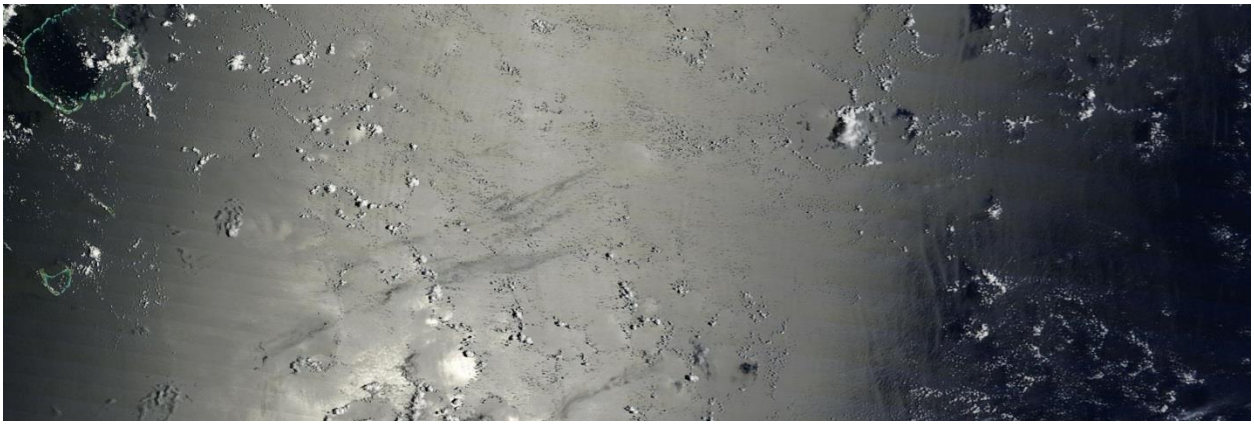

Figure 9. 17 March 2015. MODIS/Terra. ISWs approaching Addu Atoll from the East.

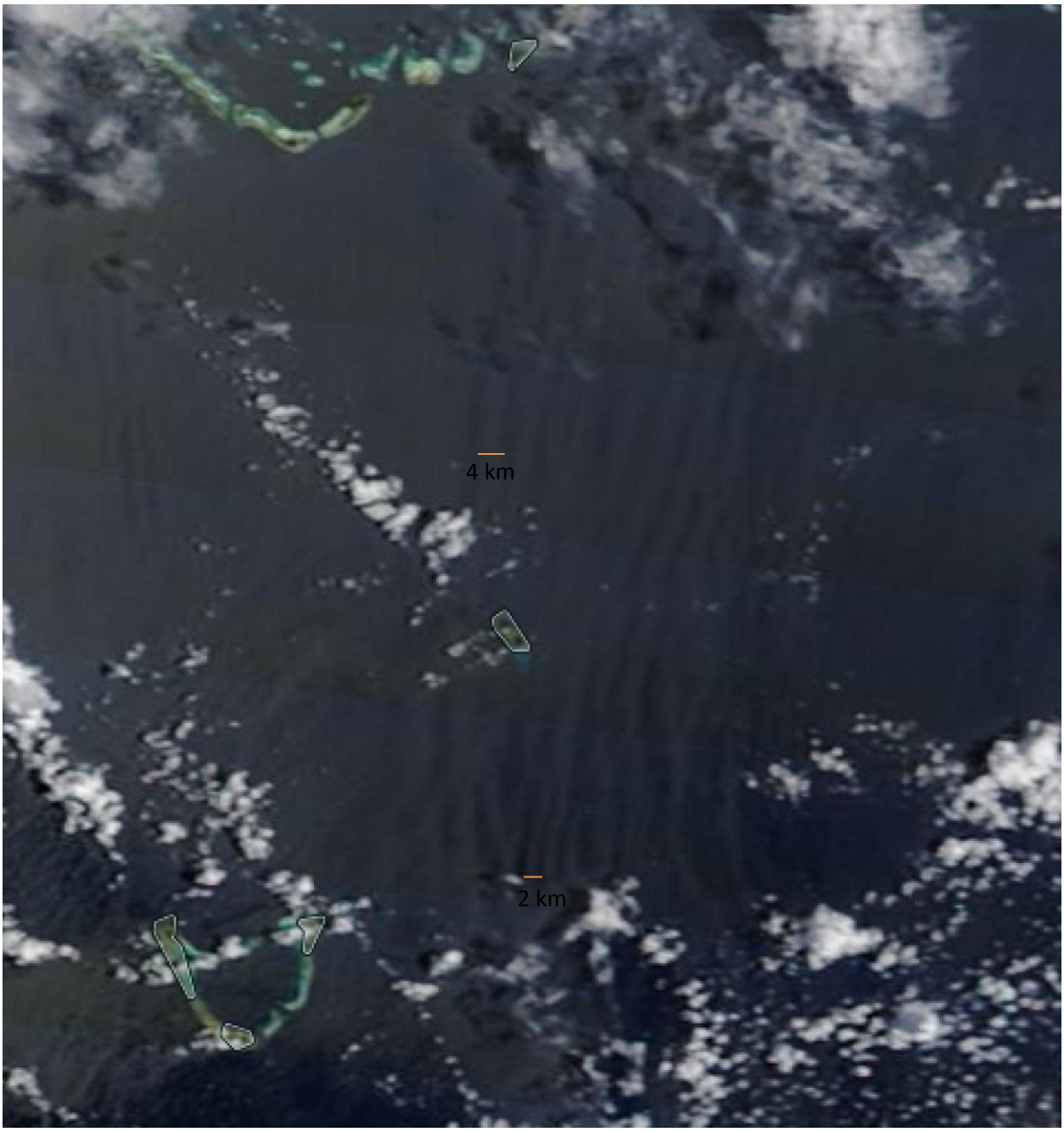

Figure 10. 22 March 2015. MODIS/Terra. Internal waves entering the Equatorial Channel, the wavelengths run from 2 to 4 km; south of the entrance of Gan Channel the wavelengths are 1.1 km.

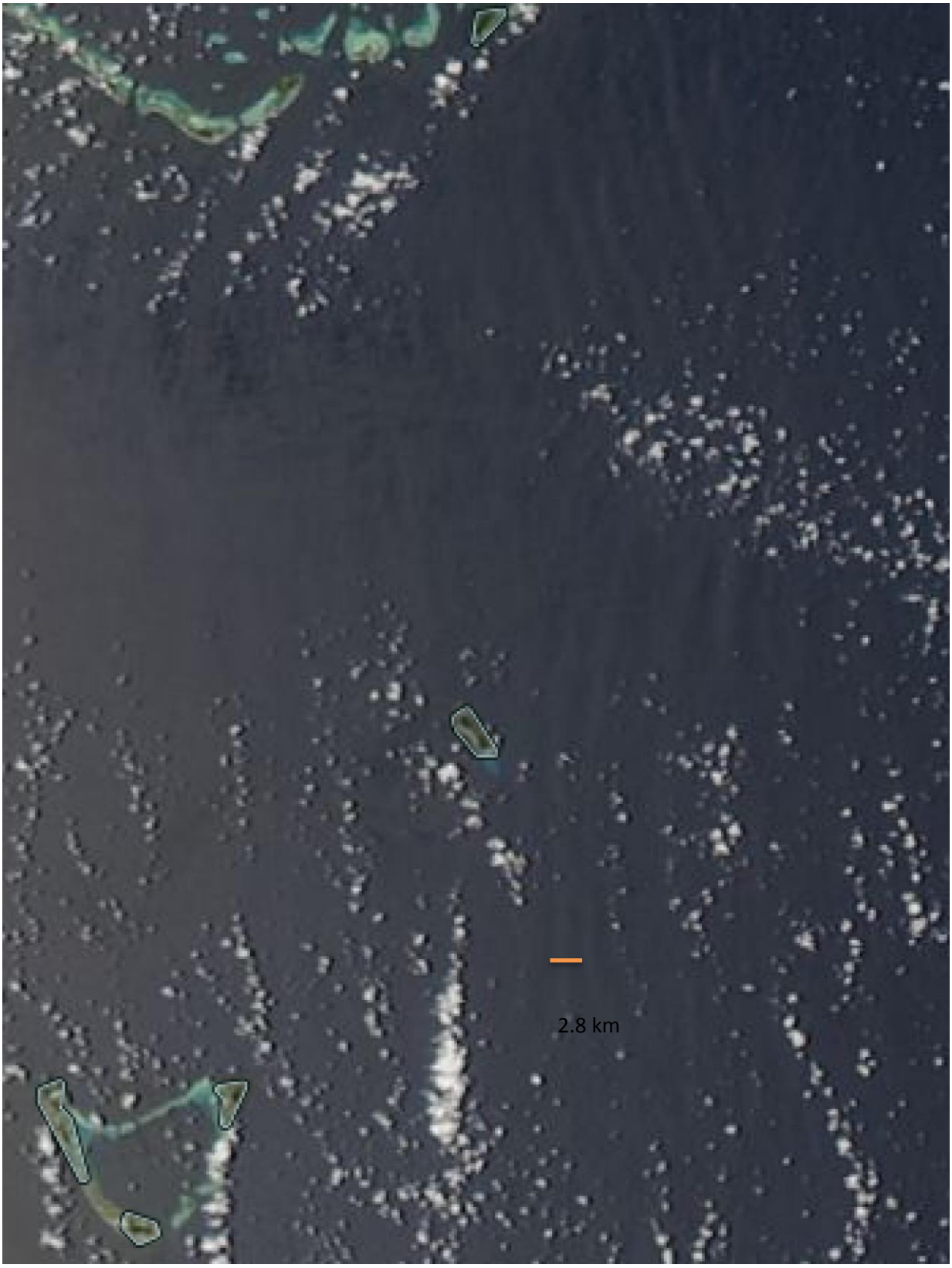

Figure 11. 24 March 2015. MODIS/Aqua. Internal waves northeast of Addu Atoll; wavelength 2.8 km.

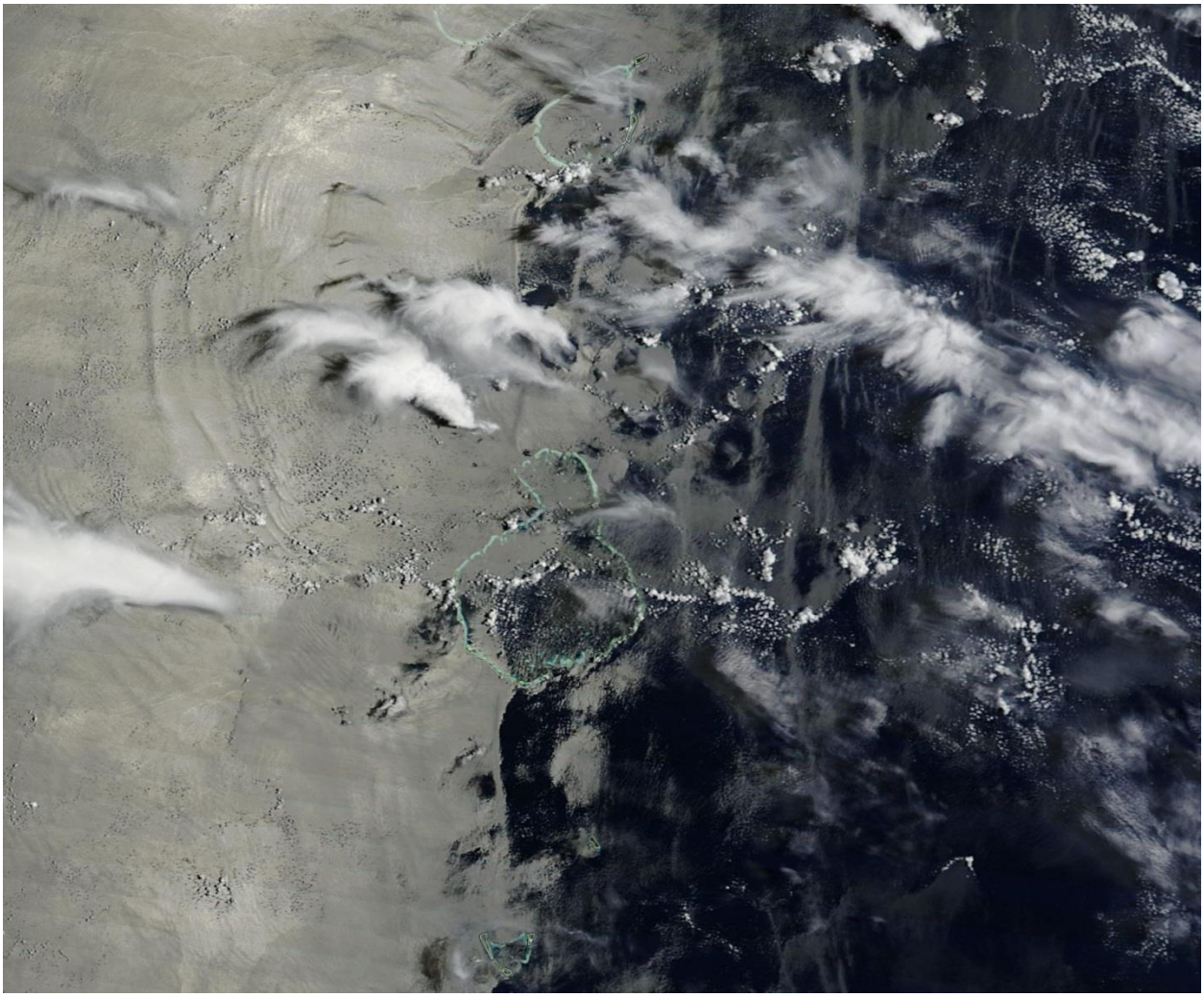

Figure 12. 31 March 2015. MODIS/Terra. Internal solitary waves entering and exiting the 1.5 degree Channel separating the Huvadhoo Atoll and the Hadhdhunmathee Atoll, larger wavelengths run from 7.6 km to 15 km.

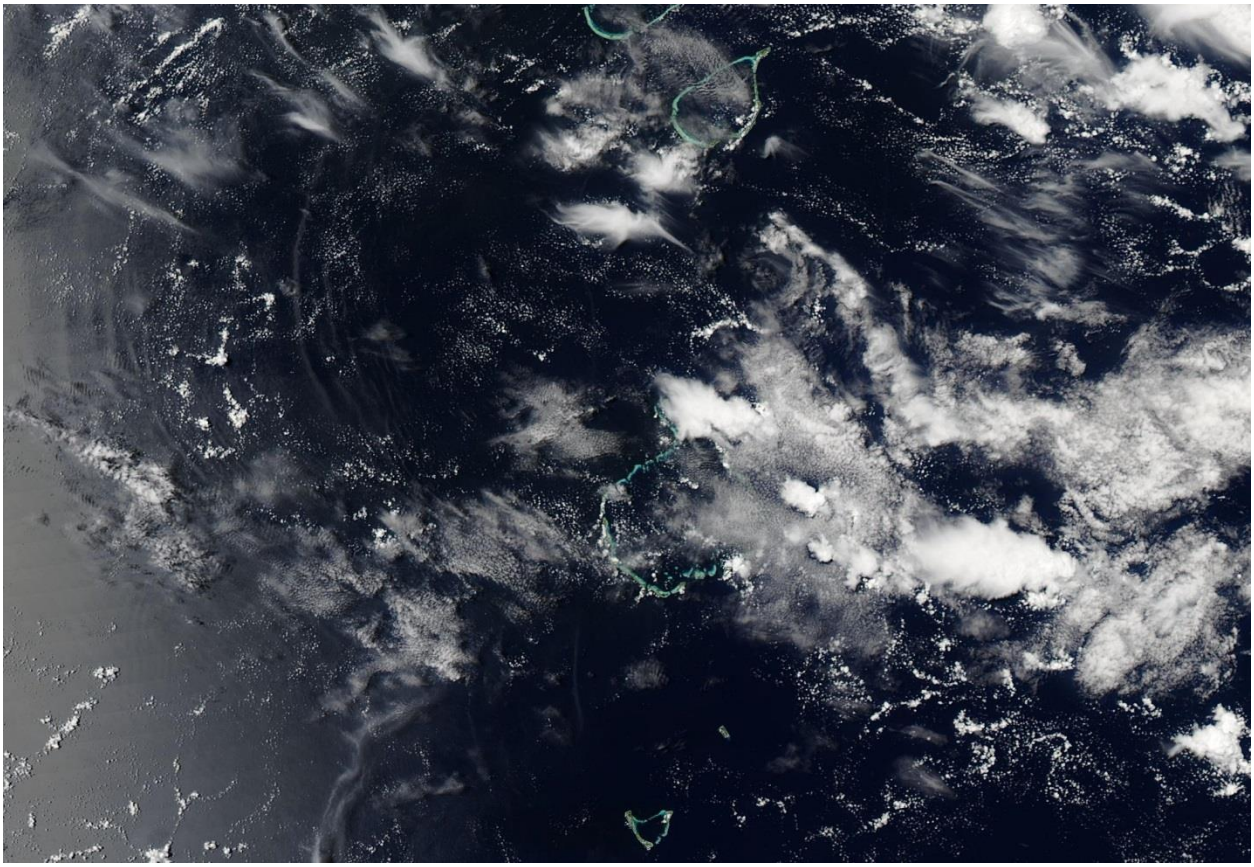

Figure 13. 31 March 2015. MODIS/Aqua. Two packets of ISWs exiting the 1.5 degree Channel separating the Huvadhoo Atoll and the Hadhdhunmathee Atoll.

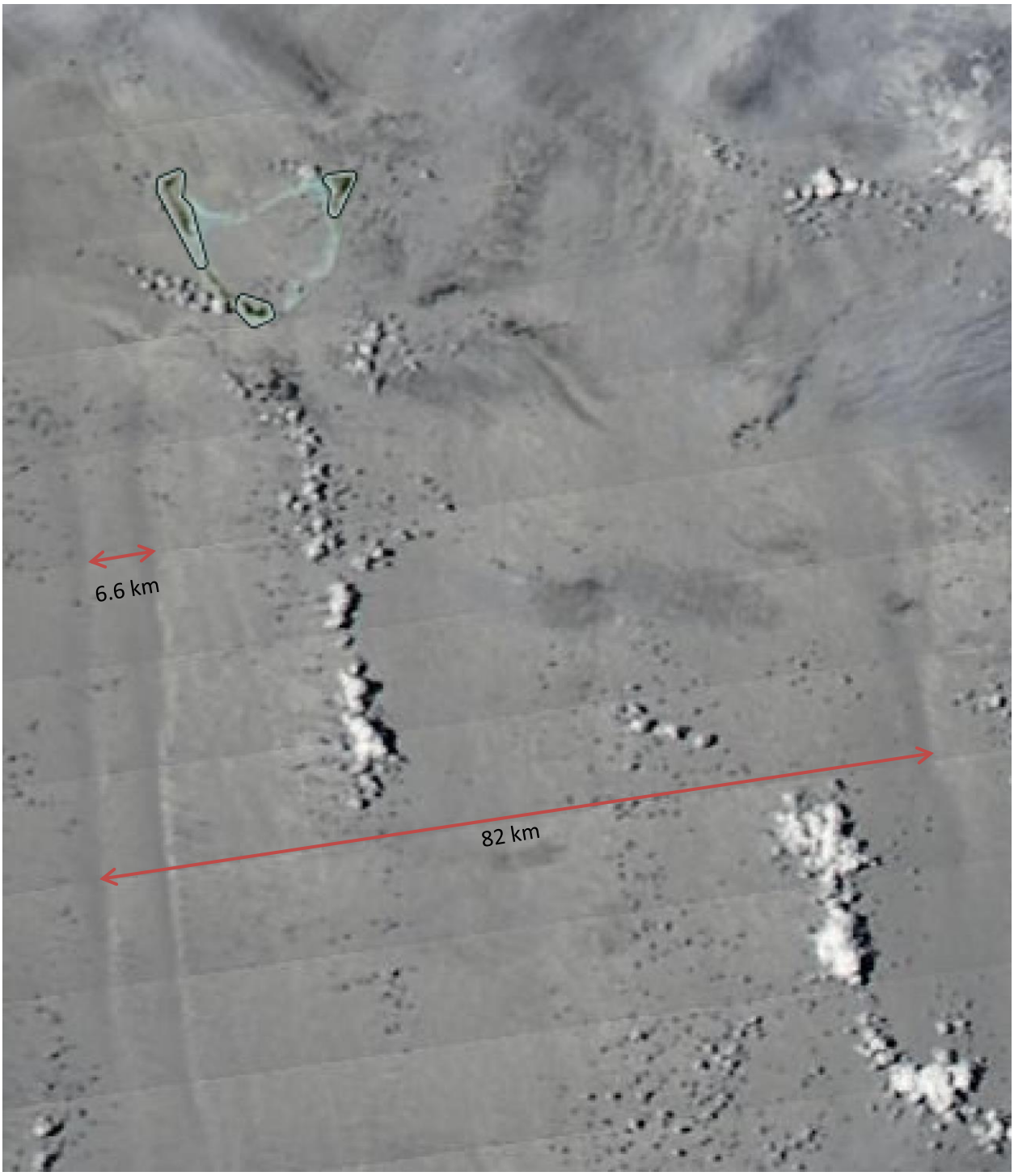

Figure 14. 2 April 2015. MODIS/Aqua. Wavelengths run from 3 km to 6.8 km and the packet separation is about 82 km.

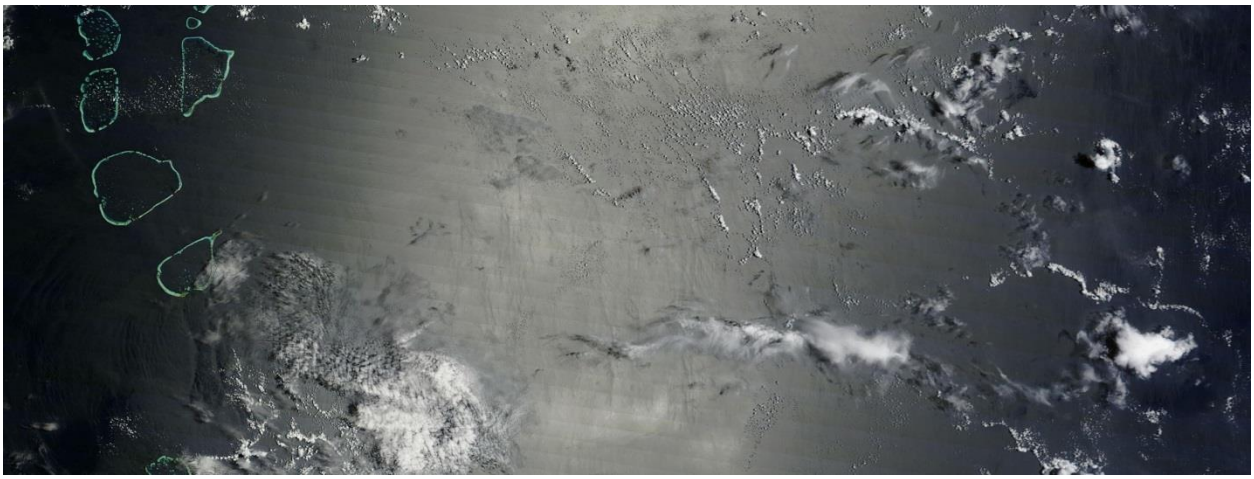

Figure 15. 2 April 2015. MODIS/Terra.

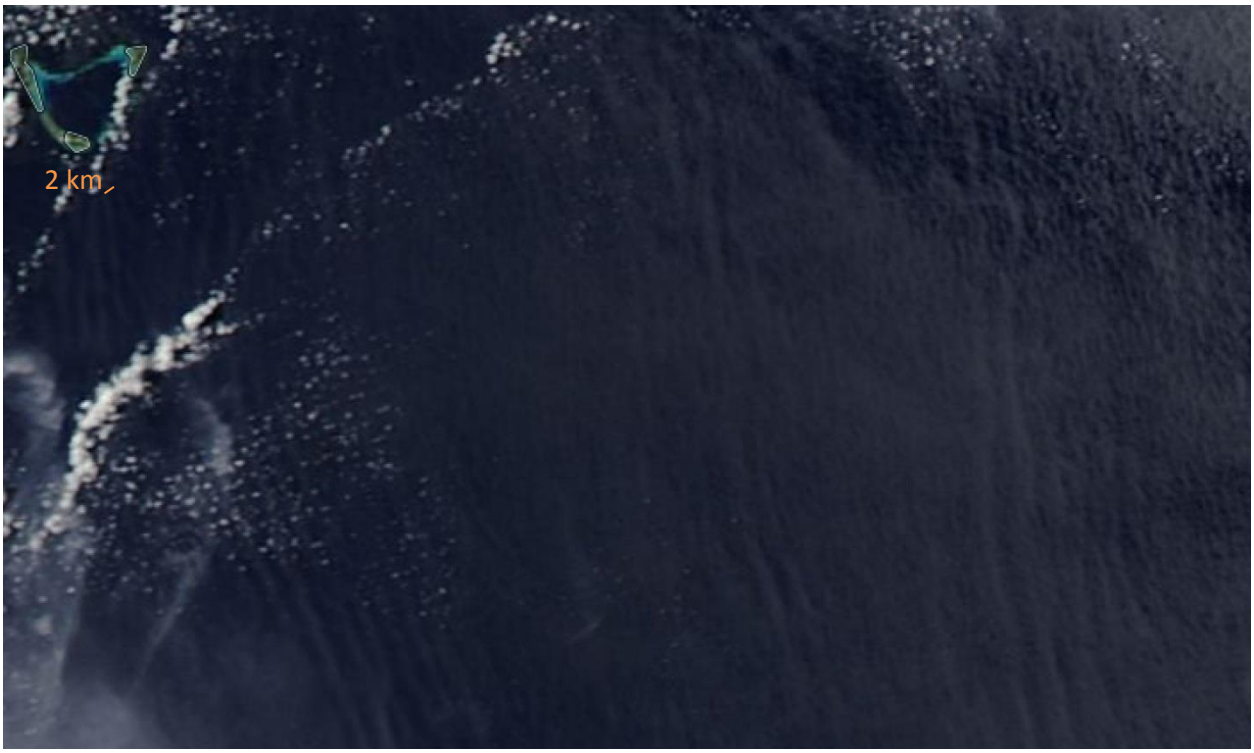

Figure 16. 4 April 2015. MODIS/Aqua. Wavelengths run from 2 km to 4 km. South of Gan Channel the wavelength is 2 km (orange line).

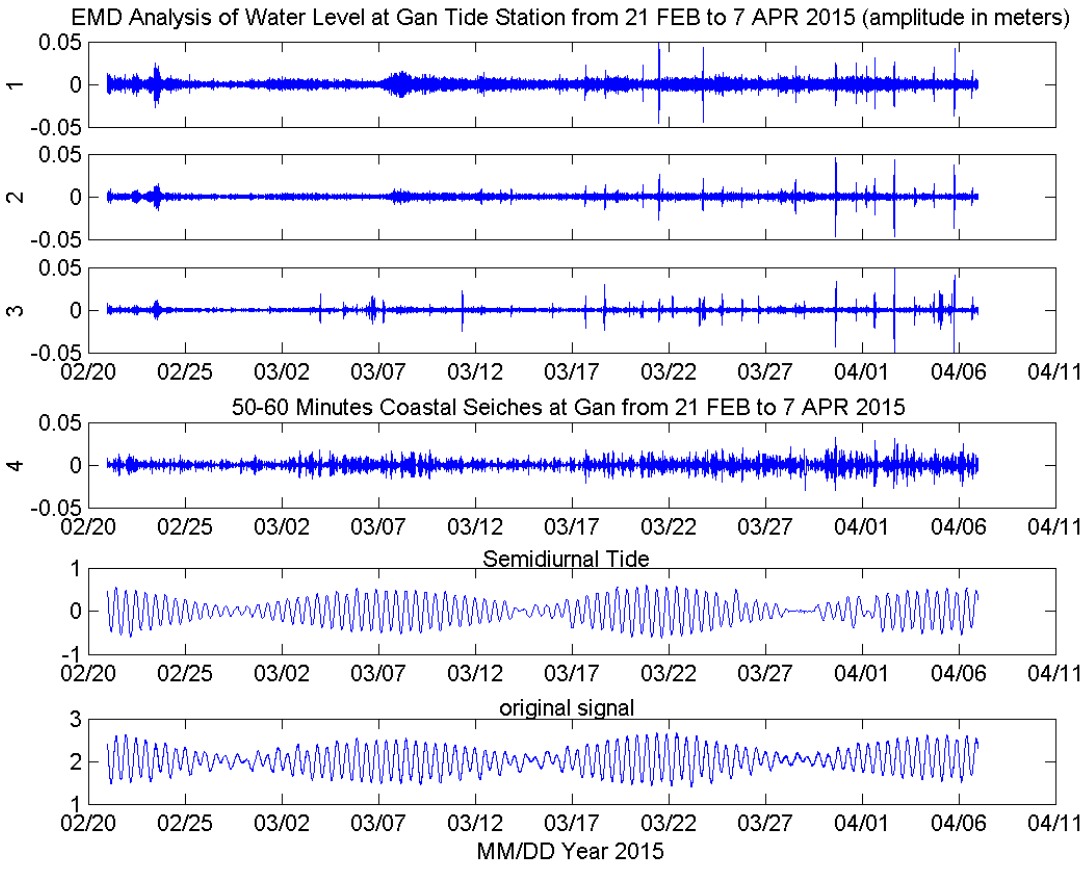

Figure 17. Empirical Mode Decomposition (EMD) analysis of water levels at Gan tide station from February 21 2015 to April 7, 2015.

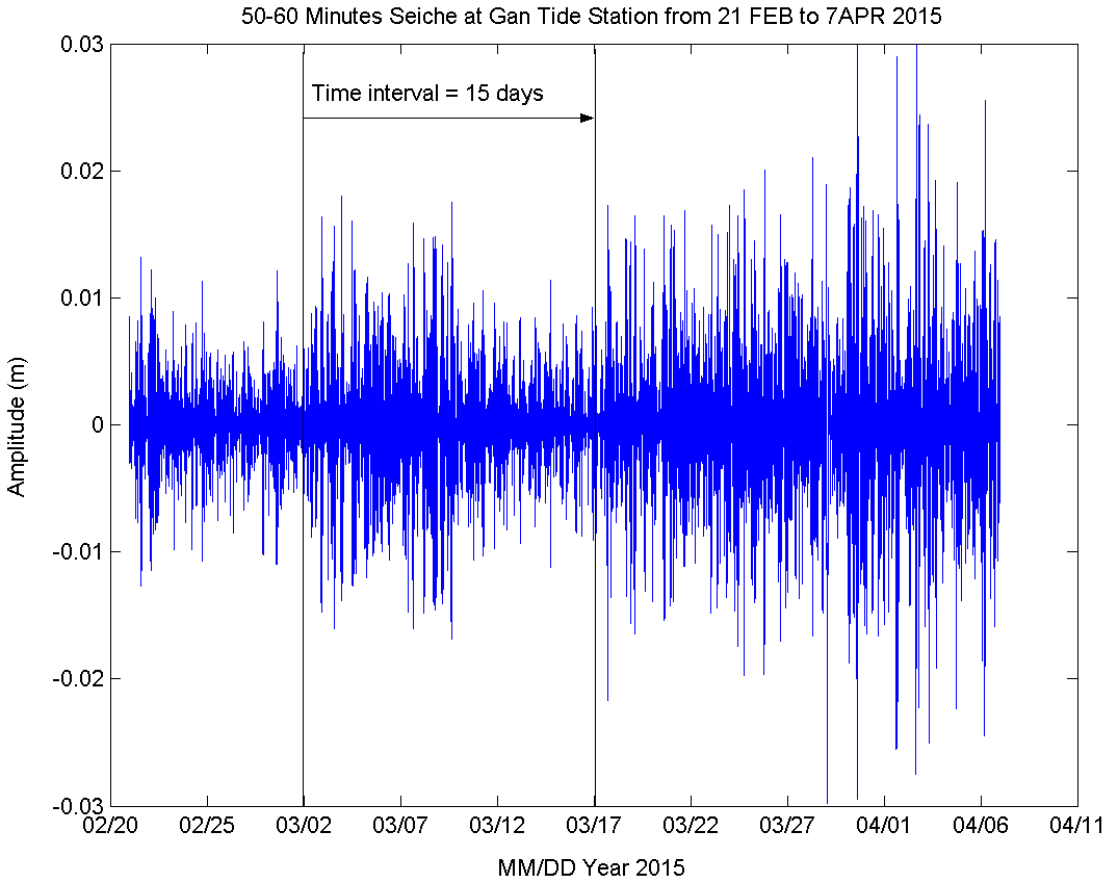

Figure 18. The fourth component of the EMD analysis from February 21 2015 to April 7, 2015.

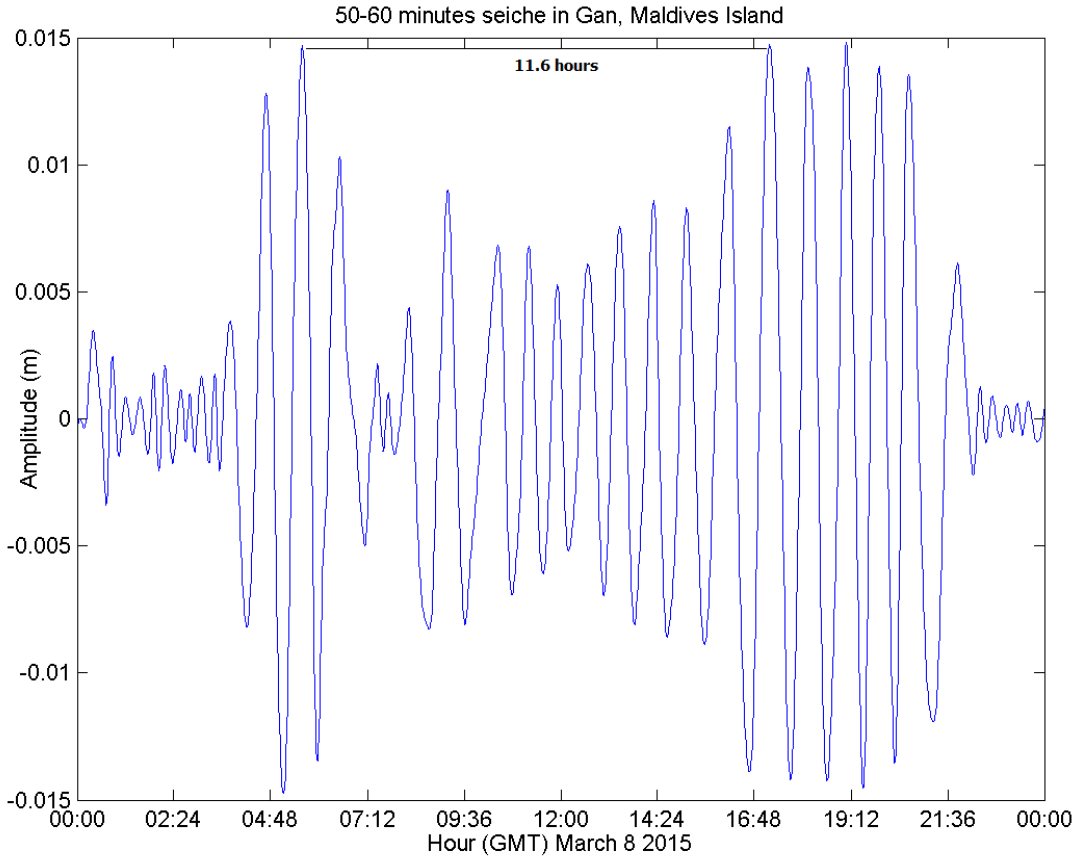

Figure 19. The fourth component of the EMD analysis on March 8, 2015.

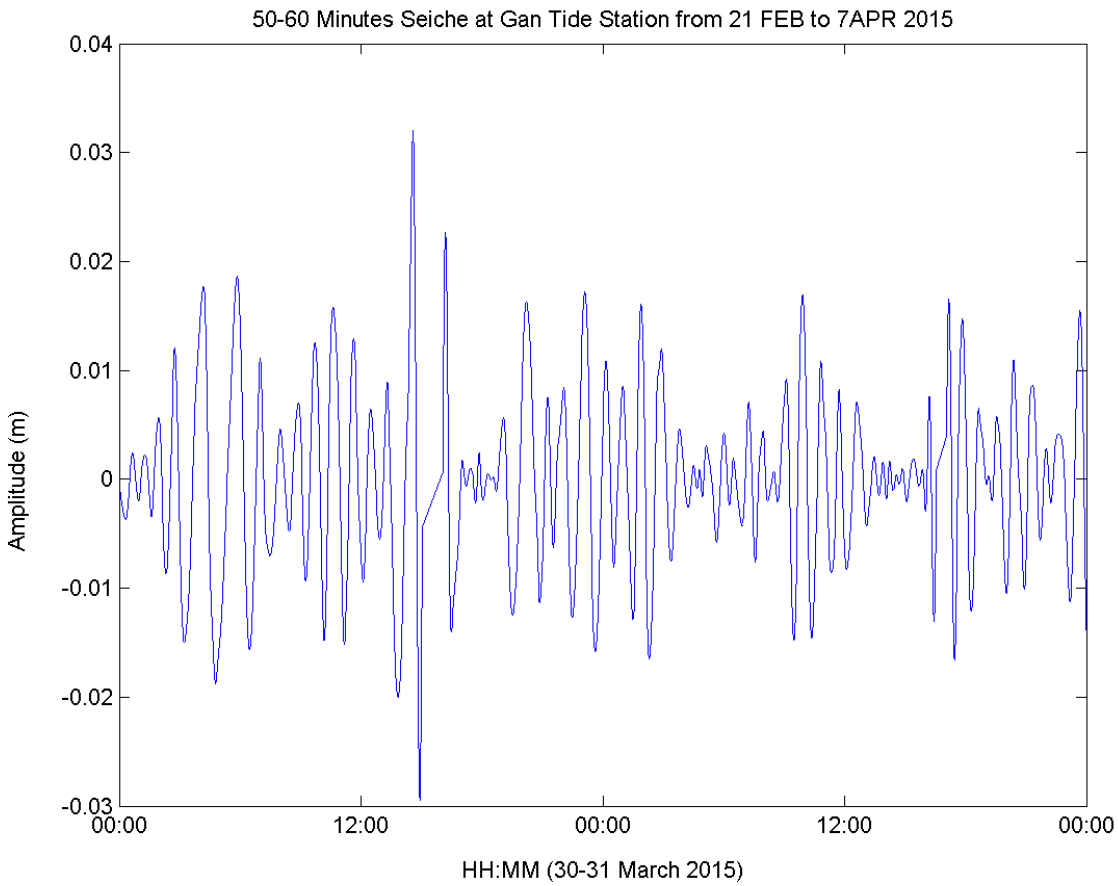

Figure 20. The fourth component of the EMD analysis from March 30 to March 31, 2015.

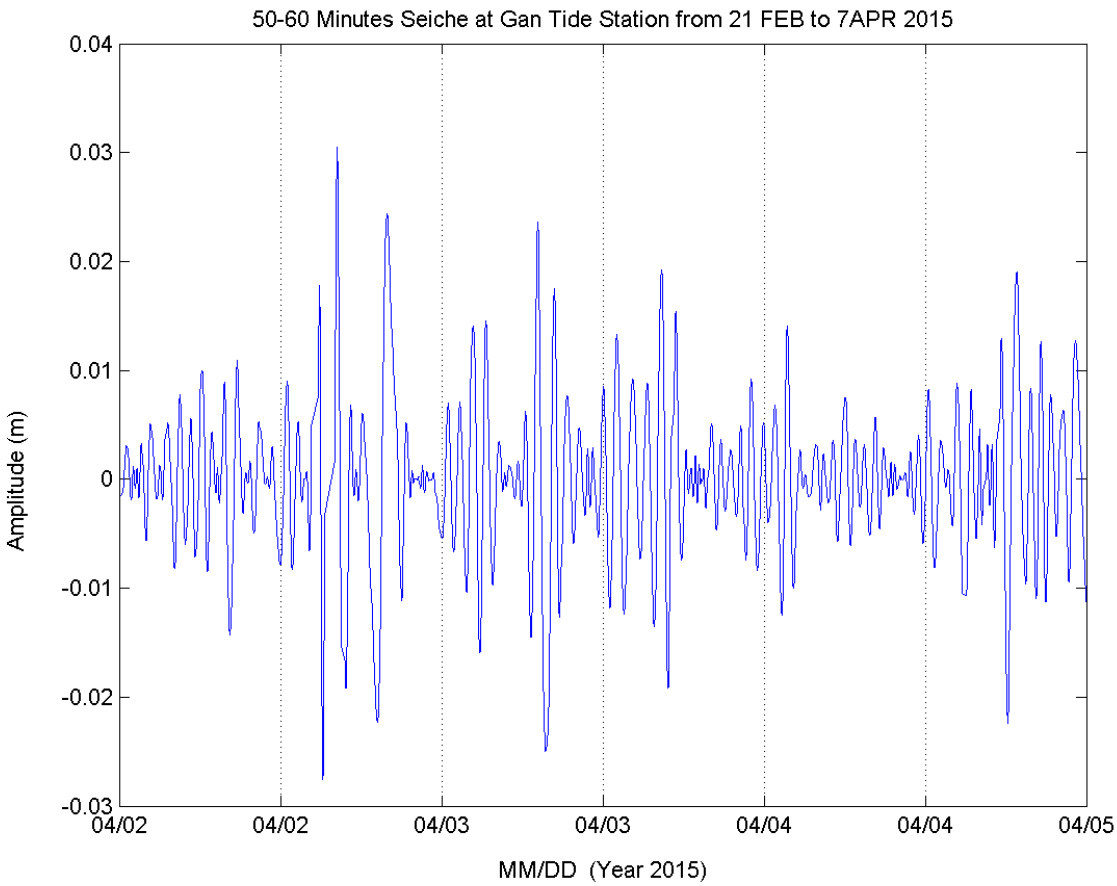

Figure 21. The fourth component of the EMD analysis from April 2, 2015 to April 5, 2015.

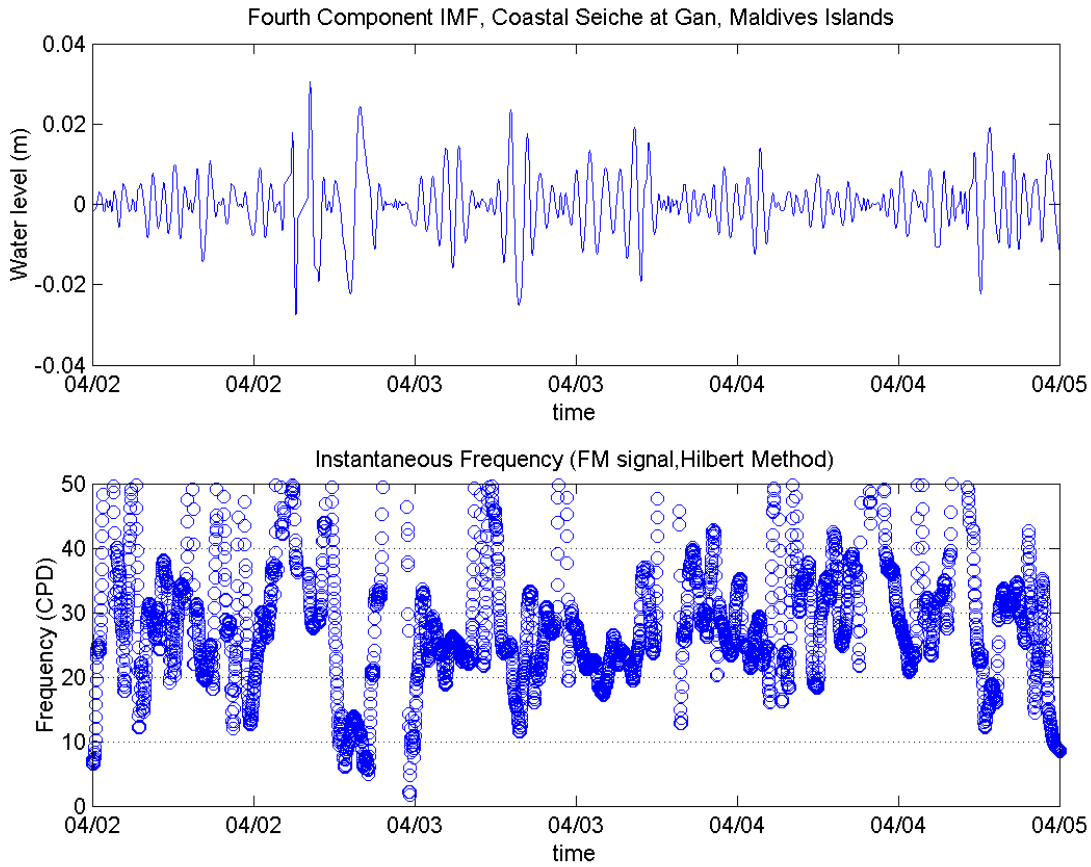

Figure 22. (Top) The fourth component of the EMD analysis from April 2, 2015 to April 5, 2015. (Bottom) Instantaneous frequency in cycles per day of the above seiche signal.