Tide-Generated Internal Solitary Waves from the Sumba Strait excite Coastal Seiches in Christmas Island

After the ISWs crossed 1503 km of the Indian Ocean in about 8 days

By

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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 Sape and Sumba Straits 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 ISWs packets propagated west-southwest (2.24 m/s) and crossed 1503 km of Indian Ocean in about 8 days to excite 2.3-minutes coastal seiches in Flying Fish Cove – Christmas Island (AUS). The seiche amplitudes range between 0.1 m and 0.3 m. Satellite images and sea level data evidence the relationship between 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 Indonesian straits are a conduit for the transport of tropical Pacific Ocean water into the Indian Ocean. The Indonesian Throughflow (IT) mainly crosses the Lombok Strait - connecting the Flores Sea to the Indian Ocean - and moves warm and lower density water over Indian Ocean water contributing to a well stratified water column. Similarly, the Sape Strait - connecting the Flores Sea to the Sumba Strait - is a secondary branch of the IT. Both narrow straits are characterized by sill depths of about 300 m and strong tidal currents. All these conditions are favorable to generate internal waves. The west end of Sumba strait its limited at the south by the NW coast of Sumba island and about 88.5 kilometers due north by the Sape strait. Strong semidiurnal tidal currents flow north-south through the 10-km wide Sape strait and generate ISWs packets. Satellite Synthetic Aperture Radars have revealed the generation of internal solitary waves (ISWs) packets in the Lombok strait (Mitnik et al., 2000; Susanto et al., 2005; Karang et al., 2012). The larger swath area 250m-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) had detected these waves in most of the Indonesian Seas (Bali Sea, Banda Sea, Flores Sea, Savu Sea, north and south of the Lombok Strait and in the Sumba Strait) (Jackson C., 2007). MODIS true-color images during fortuitous sunglint conditions allows a easy detection of the

ISWs packets. A recent catalog shows fifteen 250m-resolution true color MODIS images of ISWs in the Sumba Strait mostly during strong semidiurnal tidal forcing in the Sape Strait (Alfonso-Sosa, 2015). The ISWs packets exit the Sumba Strait and propagate in a west-southwest direction toward Christmas Island.

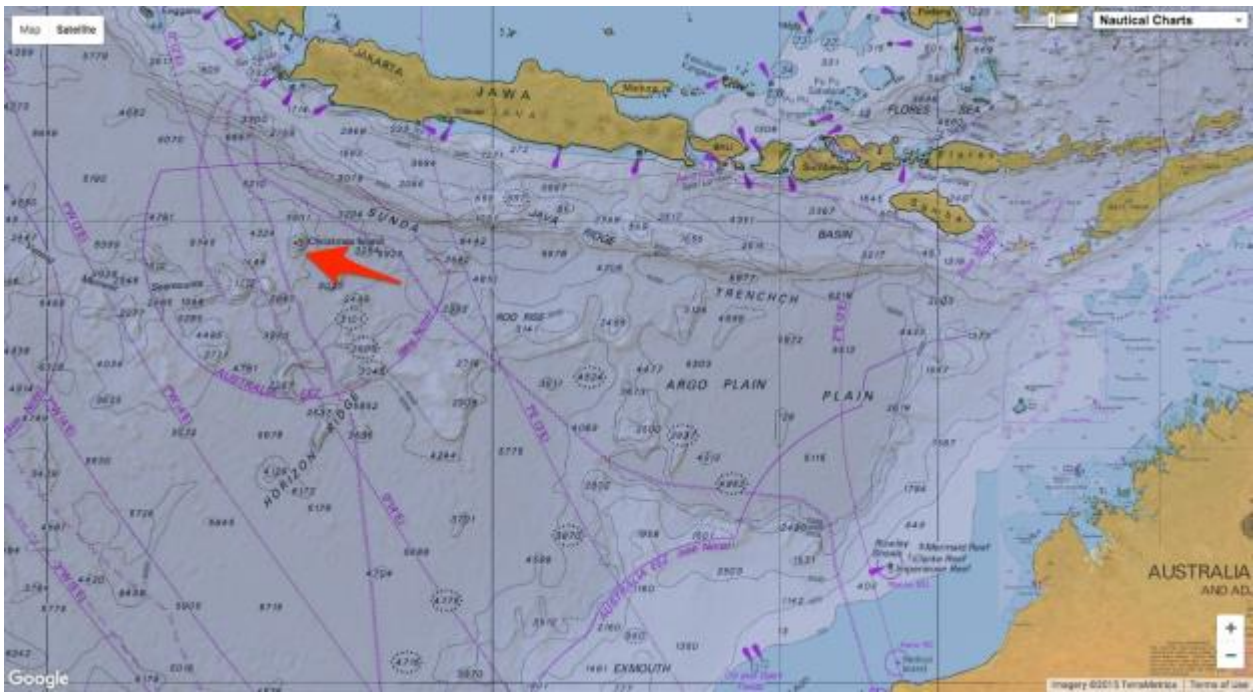
The distance separating the Sumba Strait from Flying Fish Cove - largest port in Christmas Island - is about 1503 km. The Cove is fronted by a coral reef shelf with white sand, which extends less than 0.2 miles offshore, with a depth of 10 meters (NGA Pub. 175, 2004). A narrow shelf with a length of 320 meters and a shallow depth of 9 m can oscillate with a seiche period of 2.3 minutes. Same short period coastal oscillations are observed in the water level records of the tide gauge located in the Cove (See Figures 21-23). These oscillations are small but increase their height (10 cm - 30 cm) around 9 days after the perigee-spring tides.

Coastal seiches excited by ISWs were first discovered in Magueyes Island and Guánica Harbor, both in the southwest coast of Puerto Rico (Giese et al., 1982). The ISWs generated at Aves Ridge in the Caribbean Sea travel 540 km to impinge in the upper slopes off the edge of the 10 km wide insular shelf, exciting 50-minute coastal seiches. Later, more evidence of coastal seiches excited by ISWs was found in Puerto Princesa, Palawan Island (Giese and Hollander, 1987). Coastal seiches recorded in Trincomalee Bay, Sri Lanka were excited by ISWs that crossed the Bay of Bengal (Wijeratne et al., 2010; Alfonso-Sosa, 2014). In 2016, we discovered that ISWs packets generated at the Nicobar Islands passages during perigean-spring tides can propagate a great distance (2420 km) across the Indian Ocean in 10.5 days before exciting seiches in the waters of the Addu Atoll, Maldives Island (Alfonso-Sosa, 2016). These previous works sustain the hypothesis that the 2.3-minutes coastal oscillations in Flying Fish Cove are coastal seiches excited by distant generated ISWs that impinge on the submarine slopes offshore the Cove. This paper show evidence of these oscillations, their timing and their direct relation with the ISWs exiting Sumba Strait. Satellite images are used to support these relation. At this point, the main purpose of these paper is to reveal the existence of this physical phenomenon. Further studies of the Flying Fish Cove seiche signal will be necessary to be carried on.

Methods

A record of one-minute water levels was obtained from the Sea Level Station Monitoring Facility at Flying Fish Cove, Christmas Island (Australia). Outliers and spikes were removed from the record. The station is maintained by the National Tidal Centre/Australian Bureau of Meteorology. http://www.ioc-sealevelmonitoring.org/station.php?code=chrs

MODIS/Aqua/Terra and SUOMI/VIIRS images were browsed and downloaded using NASA/Worldview. This tool from NASA's EOSDIS provides the capability to interactively browse global, full-resolution satellite imagery and then download the underlying data. Images were selected around the dates of perigee-syzygy (shown in Table 1) for the years 2014, 2015 and 2016. During the whole year 2015 and 2016, the position in the 18.6 Nodal Cycle was favorable for the generation of strong semidiurnal tides and ISWs. This conditions will repeat on year 2034. Another advantage was El Niño conditions on year 2015, allowing cloud-free images. All these favorable conditions made easier the detection of ISWs in the satellite images.



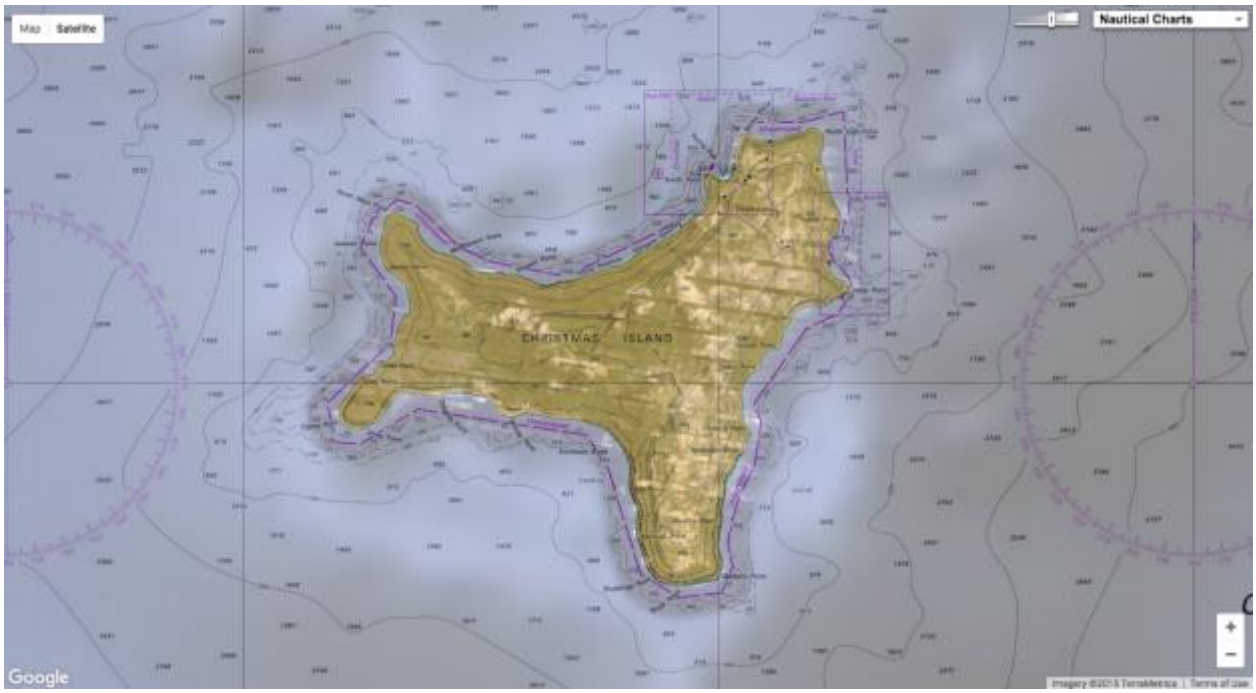


Figure 1. Location of Christmas Island. The Sumba Strait and Christmas Island are separated by 1503 km.

Results

Table 1 shows the dates of the Moon's perigee occurring less than 24 hours from syzygy, for the years 2014, 2015, and 2016. On 2014 these type of events occurred three times, five in 2015, and four in 2016. 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. During the whole year 2015 and 2016, the position in the 18.6 Nodal Cycle was favorable for the generation of strong semidiurnal tides and ISWs. On February 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. The closest perigee of 2015 was on September 28th and the closest perigee of 2016 was on November 14th with a value of 356511 km. All these factors contributed to an exceptional generation of semidiurnal internal tides and ISWs. The last time a full moon was this close occurred 69 years ago, on January 26 1948 with a distance of 356462 km. The next one will occur on November 25 2034 with a perigee of 356447 km.

Table 1 - Times of Perigee and Apogee

MM dd hh:mm Perigee Phase -/+ MM dd hh:mm Apogee Phase -/+

Year 2014

Jan 1 21:01 356921 km - N+ 9h Jan 16 1:54 406536 km + F- 2h

Jan 30 9:59 357079 km - N- 11h Feb 12 5:11 406231 km + F-2d18h

Aug 10 17:44 356896 km ++ F- 0h Aug 24 6:10 406522 km - N-1d 8h

Year 2015

Feb 19 7:31 356991 km - N+ 7h Mar 5 7:36 406385 km + F- 10h

Mar 19 19:39 357583 km N- 13h Apr 1 13:00 406011 km + F-2d23h

Aug 30 15:25 358288 km F+ 20h Sep 14 11:29 406465 km -- N+1d 4h

Sep 28 1:47 356876 km ++ F- 1h Oct 11 13:18 406388 km - N-1d10h

Oct 26 13:00 358463 km F- 23h Nov 7 21:50 405722 km N-3d19h

Year 2016

Apr 7 17:37 357163 km N+ 6h Apr 21 16:06 406350 km + F- 13h

May 6 4:15 357827 km N- 15h May 18 22:07 405933 km F-2d23h

Sep 18 17:01 361893 km F+1d21h Oct 4 11:03 406099 km N+3d10h

Oct 16 23:37 357859 km F+ 19h Oct 31 19:30 406659 km -- N+1d 1h

Nov 14 11:24 356511 km ++ F- 2h Nov 27 20:09 406555 km - N-1d16h

VISUAL INSPECTION OF THE SEALEVEL AT CHRISTMAS ISLAND

Figures 2-14, show plots of tidal heights recorded at Flying Fish Cove and the start times of the excited coastal seiches activity (signaled by a blue arrow). Below the title of each figure we wrote the date of the lunar perigee, followed by the number of elapsed days since the astronomical event and when started the increase in seiche activity. The numbers ranged between 7 and 12 days. The average number is 9.1 days. This means that about 9 days after the perigee-syzygy is highly probable to experiment an increase in coastal seiche activity at Flying Fish Cove, Christmas Island.

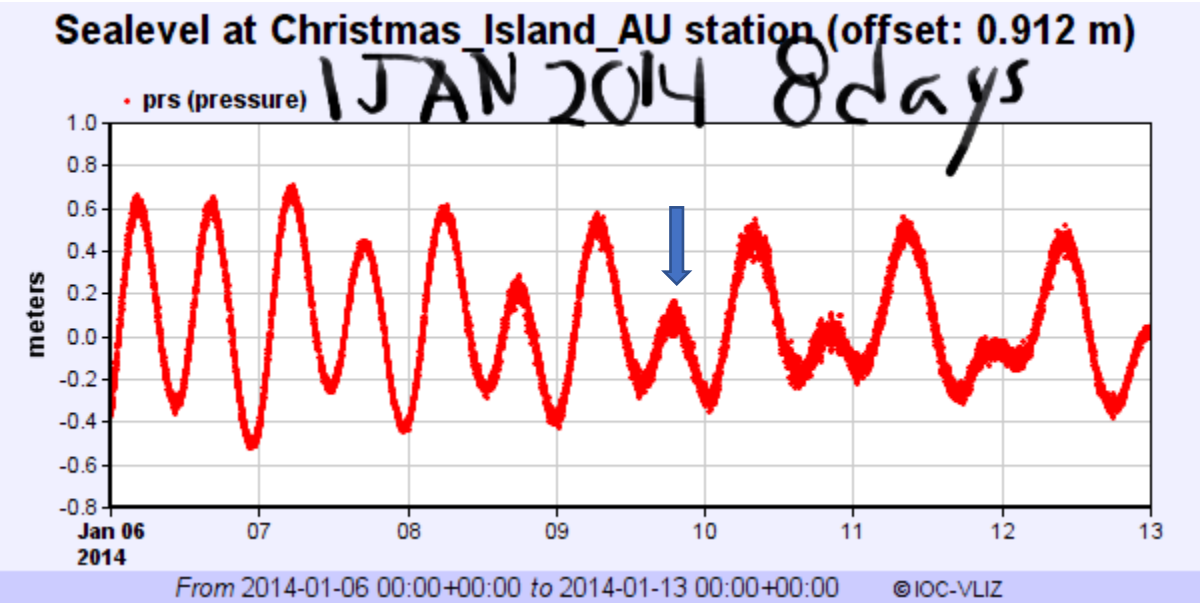


Figure 2

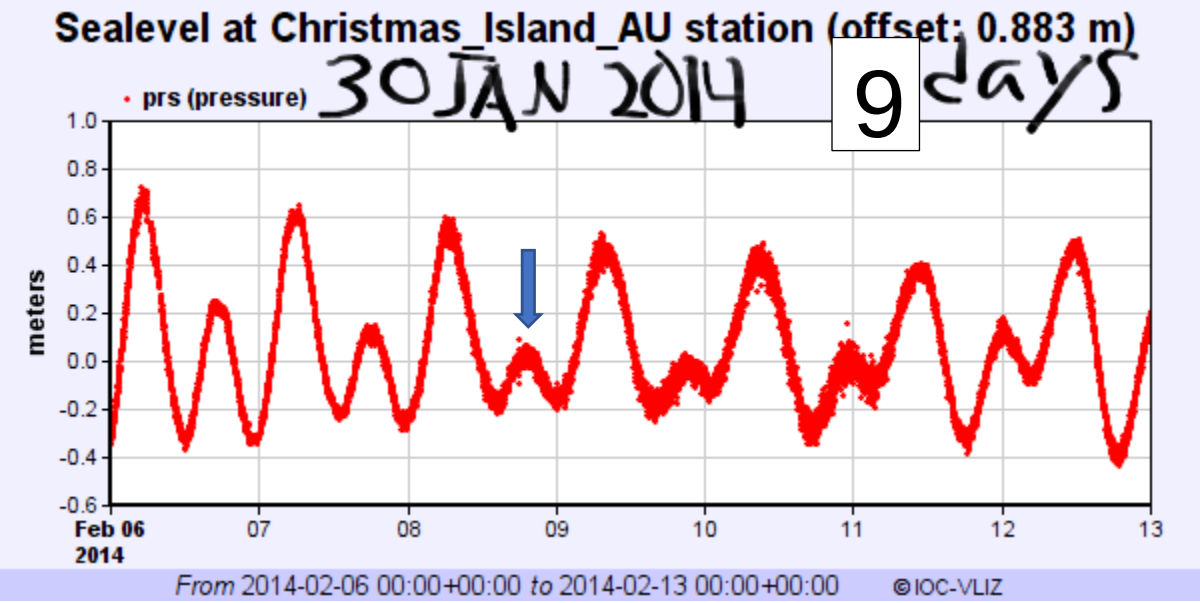


Figure 3

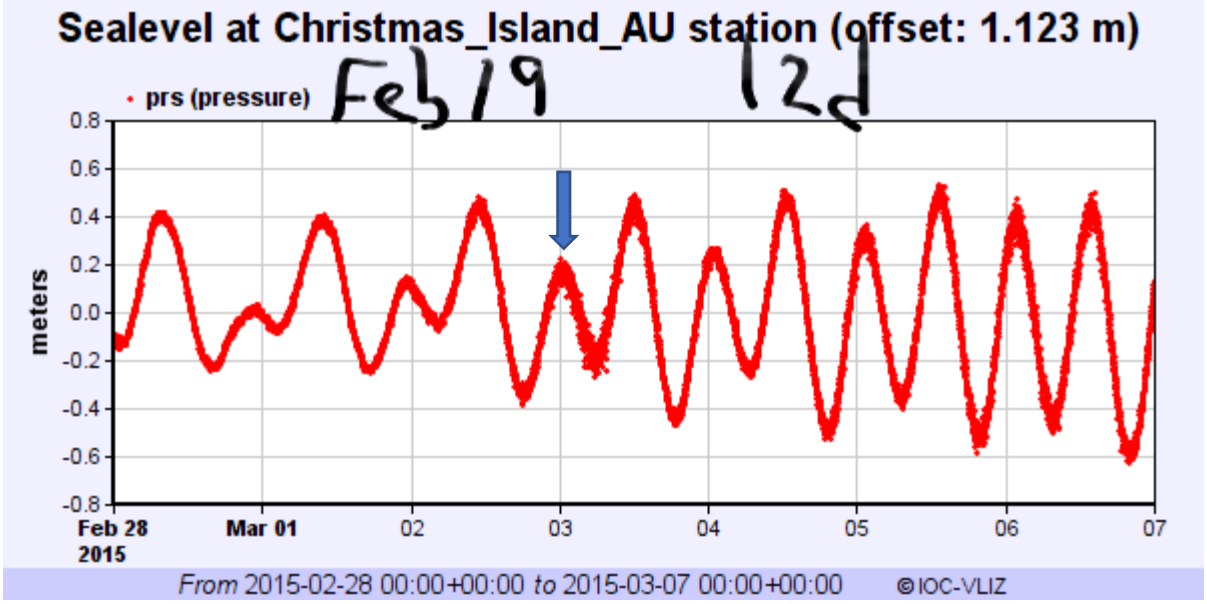


Figure 4.

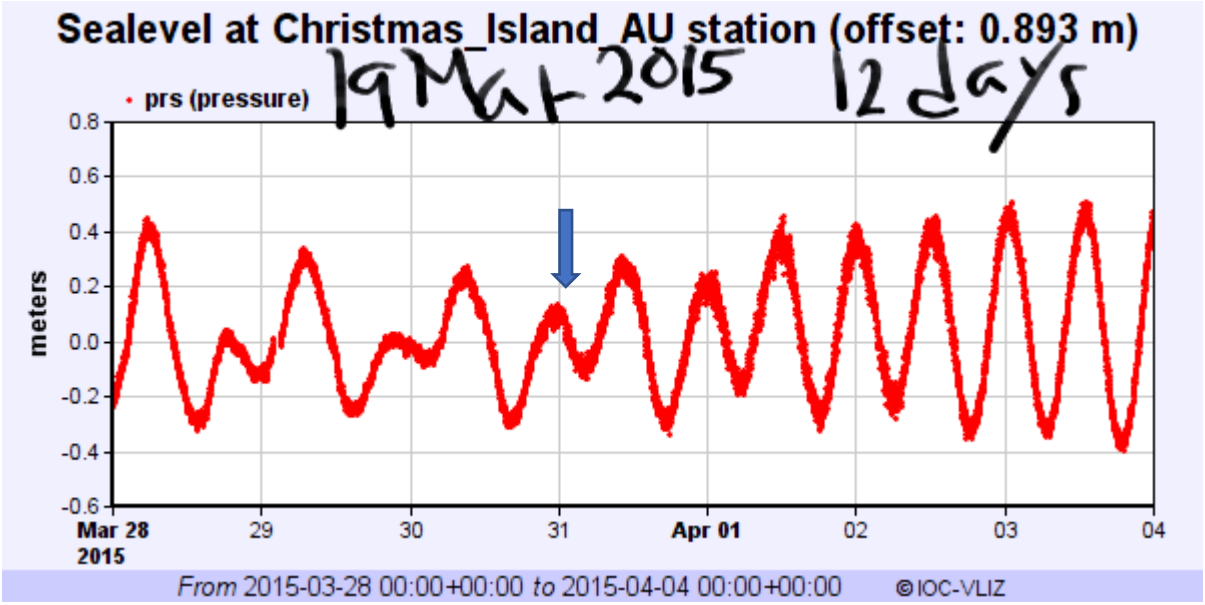


Figure 5. Day of generation of ISW from Sumba Strait was MAR-22-2015, travel time to Christmas Island was 9 days.

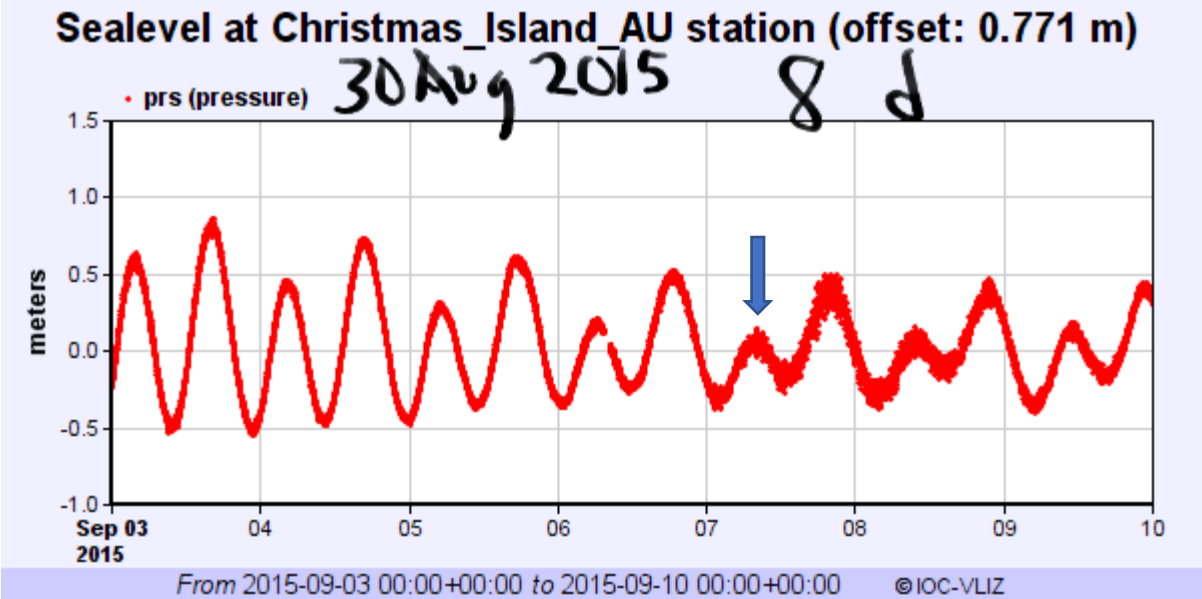


Figure 6.

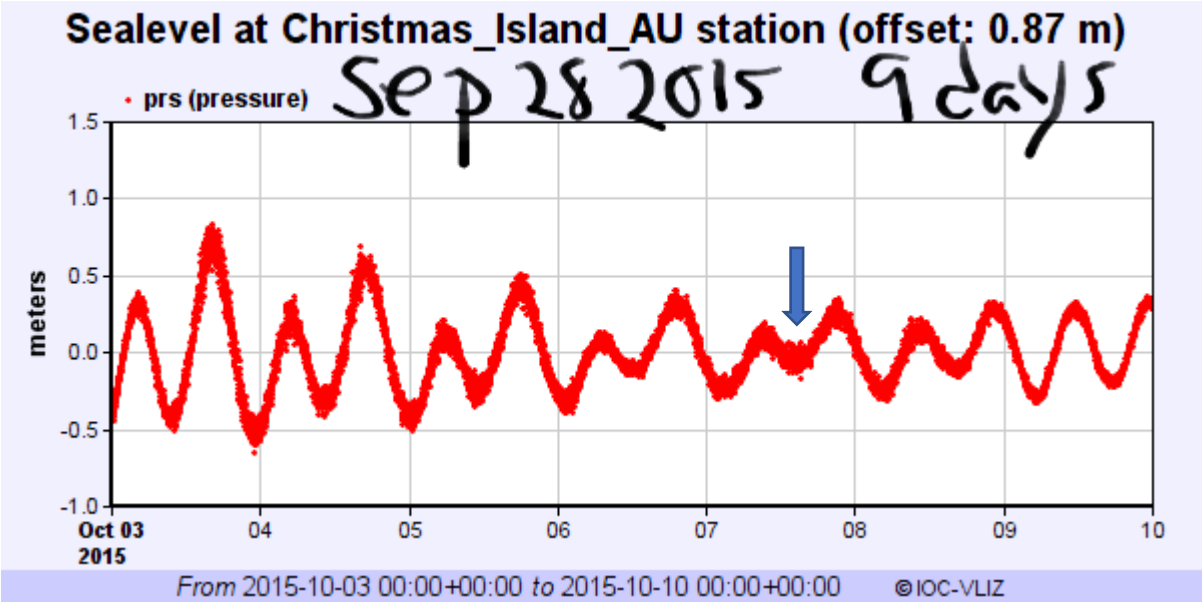


Figure 7. Day of departure of ISW from Sumba Strait was SEP-29-2015, ISW travel time to Christmas Island was 8 days. The blue arrow shows an amplification in the seiche oscillation corresponding to the arrival of the ISW packet.

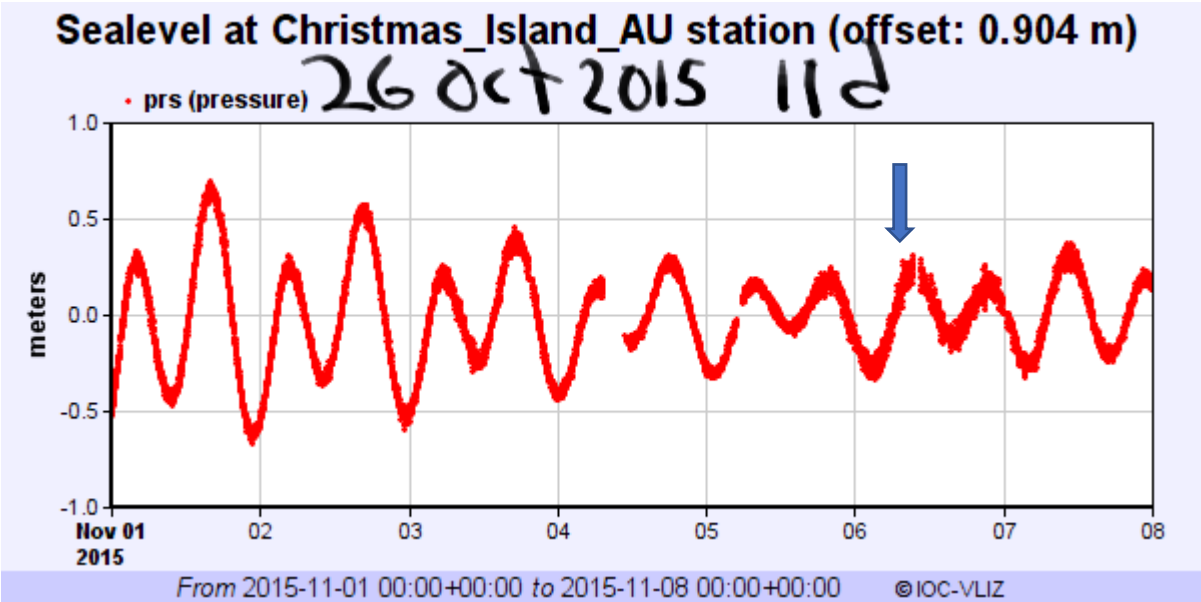


Figure 8. Day of generation of ISW from Sumba Strait was OCT-29-2015, ISW travel time to Christmas Island was 8 days.

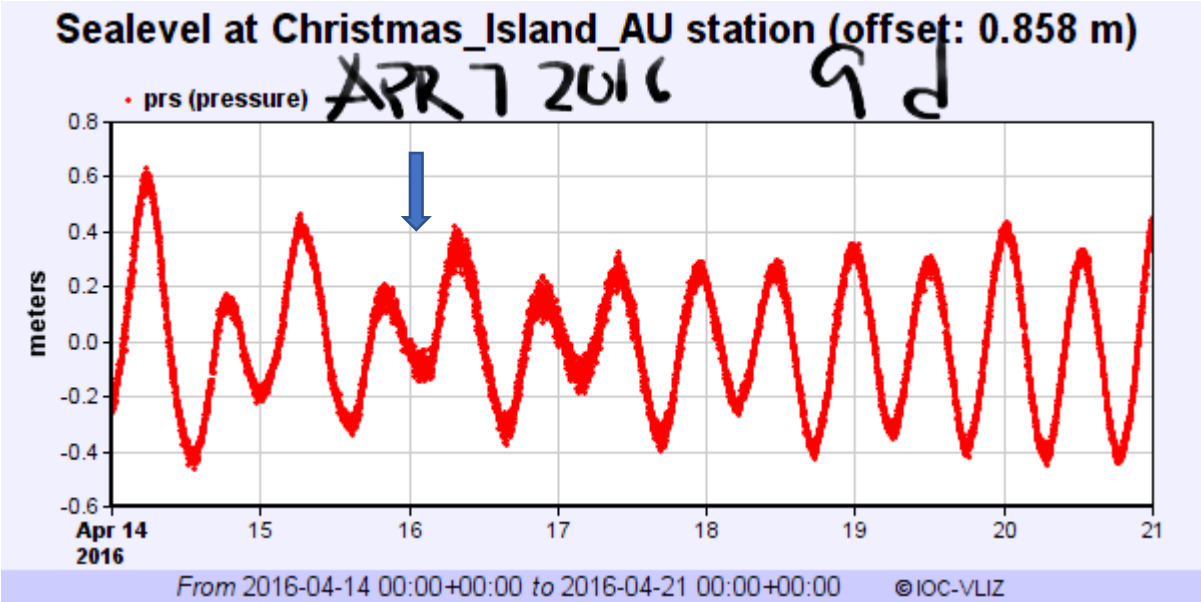


Figure 9.

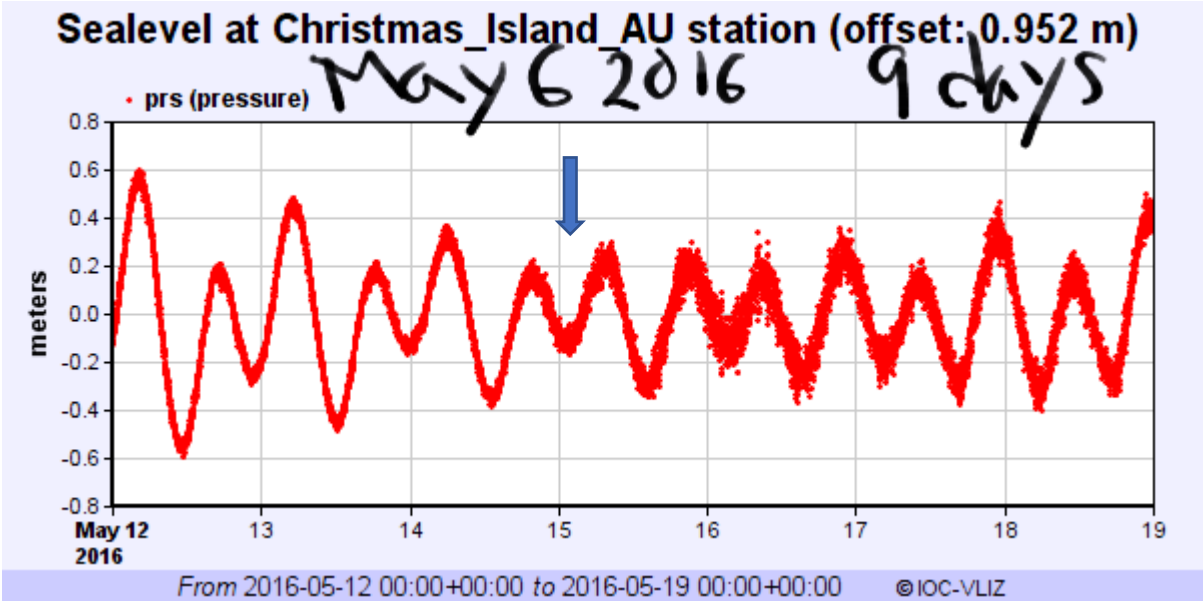


Figure 10.

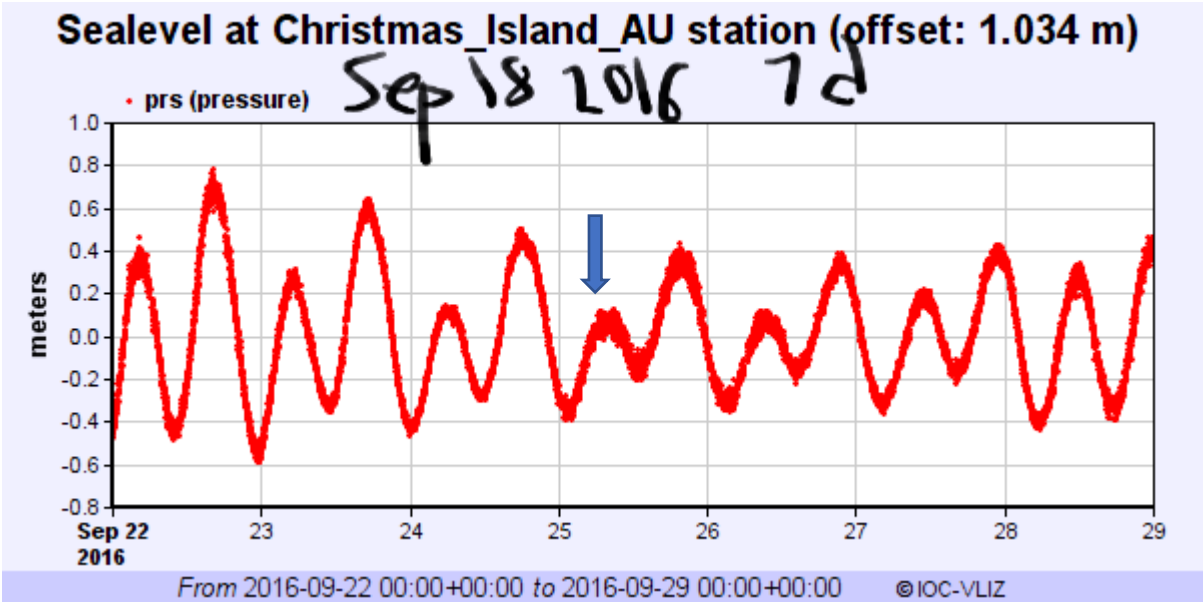
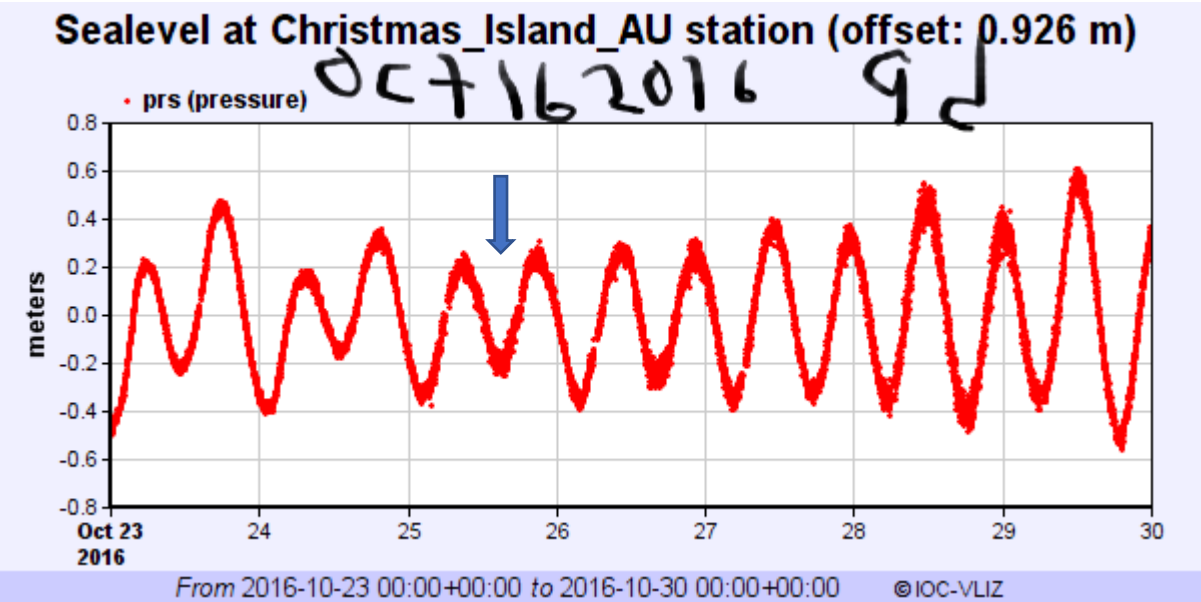


Figure 11.



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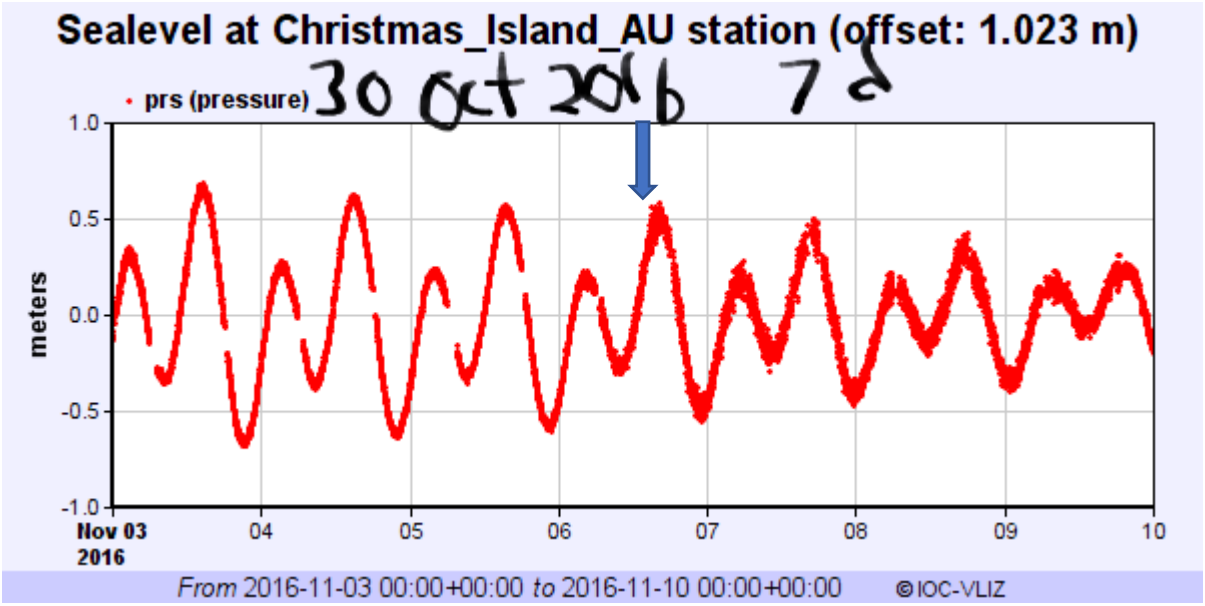

Figure 13.

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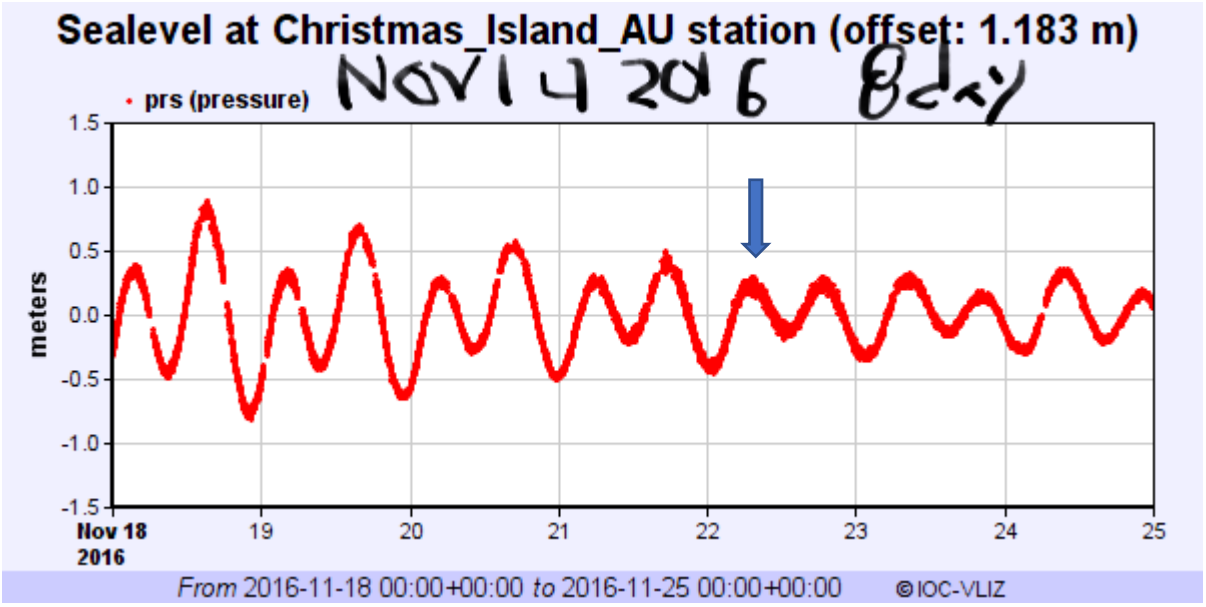

Figure 14.

IMAGE ANALYSIS

On September 30th 2015 the MODIS/Aqua/Terra sensors captured two cloud-free sunglint images of two different packets of ISWs (Figure 15-16). The interpacket distance in the Terra and Aqua images were 103 km and 101 km, respectively. We can estimate a ISW speed value of 2.24 m/s based on the 100 km distance travelled by the packet in a M2 period (12.42 h). A second analysis of these images provided us with two independent estimates of the propagation speed for each ISW packet lead wavefront. The results are summarized in the table shown below the images. The packet located in the Sumba Strait propagated with a speed of 2.24 m/s. The ISW packed located west of Sumba showed a similar speed 2.05 m/s. The distance separating the Sumba Strait and Christmas Island is about 1503 km, the ISWs packets will cover such distance in 7.8 and 8.5 days, respectively. A ISW packet generated 12 hours after a perigee-syzygy will reach Christmas Island in 9 days, as shown in Figure 7. Typical speeds of ISWs measured in other locations range between 1.75 m/s and 2.4 m/s. These speed values imply travel times between 7 and 10 days to reach Christmas Island. A 12-day span from perigee-syzygy to seiche excitation occurred on February 19th and March 19th 2015. These results suggests a 2-day delay in the generation of the ISW that impinged in Christmas Island. Figures 17-18 show two possible candidates of ISWs packets responsible for the seiche excitation. For the first case, a ISW packet departed from Sumba Strait on March 22nd to arrive on the 31st requires a propagation speed of 1.9 m/s. For the second case, departing on the 24th implies a speed of 2.5 m/s. The first case is inside the range of typical speeds. Examining a MODIS image corresponding to October 30th 2015 (Figure 19) it shows a ISW packet propagating in a WSW direction, this packet was generated the previous day, and it took eight days to reach Christmas Island with an approximate speed of 2.15 m/s.

Figure 15. MODIS/Terra SEP 30 2015 2:42. Interpacket distance is 103 km.

Figure 16. MODIS/Aqua SEP 30 2015 5:33. Interpacket distance is 101 km.

Calculate Internal Solitary Waves Speed from Image Analysis

Location	LAT1	LON1	Time	LAT2	LON2	Time	Distance (m)	Time Interval (s)	Speed (m/s)
W. Sumba	-9.8692	118.6989	9/30/2015 2:42	-10.0577	118.6871	9/30/2015 5:33	2.10E+04	10260	2.05
Sumba Strait	-9.1446	119.2804	9/30/2015 2:42	-9.3473	119.2694	9/30/2015 5:33	2.30E+04	10260	2.24

Travel distance from Sumba Strait to Christmas I. (km)	time (days)
1503	7.8
1503	8.5

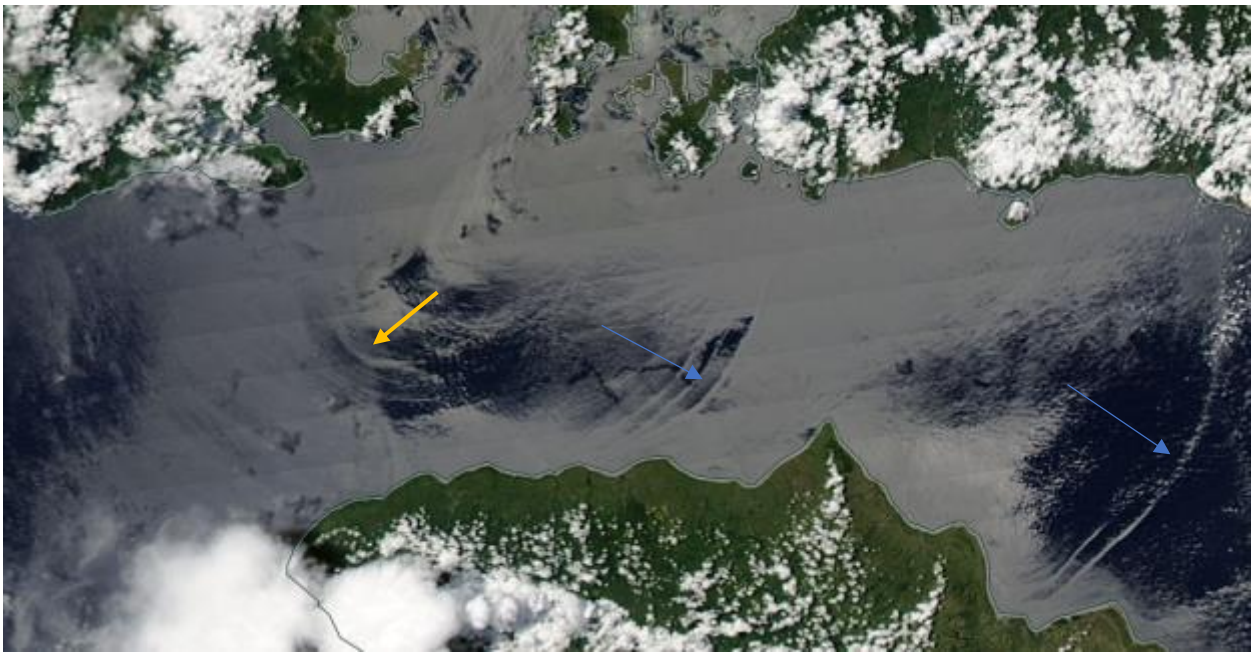

Figure 17. March 22 2015. MODIS/Aqua. Orange arrow points to wavefront of ISW propagating WSW out of Sumba Strait and the blue arrows point to wavefronts of ISWs propagating ESE out of Sumba Strait.

Figure 18. March 24 2015. MODIS/Terra. Orange arrow points to wavefront of ISW propagating WSW out of Sumba Strait and the blue arrow points to wavefront of ISW propagating East into Sumba Strait generated at the Lombok Strait.

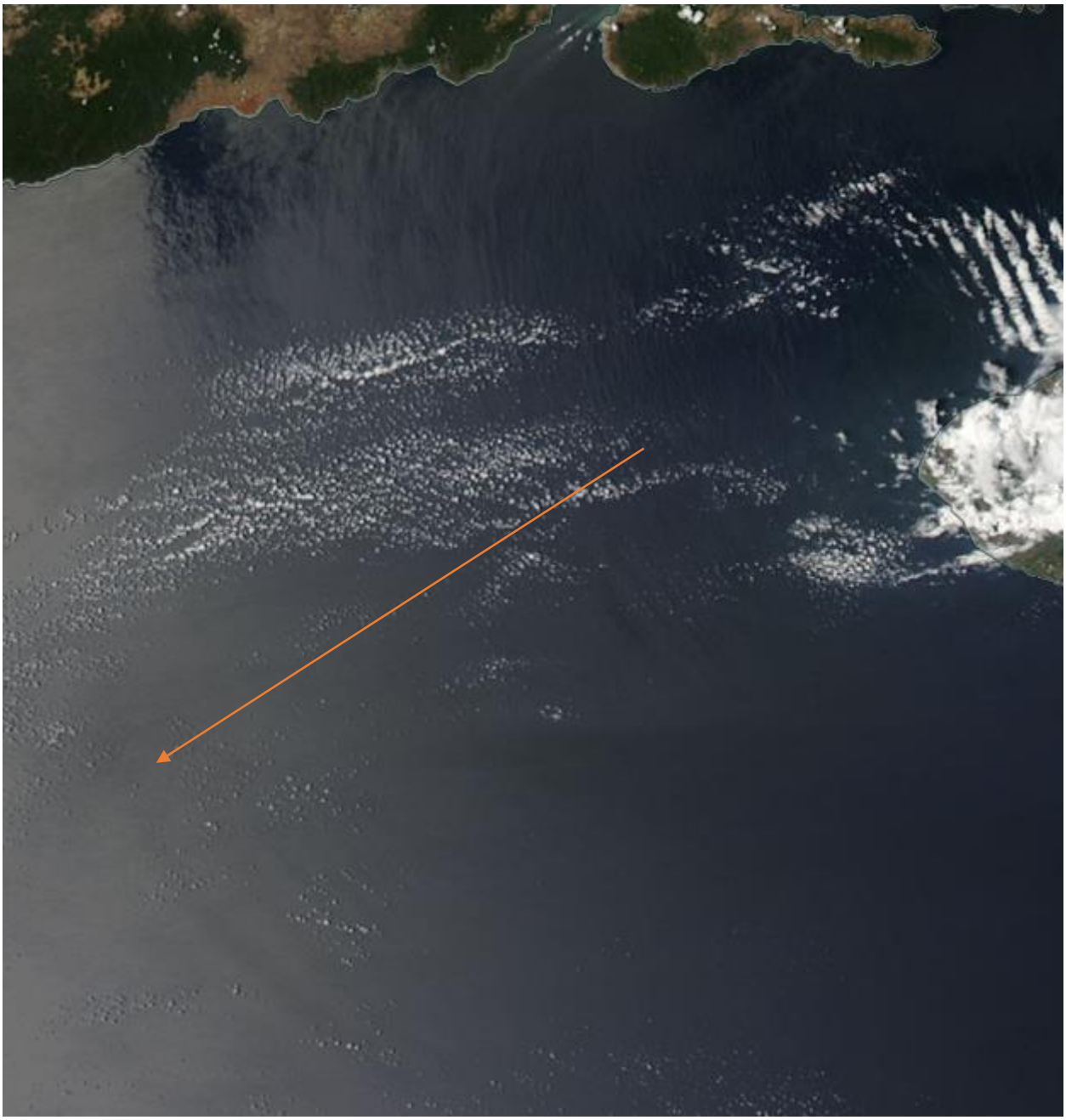
Figure 19. OCT-30-2015. MODIS/Aqua. ISWs exit the Sumba Strait in a WSW direction.

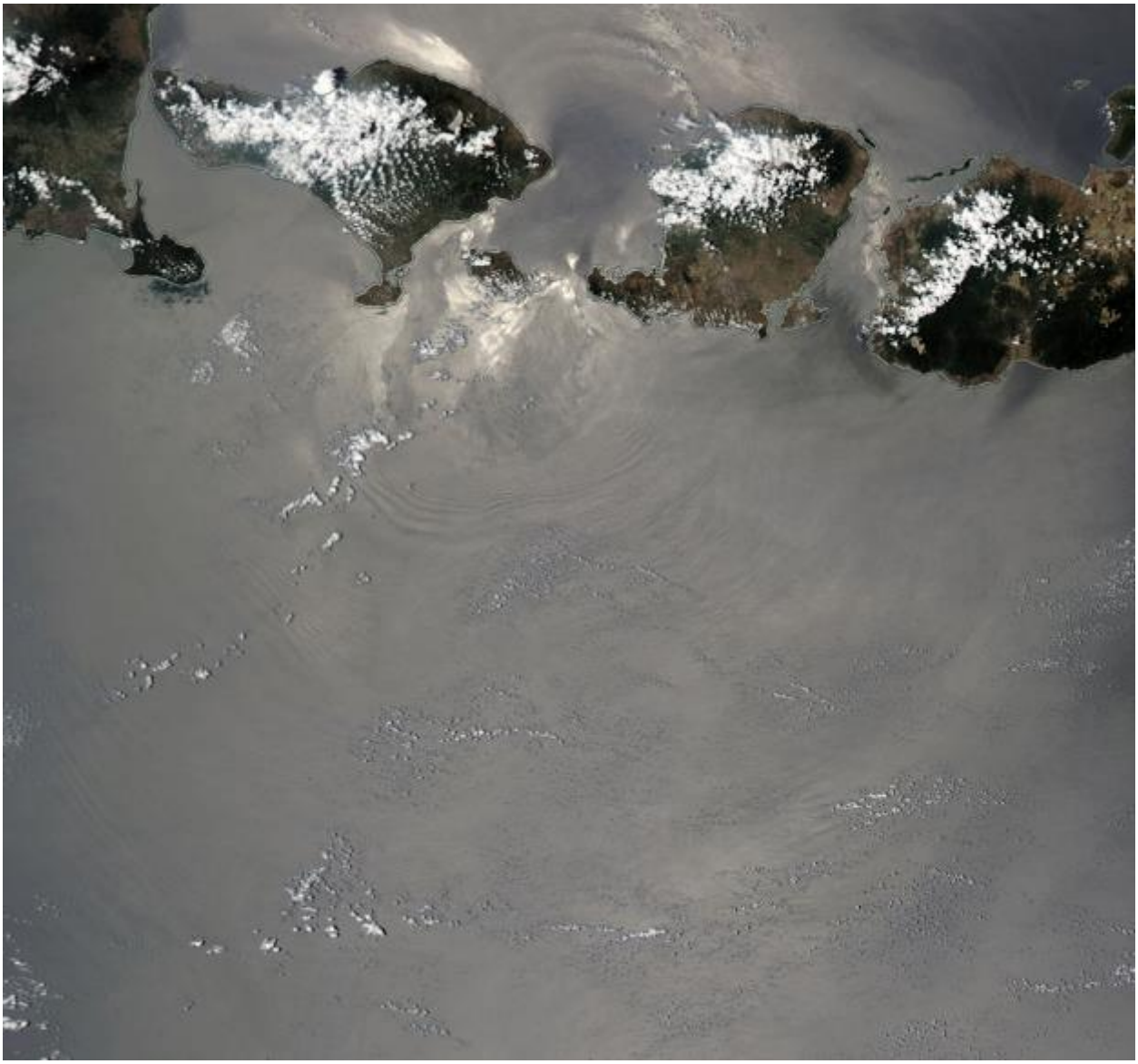
Figure 20. OCT-30-2015. MODIS/Aqua. Lombok Strait. ISWs propagating south.

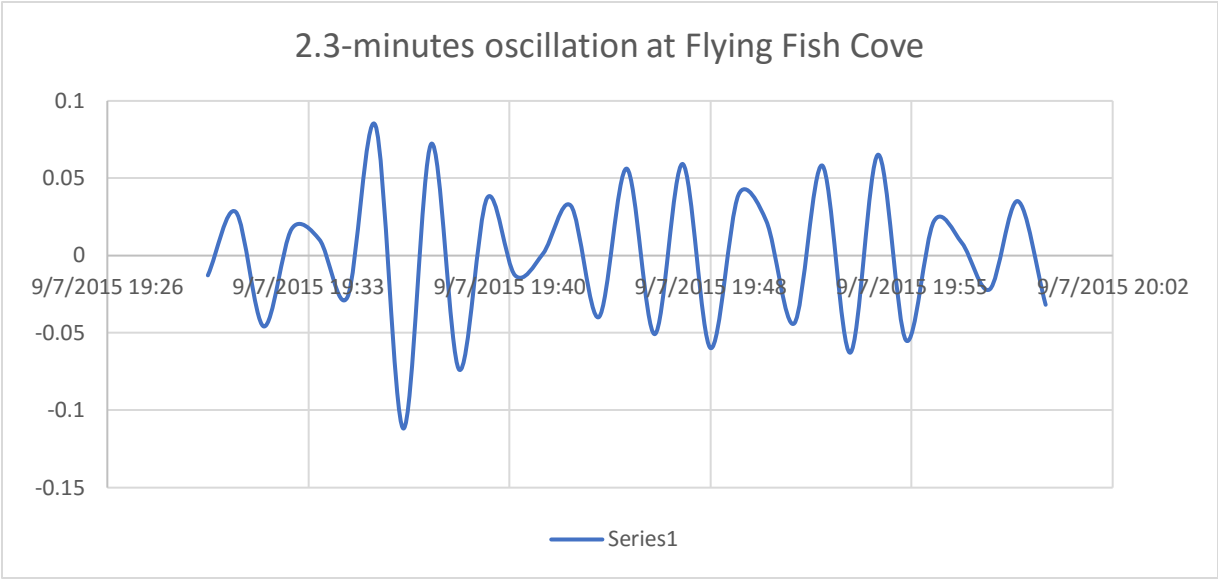

Figure 21.

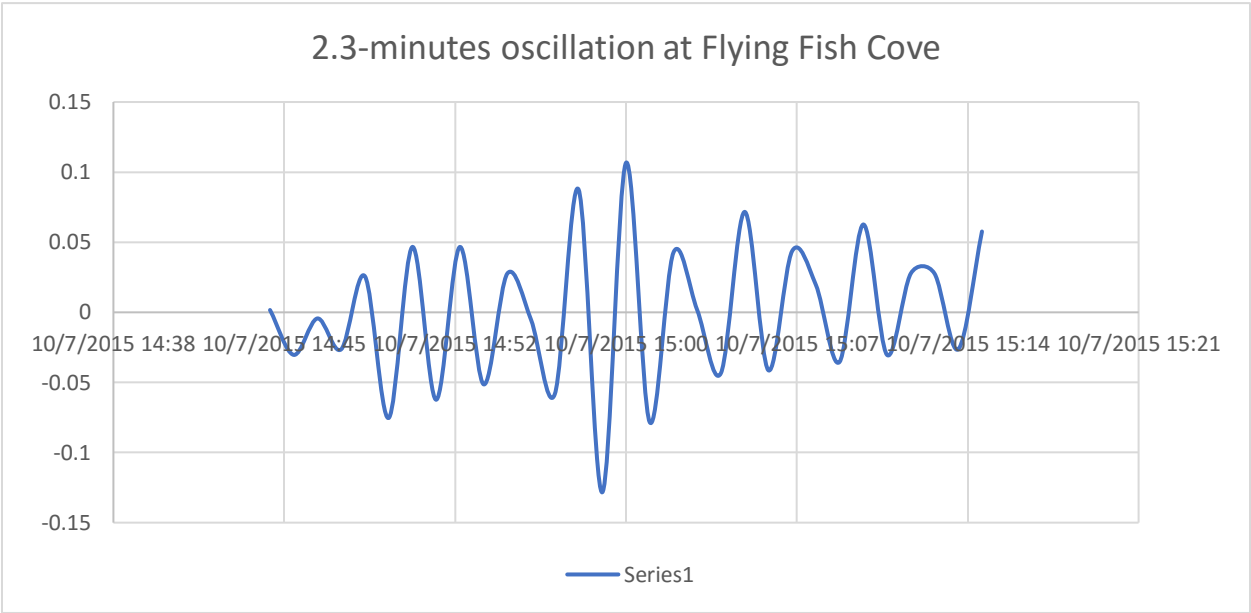

Figure 22.

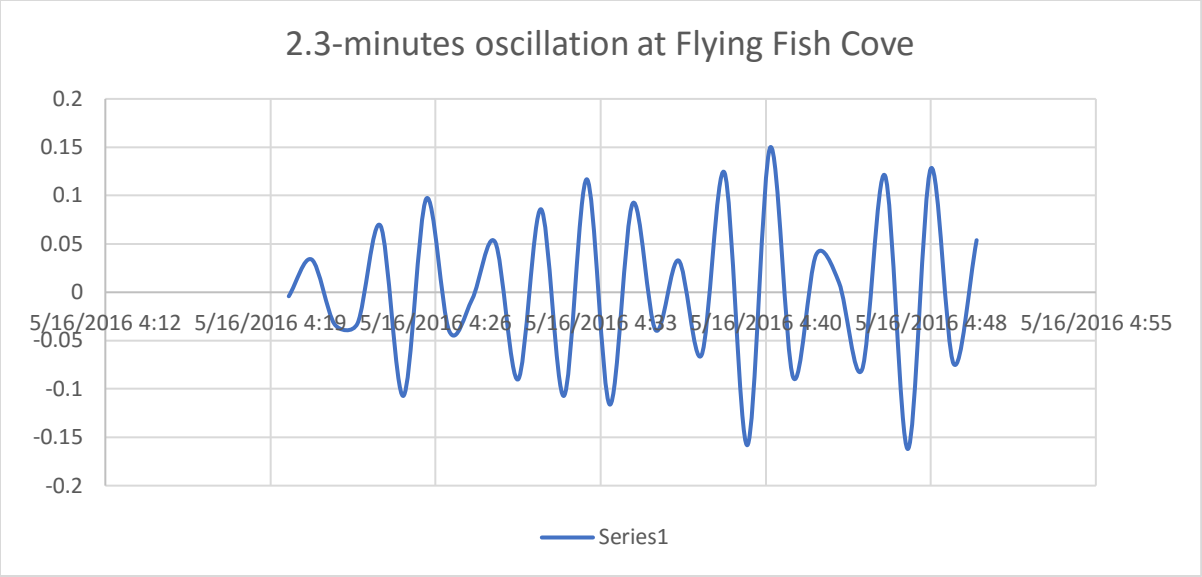

Figure 23.

Discussion

Our results show that the 2.3 minute seiches recorded by the Flying Fish Cove tide-gauge could be excited by internal solitary waves generated by strong semidiurnal M2 tides in the Sape Strait and exiting the Sumba Strait in a west-southwest direction. The time delay between the Moon's perigee and the start of the amplified coastal seiche (7-12 days) can be explained by internal solitary waves travelling with speeds between 1.9 m/s and 2.24 m/s. The satellite image analysis confirmed these speeds. At this moment we haven't found any image showing the ISWs approaching close (< 100 km) to Christmas Island. But this is not a surprise because in other locations such in Puerto Rico we have found only four images showing ISWs close to the SW coast of the island after examining many years of satellite data. We hope in the future to find this image for Christmas Island.

Lombok strait is source of ISWs (Figure 20) and is located 1120 km from Flying Fish Cove, about 383 km nearer than Sumba Strait but their ISWs propagate more in a southward direction. On the contrary, the Sumba Strait ISWs are constrained in their southward propagation by Sumba's North Coast and the wavefornts are free to propagate in a west-southwest direction. Despite these waves being farther away, they can hit Christmas Island easier that the ones generated in Lombok Strait. In this particular case, propagation direction is more important than distance from source.

A careful analysis of the Flying Fish Cove seiche signal using the method called *Seichelogía* (Alfonso-Sosa, 2013) could reveal information about the offshore vertical stratification and the amplitudes of the ISWs that are responsible for the amplification and changes in the instantaneous frequency of the seiche signal.

Coastal seiche excitation by ISWs that are generated hundreds or even thousand miles from the coast have been reported in four previous locations: Magueyes Island, Puerto Princesa, Trincomalee Bay and Addu Atoll. Now, Flying Fish Cove can be added to this list. These findings support the hypothesis that barotropic tidal energy can be transferred into baroclinic waves that do not dissipate locally and travel

long distances before impinging on topographic slopes converting part of their energy back into barotropic coastal oscillations.

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