Tidal mixing in the Sumba Strait and internal wave activity detected during strong semidiurnal forcing

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Abstract

G1SST images clearly show the enhancement of a colder (23.5 °C) water patch during strong tidal forcing, between 29-SEP and 3-OCT 2015. The patch is located just west of a warmer water plume that exits the Sape Strait producing a local surface temperature gradient in the Sumba Strait. Concurrent ISWs are seen departing from the same location and crossing the Sumba Strait. Both ISWs generation and cold patch enhancement by tidal mixing occurred in the same location and on the same day. Strong internal tide activity could be linked to both phenomena.

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 ISW's 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 easy detection of the ISW's 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).

High resolution sea surface temperature data acquired by satellite remote sensors can reveal areas of tidal mixing. The SST largest fortnightly signals are found to be localized to relatively small straits, channels, and sills (Ray and Susanto, 2016), such is the case of the Sumba strait. This paper shows G1SST images from the Sumba straits from September 25 to October 5 2016. MODIS/Aqua/Terra images captured on September 30 2015 show large internal activity. Both set of images were compared.

A period of strong semidiurnal forcing occurred between September 29-October 02, 2015. The 18.61 year lunar nodal precession has a large effect on the Moon's declination (its celestial latitude), minimizing the declination when N = 180° (23° 27′ − 5°9′ = 18°18′) (Haigh et al., 2011). The low lunar declination increases the semidiurnal form of the tides. In addition, this period was near the equinoxial tides then increasing the semidiurnal form of the tides. More important, on September 27 the perigean and spring tides coincided. The sum of all the above factors explains why during this time period in 2015 we expected to see a strong semidiurnal forcing. Strong semidiurnal tidal currents are necessary to generate large amplitude internal ISWs, nonlinear internal tides and turbulent vertical mixing.

Methodology

Multi-mission/GHRSST data are those produced under the auspices of the Group for High-Resolution Sea Surface Temperature (GHRSST) [Donlon et al., 2009]. G1SST 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. The default color palette spans from 0°C to 32°C. MODIS/Terra/Aqua images were also downloaded from NASA/Worldview. We compared both set of images looking for areas of internal wave generation-dissipation and if colder SST patches correspond to these same areas.

Results

Figure 1 shows the fortnightly tidal height cycle recorded at the Waikelo tidal station located in the northwest coast of Sumba. Tidal ranges above three meters occurred between September 29-October 02, 2015. The largest one, 3.6 m, was recorded on September 30, 2015. During this period the semidiurnal currents are stronger and tidal mixing is expected to increase. Figure 2 shows a 12-day sequence of sea surface temperatures (G1SST) that spans from September 25th to October 6th . The first three days of the sequence show warm 27 ° C water crossing from North to South across the Sape Strait into the northern Sumba Strait, but no sign of colder water near the southern exit. But two days later, on the 29th a big patch of colder water is located west of the southern exit (see blue arrow at Figure 2), this 23.5 °C SST patch is located just west of a warm water plume exiting the Sape Strait (Figure 3). Following the images sequence from SEP-29 to OCT-3 we can see apparent advection of the 23.5 °C surface water along the Sumba Strait in a west-southwestern drift. Concurrent MODIS/Aqua/Terra images captured on SEP-30 show ISWs at the southern exit of the Sape Strait propagating into the Sumba Strait (Figure 4). The ISWs packets move west-southwest and exit the Sumba Strait. Part of the ISWs wavefronts impinge in the northwest coast of Sumba Island but the east side of the wavefronts refract around the west side of the island to continue in a southward propagation path. Figure 5 shows that during the turning the ISWs fission into smaller waves. This is a clear signature of internal waves dissipation (see discussion). Figure 6 shows the SST one day later, west-southwest of Sumba the surface waters are cooler (inside blue curve). The next day the colder water patch disappeared.

Discussion

G1SST images clearly show the enhancement of a colder (23.5 °C) water patch during strong tidal forcing, between 29-SEP and 3-OCT 2015. The patch is located just west of a warmer water plume that exits the Sape Strait producing a local surface temperature gradient. Concurrent ISWs are seen departing from the same location and crossing the Sumba Strait. Both ISWs generation and cold patch enhancement by tidal mixing occurred in the same location and on the same day. Both phenomena have in common that their generation requires strong tidal currents. A baroclinic model of the Indonesian Seas (Robertson and Ffield, 2005) revealed that strong baroclinic M2 tides are generated along the shelf slope break and over rough topography, particularly in the straits. Zooming Figure 2 and Figure 3d of their article show an amplification of the M2 baroclinic tide at the south exit of the Sape Strait. In the upper south slope of the Sape Strait internal tides are generated. The generation of internal tides where the bottom slope is critical, and their local dissipation can increase turbulent vertical diffusivities. Nonlinear internal tides during strong shear ($Ri_G < ¼$) can dissipate energy locally by means of K-H Instabilities that break and mix the waters. This mixing could lead to a decrease in the mixed layer water temperatures. A numerical model of the internal tidal mixing in the Indonesian Seas (Koch-Larrouy et al., 2007) demonstrated that significant mixing was necessary for the transformation of Pacific waters into Indonesian Throughflow waters. In the Ombai Strait, the reported average value of the turbulent mixing was 833.5 x 10^{-4} m^2 s^{-1} but in the mixed layer was 103.0 x 10^{-4} m^2 s^{-1} (Suteja et al., 2015). The interaction of strong semidiurnal internal tides near the sill topography can increase dramatically the vertical mixing.

One possible explanation for the cold patch west of Sumba shown in Figure 6 is by means of the interaction of the ISW with a seamount. A seamount located (-9.5422233°, 118.7716933°) about 17 km from the west point of Sumba coast could be responsible for the fission of the ISWs, the position of the seamount was marked with a star in Figure 5. The seamount is located about 100 km southwest from the southern exit of the Sape Strait. Since the 70s variable coefficient KdV equation analytic models have demonstrated that ISWs can fission into internal solitons or disintegrate into a dispersive packet (Djordjevic and Redekopp, 1978). More recently, experimental models have examined the shoaling and breaking of ISWs as they approach a constant bottom slope and their different breaking regimes (Sutherland et al., 2013). The fission and subsequent breaking of ISWs can enhance the vertical mixing around the critical slopes of the seamount and reduce momentarily the SST. The catalog of images of ISWs in the Sumba Strait (Alfonso-Sosa, 2015) show the fission and dispersion of the ISWs as they approach the slopes north of Sumba Island. But on some occasions the solitons are reflected back north (Figure 10 in the catalog), so they do not break. This could explain why did not detected in our SST images sequence any mixing temperature signature near the north coast of Sumba. Figure 7 shows the surface wind vectors in Sumba Strait and west of Sumba island. Near the seamount ASCAT detected southeast winds of less than 20 knots in that particular day. A similar wind regime was observed the two previous days.

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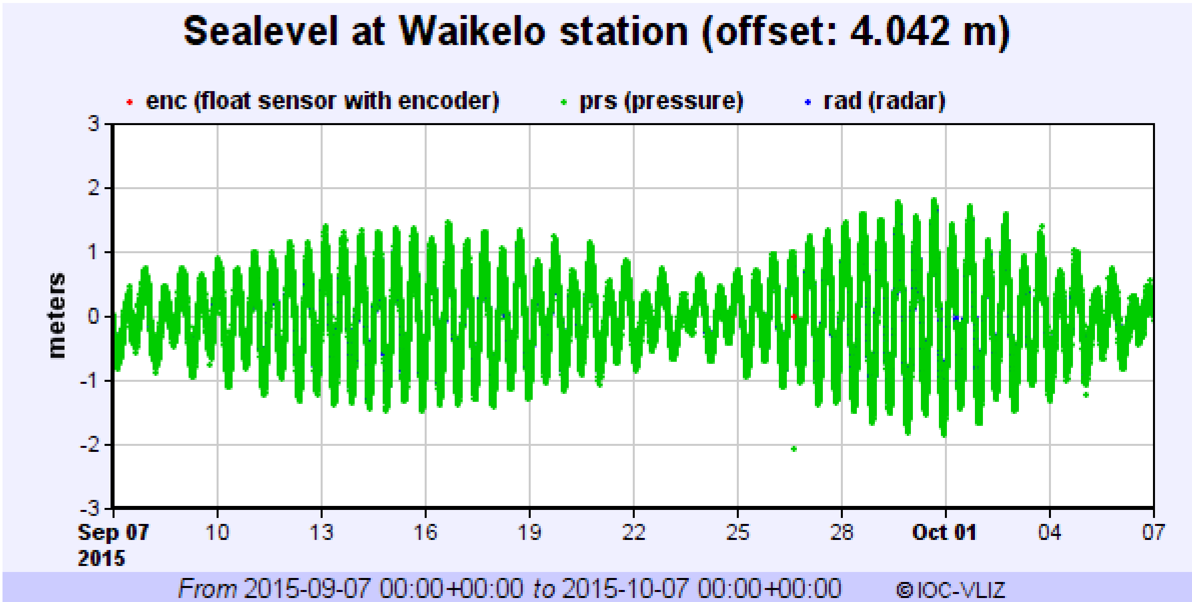
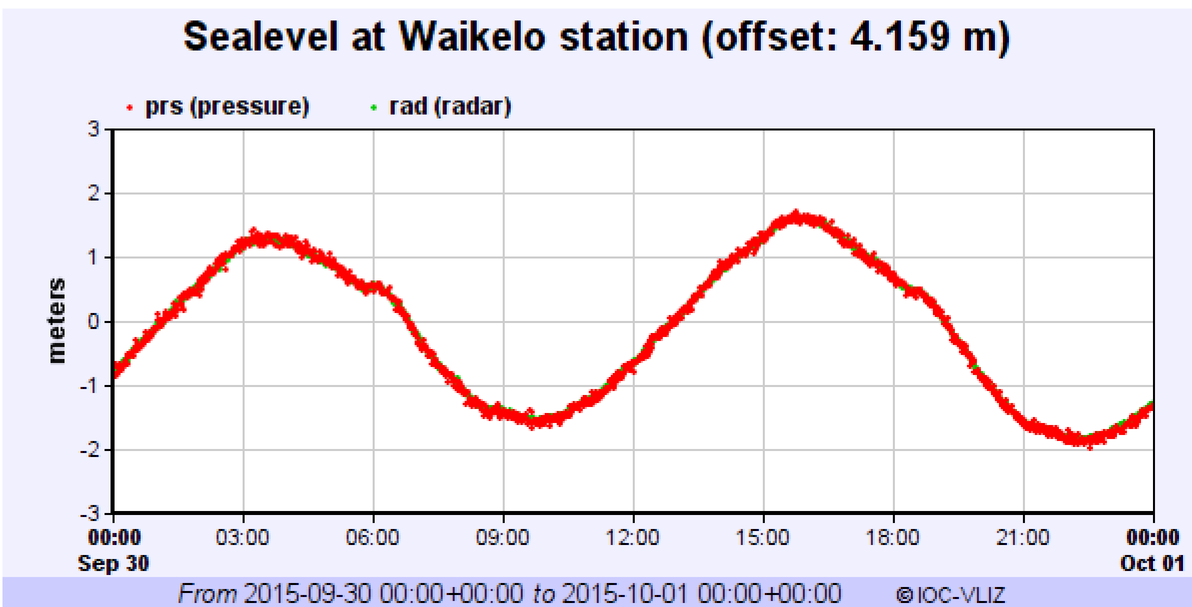
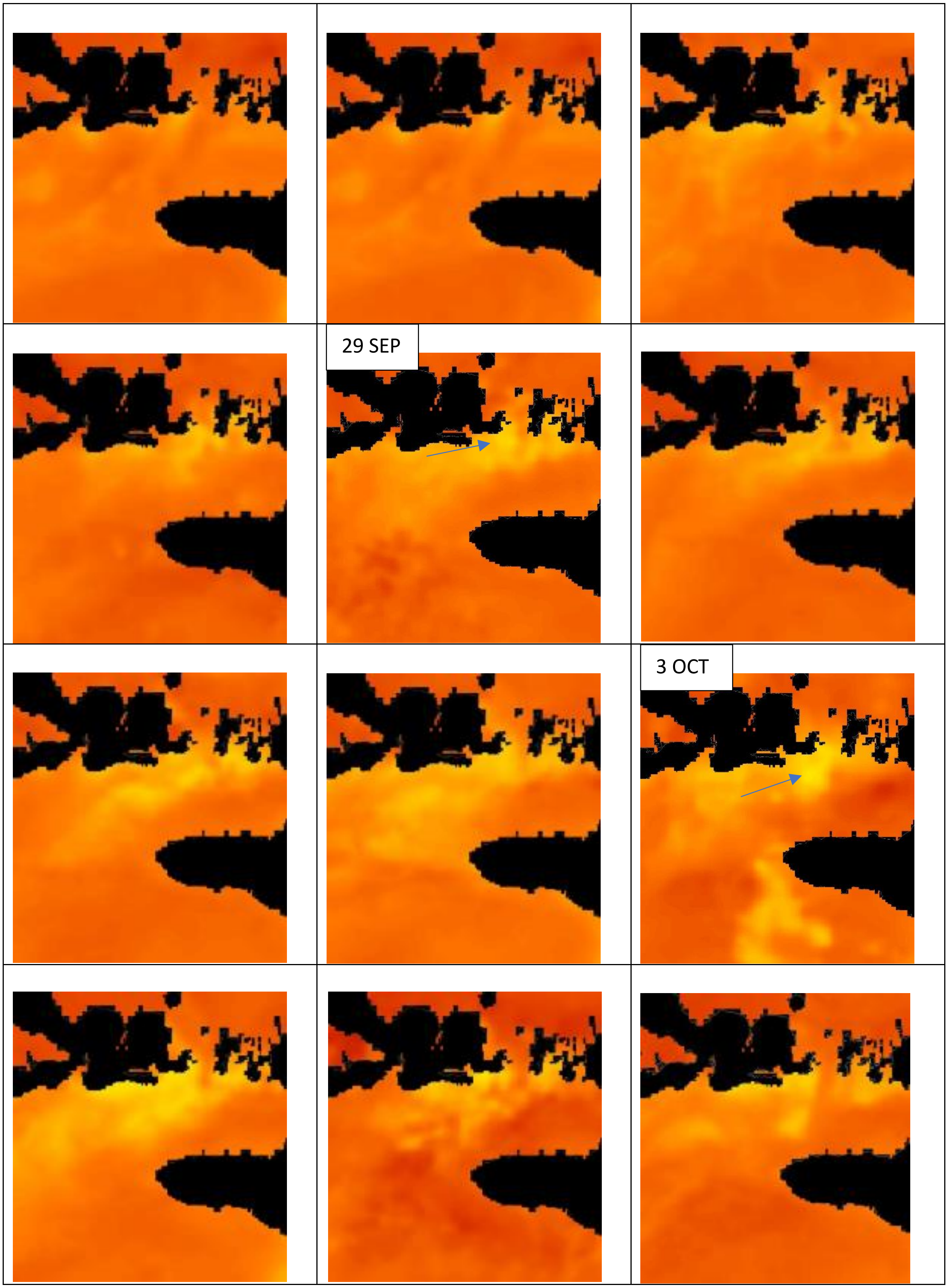


Figure 1. Tidal heights at Waikelo station located at the northwest coast of Sumba Island. Largest tidal



height occurred on 30 September 2015.



Caption in the next page.

Figure 2. (L4,G1SST) daily sequence (left to right) from 25-SEP-2015 to 6-OCT-2015. Light yellow colors represent SST from 23.48 °C to 23.64 °C, darker yellow goes from 24.76 °C to 24.92 °C. Light orange goes from 25.09 °C to 25.25 °C and darker orange goes from 27.34 °C to 27.50 °C. Red color represents values above 27.95 °C.

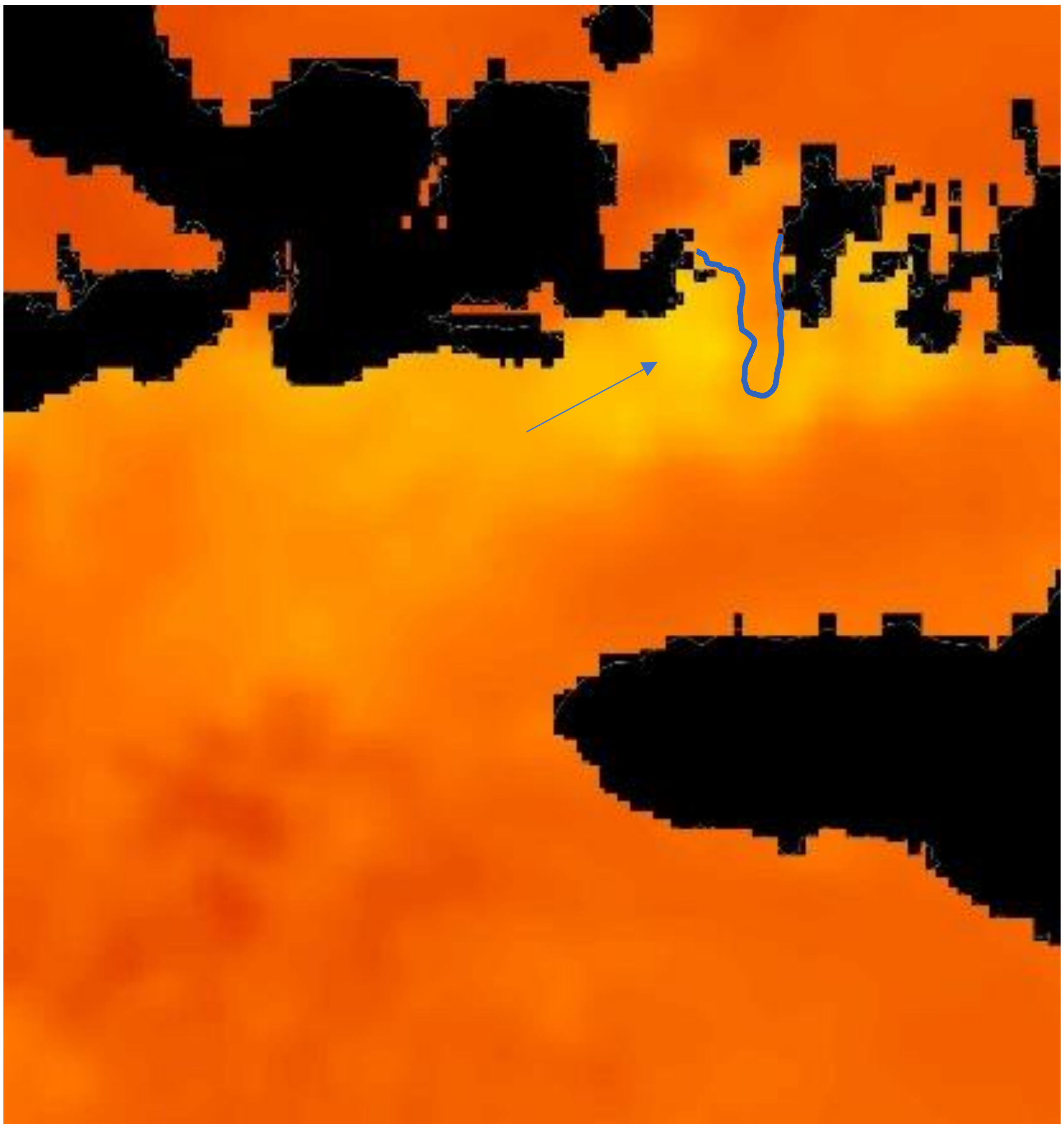


Figure 3. G1SST, September 29, 2015. Blue line delimits a higher temperature water plume (around 25.25 °C) exiting the Sape Strait. Contiguous west of the plume we can see a patch of colder water with a SST around 23.5 °C (light yellow patch pointed by the blue arrow).

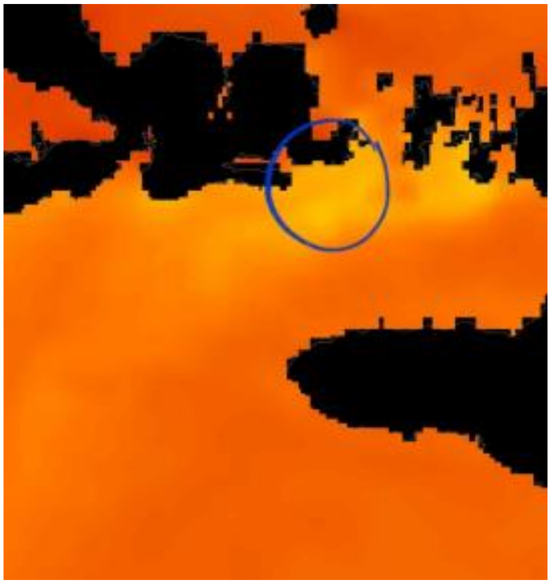


Figure 4. G1SST, September 30, 2015. Terra/MODIS 30-SEP-2015 02:42 GMT.

Inside the blue circle there is a patch of colder water with SST values around 23.5 °C.

Aqua/MODIS 30-SEP-2015 05:33 GMT

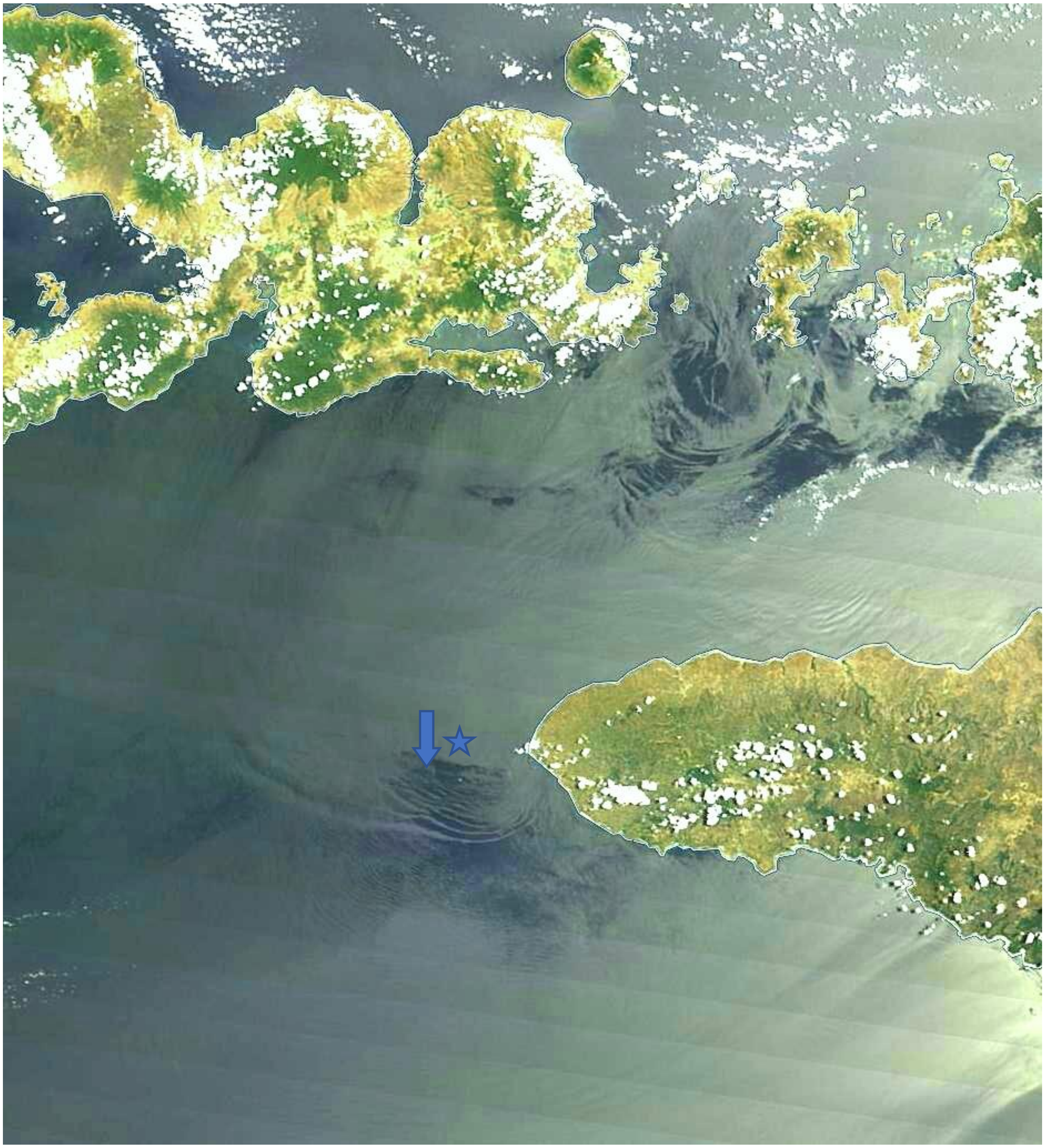


Figure 5. Internal waves dissipate west of Sumba (below blue arrow) after impinge of a seamount (location marked with blue star). Image captured by MODIS/Terra on 2-OCT-2015.

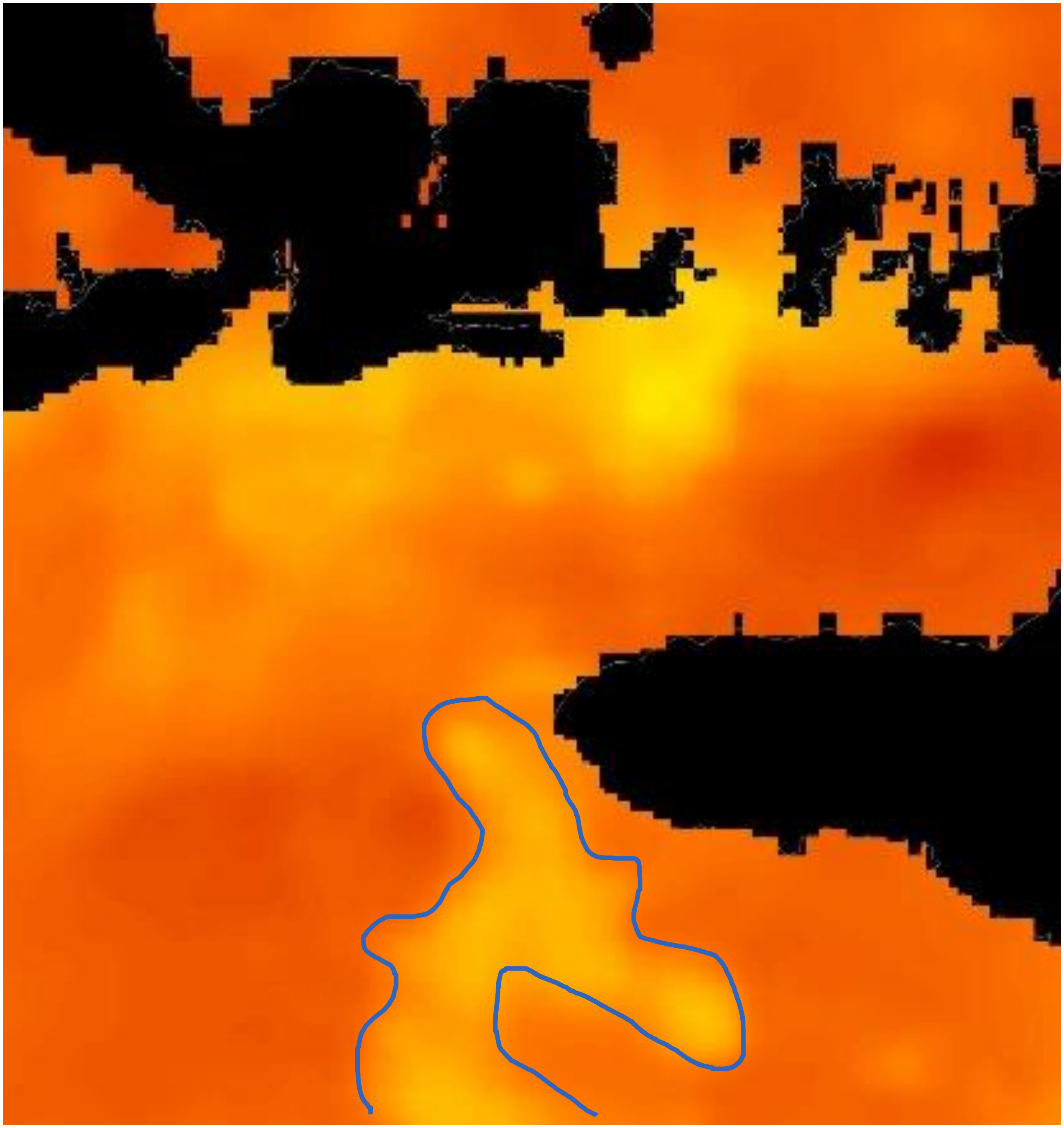


Figure 6. G1SST, October 3, 2015. Blue line delimits the patch of colder water.

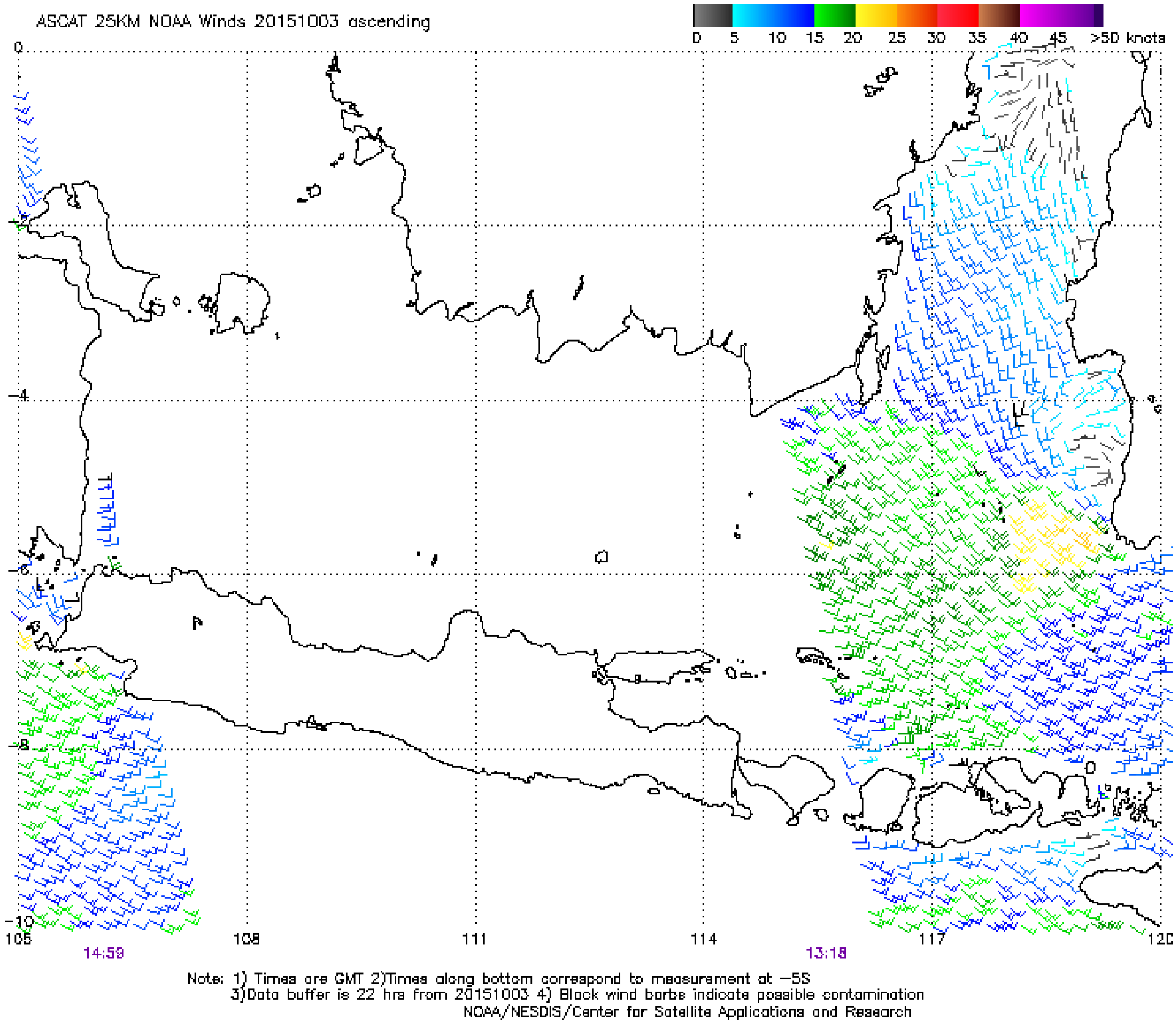


Figure 7. Surface winds in the Sumba Strait and west of Sumba island are shown in the right inferior margin (LAT -9 LON 118-120). Data from ASCAT 25 km NOAA Winds on October 3, 2015 13:18 UT.