Seasonal and Fortnight Variations in Internal Solitary Waves in the Indonesian Seas from the SWOT Measurements

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Summary

- Using the wide-swath sea surface height data from the 1-day repeat calibration/validation phase of the Surface Water and Ocean Topography (SWOT) mission, we explored fine-scale evolution of nonlinear internal solitary waves (ISWs) in the Banda/Molucca Seas in the Indonesian Archipelagos (Fig.1).
- Generated in the Ombai Strait and Lifamatola Passage through semidiurnal tide-topography interaction, ISWs in the Banda and Molucca Seas have a sea surface height amplitude of 10 20 cm and exhibit multiple wave packets with the leading wave crest followed by a series of rank-ordered secondary wave crests.
- Due to nonlinearity, the ISWs are observed to propagate northward at a speed faster than the mode-1 internal gravity waves and their amplitudes are modulated fortnightly following the regional spring-neap tidal cycle. On longer timescale, the observed ISW amplitudes are controlled by seasonal upper ocean stratification changes with a weaker stratification favoring a larger amplitude.
- By converting the SWOT-measured sea surface height data to the interior ocean pressure signals, we quantified the depth-integrated energy flux associated with the northward-propagating ISWs to be 5 kW/m and 2 kW/m in the central Banda and Molucca Seas, respectively.
- Comparisons with past studies indicate that the ISWs contribute to close to 100% and 40% of the tidally-induced, northward energy fluxes, respectively, across the Banda and Molucca Seas.

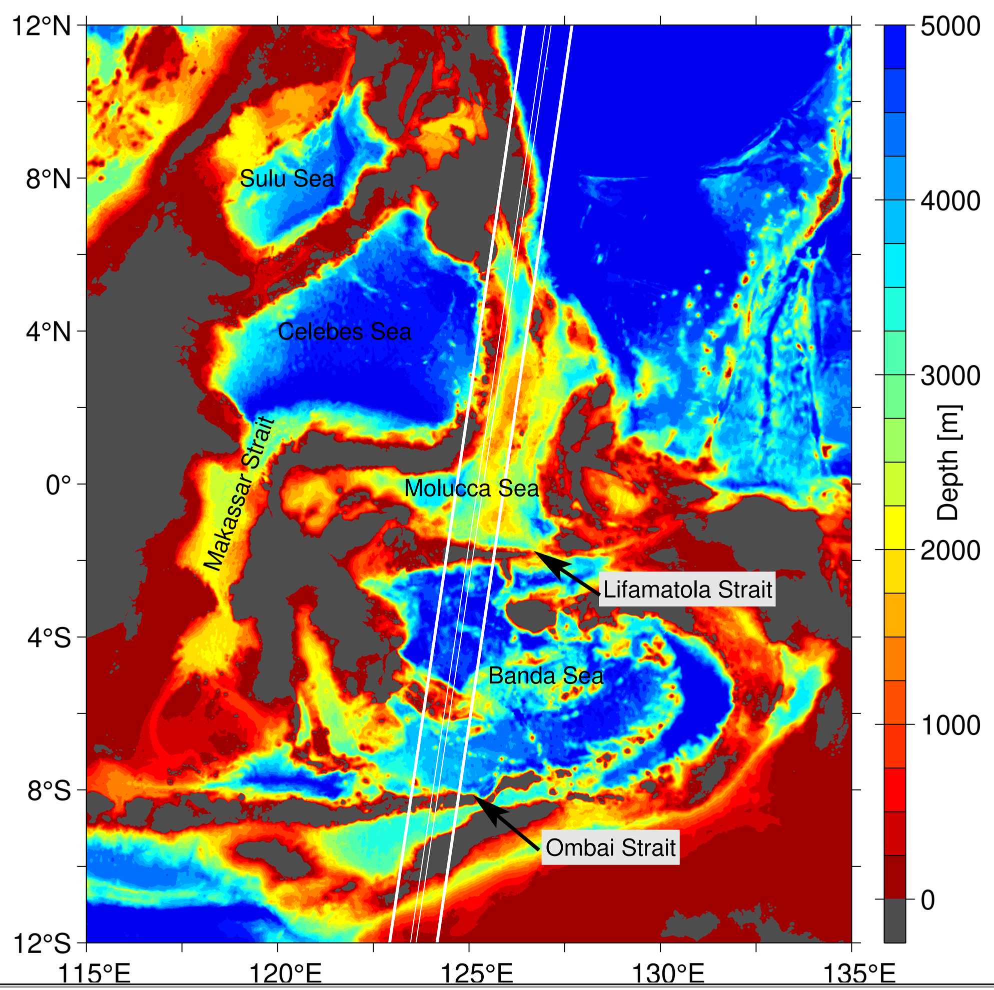

Figure 1. Study area bathymetry surrounding the Indonesian seas based on Smith and Sandwell (1994). Thick white lines show the 120-km-wide SWOT ascending Pass 021 during its 1-day repeat CAL/VAL phase and thin while lines denote the 20-km-wide nadir gap.

Kinematics Results

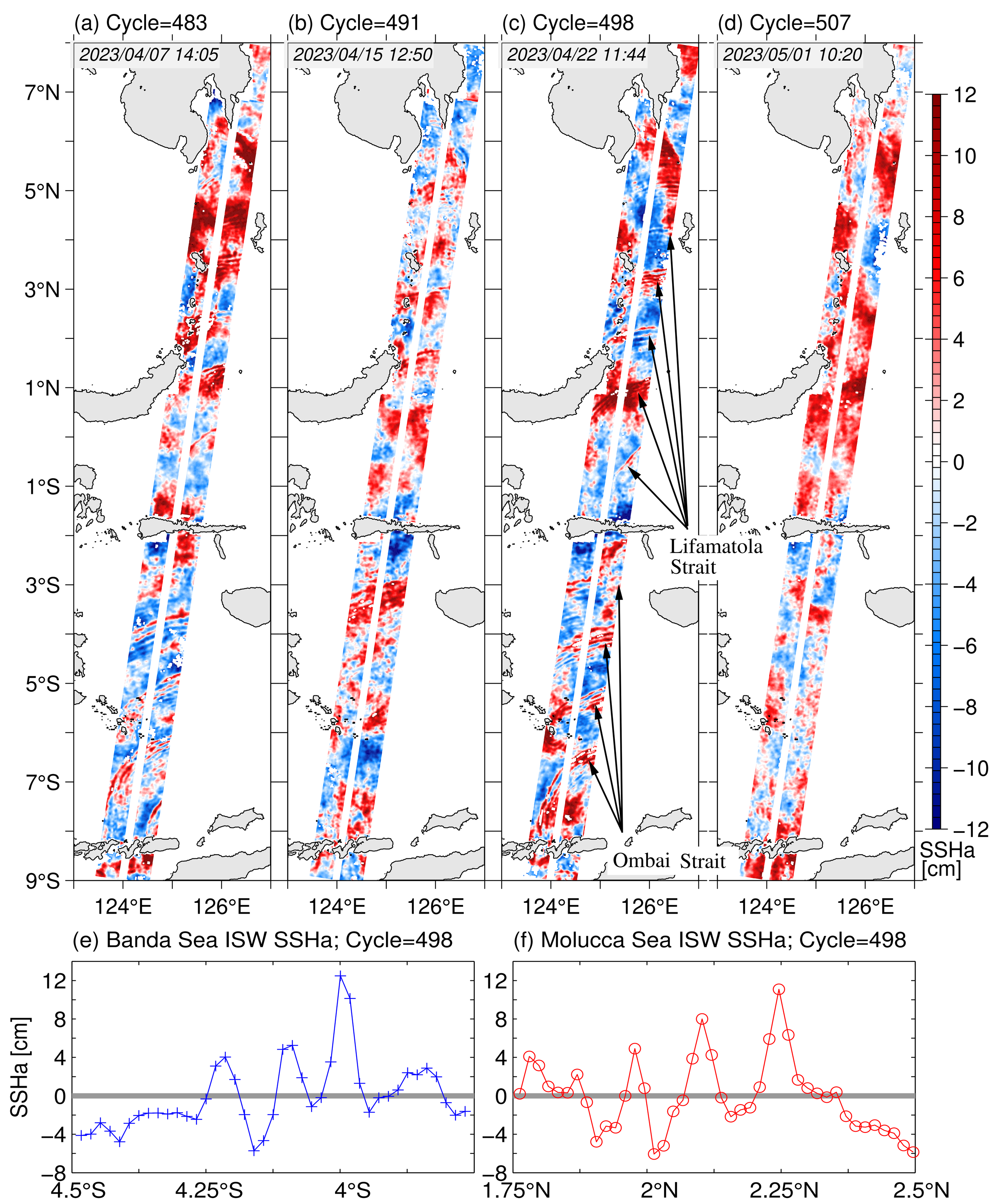

Figure 2. Examples of the KaRIn-measured SSH anomaly maps along Pass 021 on (a) April 7, (b) April 15, (c) April 22, and (d) May 1, 2023. Arrows in (c) show the ISW propagation vectors normal to the 2-dimensional ISW crests. (e) and (f) show the typical ISW-packet SSH anomaly profiles in the Banda and Molucca Seas along the Pass 021 right-swath center on April 22.

- Presence of multiple ISW patches with the consecutive, semi-circular wave crests are clearly visible in the Banda/Molucca Seas (Fig.2). The leading wave crest of an ISW packet exhibits the largest SSH elevation of 10∼20 cm and is followed by multiple (up to 5) rank-ordered wave crests with progressively decreasing amplitudes.
- By tracing the pathways normal to the semi-circular ISW packets (arrows in Fig.2c), we are able to identify the generation site for the ISW packets in the Banda and Molucca Seas to the Ombai Strait and Lifamatola Passage, respectively.

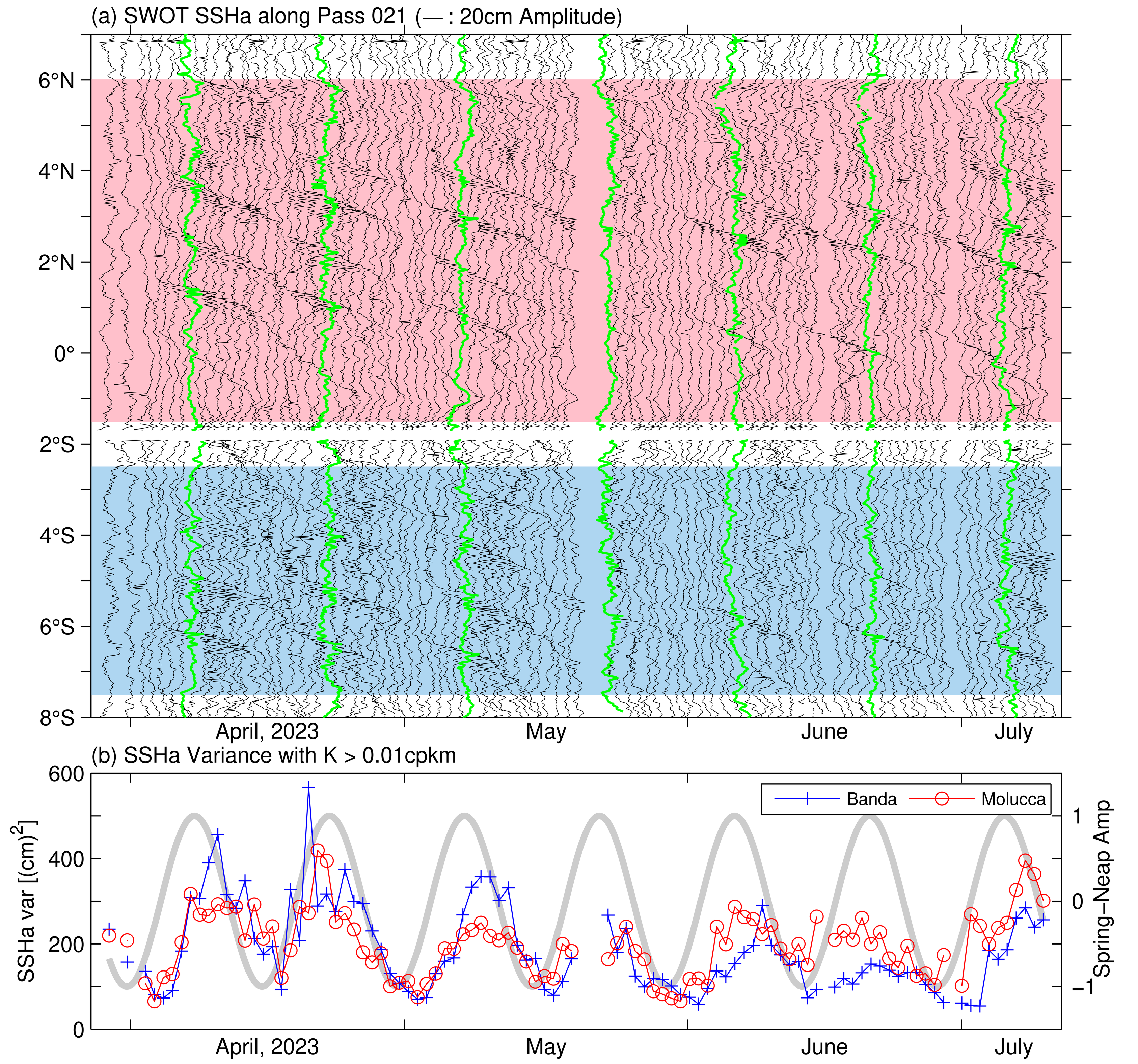

Figure 3. (a) SSH anomaly data along the right-swath center of the ascending Pass 021 as a function of time. SSH amplitude scale is indicated in the figure title. Blue and pink bands denote the segments of the Band and Molucca Seas. (b) SSH variance time series estimated from the SSH anomaly data with wavelengths shorter than 100 km in the Banda (blue crosses) and Molucca (red circles) Seas. Grey line shows the normalized spring-neap tidal amplitude in the Banda/Molucca Seas.

- In both the Banda and Molucca Seas, the ISW variance has a clear fortnightly modulation with its phase lagging by 2 days behind the spring-neap tidal cycle (Fig.3).
- The false southward propagation in Fig.3a is caused by the stroboscopic effect and it occurs because the daily (23.844 hours) sampling during the SWOT CAL/VAL phase is close to twice the ISW period dictated by the locally-dominant M2 tides with a period of 12.42 hours.
- Through a lagged correlation analysis, the radial ISW propagation speed in the Banda and Molucca Seas is evaluated at 3.02 m/s and 2.74 m/s, respectively. These ISW speed values are roughly 10% larger than the theoretical, mode-1, internal gravity wave speeds, $c_1 = 2.77$ m/s and 2.45 m/s, based on regional vertical eigen-mode decomposition.
- Amplitude of mode-1 ISWs is governed by the Korteweg-de-Vries (KdV) equation (e.g., Holloway et al., 1997):

$$\frac{\partial \eta}{\partial t} + c_1 \frac{\partial \eta}{\partial x} + \alpha \eta \frac{\partial \eta}{\partial x} + \beta \frac{\partial^3 \eta}{\partial x^3} = 0,$$

That has analytical solution:

$$\eta = \eta_0 \text{sech}^2(\frac{x - c_p t}{\Delta}),$$

where η_0 is the maximum isopycnal displacement, $c_p = c_1 + \alpha * \eta_0/3$ is the phase speed of ISW. Using the mean value 70 m (or, equivalently, a mean SSH elevation of 14 cm), c_p becomes 3.00 m/s and 2.74 m/s in the Banda and Molucca Seas.

- An increase in upper ocean stratification favors generation of larger-amplitude ISWs. The upper ocean in the Banda Sea is in its seasonal maximum in April and decreases progressively in May and June (Fig.4). The upper ocean remains largely unchanged from April to June in the Molucca Sea. By and large, these seasonal upper ocean changes can qualitatively explain the monthly ISW amplitude fluctuations observed in the Banda/Molucca Seas (Fig.3b).

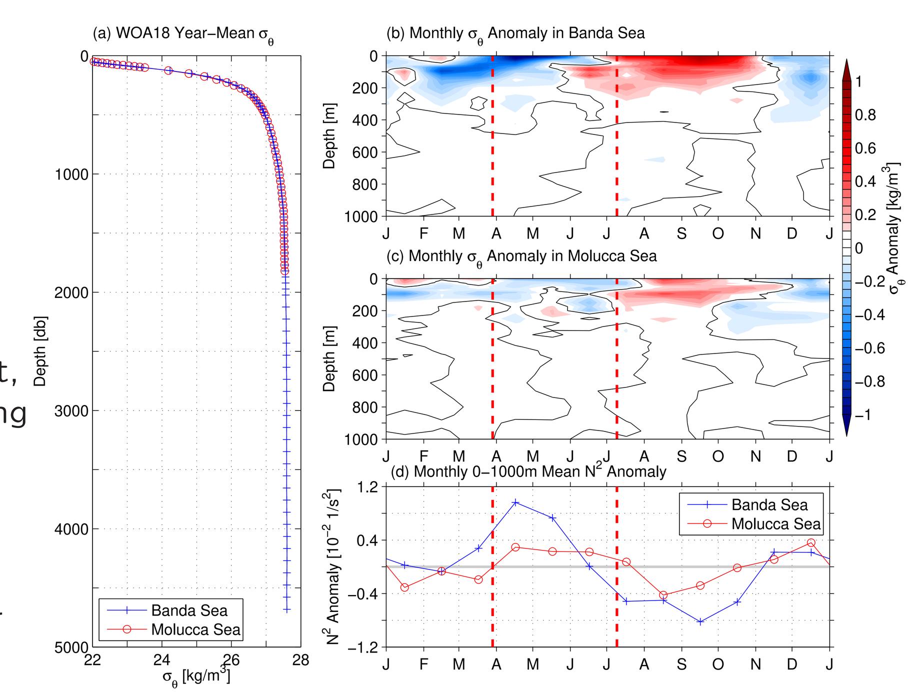

Figure 4. (a) Potential density profiles in the Banda (blue crosses) and Molucca (red circles) Seas based on World Ocean Atlas 2018 climatological temperature/salinity data. Upper ocean (0-1,000 m) density anomalies as a function of calendar months in the (b) Banda and (c) Molucca Seas. (d) Monthly N2 anomaly values averaged in the 0-1,000 m upper ocean. In (b)-(d), red dashed lines denote the SWOT 1-day repeat CAL/VAL phase in terms of its time in calendar months.

Energetics Results

- An important contribution the SWOT measurements can make for the ISW exploration, is that the KaRIn-measured fine-scale SSH signals can be dynamically linked to the ISW's baroclinic pressure signals.
- By integrating the hydrostatic equation and by recognizing that surface pressure anomaly is given by $\rho_0 g a$ where a is SSH anomaly, we have:

$$p'(z) = \rho_0 g a + \rho_0 \eta_0 \int_z^0 N^2(z)\Phi(z)dz. \quad (1)$$

Because the baroclinic pressure anomaly integrated from surface to bottom is zero by definition, Eq. (1) allows us to convert the SSH signal a to η_0 via:

$$\eta_0 = -\frac{agH}{\int_{-H}^0 [\int_z^0 N^2(z')\Phi(z')dz']dz}. \quad (2)$$

- Once η_0 is determined, its time-varying 2-dimensional isopycnal displacement becomes:

$$\eta = \eta_0 \text{sech}^2(\frac{x - c_p t}{\Delta}). \quad (3)$$

From Eq. (3), the vertical velocity associated with the ISW can be expressed by:

$$w(x,z,t) = \frac{\partial \eta}{\partial t} = \frac{2c_p}{\Delta}\eta_0 \text{sech}^2(\frac{x - c_p t}{\Delta})\tanh(\frac{x - c_p t}{\Delta}), \quad (4)$$

and, from the continuity equation, $\partial u/\partial x + \partial w/\partial z = 0$, the horizontal velocity becomes:

$$u(x,z,t) = c_p \eta_0 \frac{\partial \Phi}{\partial z} \text{sech}^2(\frac{x - c_p t}{\Delta}). \quad (5)$$

- From Eqs. (1)-(5), we can calculate the ISW's depth-integrated energy flux, $F(x,t)$, by:

$$F(x,t) = \int_{-H}^0 u(x,z,t) \times [p(x,z,t) + K_e(x,z,t) + P_e(x,z,t)]dz, \quad (6)$$

where $p(x,z,t) = p'(z)\text{sech}^2(\frac{x-c_p t}{\Delta})$, $K_e = \rho_0[u^2(x,z,t) + w^2(x,z,t)]/2$, and $P_e(x,z,t) = \rho_0 N^2(z)\eta^2(x,z,t)/2$.

- Figures 5a and 5c show the averaged profiles for cycle 498 in the Banda and Molucca Seas, respectively. To obtain the time-mean energy flux values across the Banda/Molucca Seas, we calculate the $F(x,t)$ profiles like in Figs.5a and 5c from all available CAL/VAL cycles.
- Because the daily sampling over the 3-month CAL/VAL mission is insufficient to capture the ISW signals across the Banda/Molucca Seas uniformly, we interpolate the daily $F(x,t)$ values linearly along the ISW propagating paths and Figs.5b and 5d show the time-mean energy flux values in the Banda and Molucca Seas based on the interpolated $F(x,t)$ profiles.

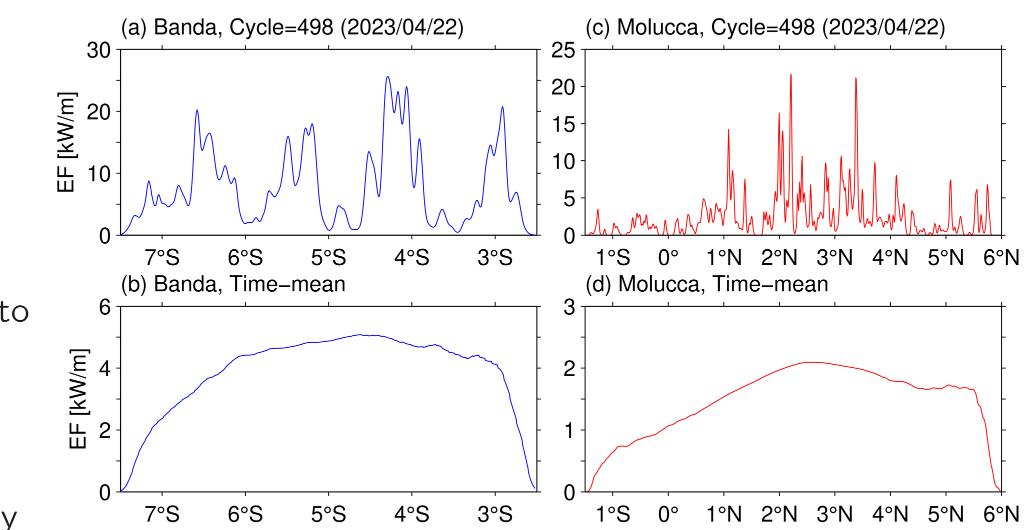

Figure 5. Depth-integrated northward energy flux associated with the ISWs across (a) the Banda Sea and (c) the Molucca Sea during the CAL/VAL cycle = 498. (b) and (d) show the time-mean depth-integrated northward energy flux averaged over all CAL/VAL cycles in the Banda and Molucca Seas.

- In the Banda Sea, energy flux has a maximum of 5 kW/m in the middle basin and the flux value tapers off toward the southern and northern boundaries. Based on a high-resolution simulation forced by barotropic M2 tides, Nagai and Hibiya (2015) found that the depth-integrated northward energy flux in the Banda Sea is about 10 kW/m near the Ombai Strait and it decreases to 5 kW/m toward the middle of the basin (Fig.6). This result implies that while the internal M2 tides play a major role in determining the northward energy flux near the Ombai Strait, the ISWs become increasingly dominant in providing the northward energy flux in the central basin of the Banda Sea.
- Like in the Banda Sea, the time-mean, depth-integrated, northward energy flux across the Molucca Sea exhibits a similar spatial pattern (Fig.5d), with an exception that the mid-basin energy flux is at a lower level around 2 kW/m. This northward energy flux value is smaller than that simulated by Nagai and Hibiya (2015) inside the Molucca Sea. It implies that both the M2 internal tides and ISWs contribute jointly to the northward energy flux across the Molucca Sea.

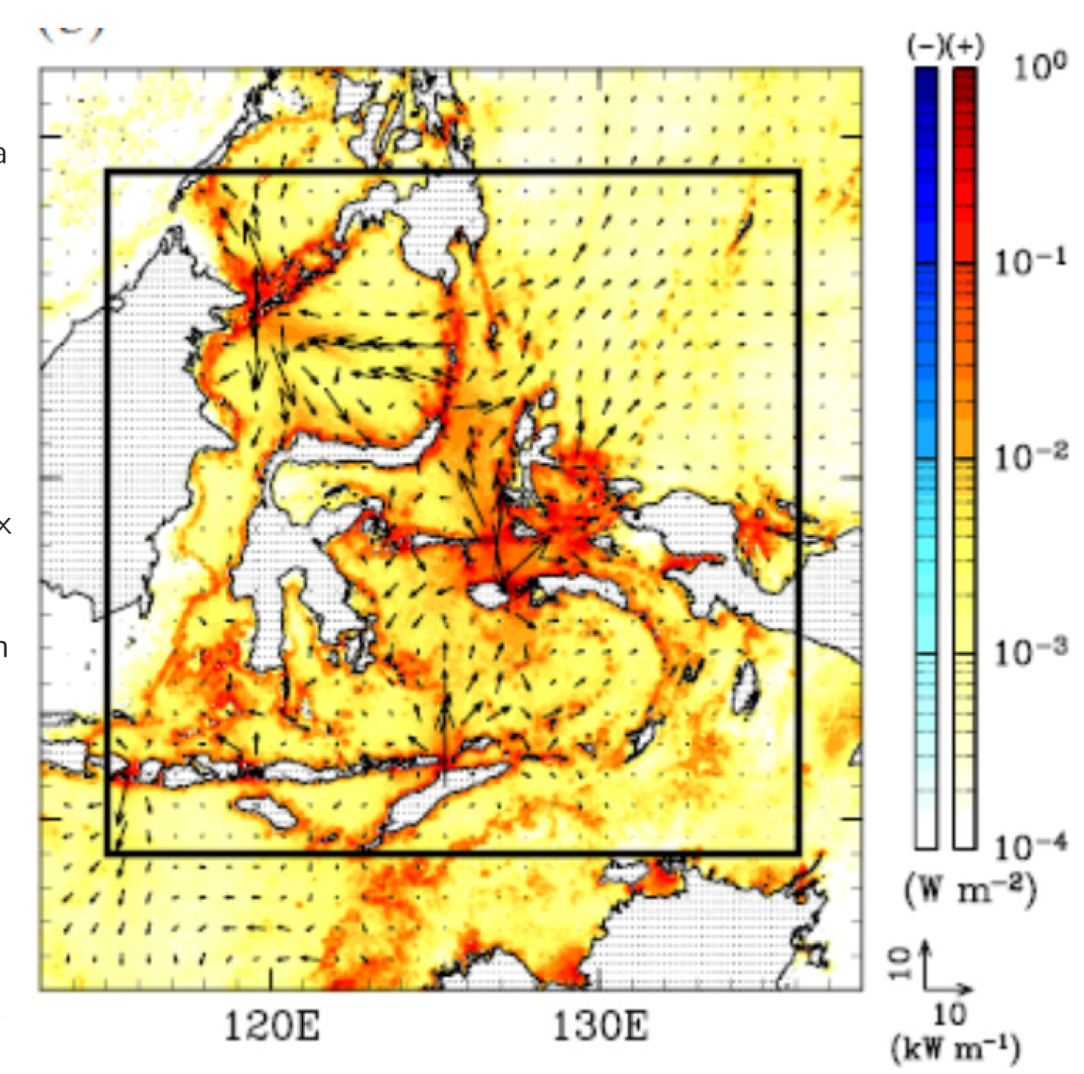

Figure 6. Depth-integrated baroclinic energy flux (vector) and depth-integrated baroclinic energy dissipation (color shading) from the high-resolution simulation of Nagai and Hibiya (2015).

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