Energetics of internal tides over the Sangihe-Talaud ridge - Sulawesi sea

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Abstract. An estimate of energetic barotropic and baroclinic tides over Sangihe-Talaud ridge (STR) - Sulawesi Sea is carried out by using a three-dimensional ROMS (Regional Ocean Modeling System) ocean model. The model is validated with satellite data. The estimate of tidal energy consists of generation, radiation, and dissipation. The model identified the generating internal tide area with strong barotropic-to-baroclinic conversion (above 10 kW/m) over S-T ridge. Away from this generating internal tides area that is in deep Sulawesi Sea basin, energy conversion is very weak (below 10⁻³Wm⁻²). Baroclinic energy is mostly dissipated in area near the coast. From the total of 9.45 GW (100%) of barotropic-to-baroclinic energy conversion, about 7.19 GW (76%) is converted into baroclinic energy through the generation of internal tide and about 4.13 GW (57%) of this baroclinic energy radiate to deep open sea. Distribution of tidal energy is highly dependent on topographic features. Estimate of strong vertical eddy diffusivity ($K_V$) over the steep S-T ridge varies between 10⁻³ and 10⁻² m²/s, in contrast to the weak $K_V$ in deep flat Sulawesi basin of about 10⁻⁴ m²/s.

1. Introduction
The main component for the system of earth’s climate is the ocean. The process of mixing in the ocean is very important on determining the distribution of salinity, heat, and energy. Tidal energy is the one of main sources of energy for the mixing process in the ocean. Previous study showed that in the ocean, there are 25%-30% of barotropic tidal energy dissipate and vanish [1-3]. While transferring the energy into the deep sea turbulence, the internal wave has the significant role. When barotropic tidal flow over to the sill of topography, some energy of barotropic will be vanish through local mixing, dissipation, and the other the energy of barotropic that is convert to the process of generating internal tides (baroclinic). The result of baroclinic energy will be dissipated locally or radiated to the open ocean.

Internal waves is formed in order to encounter between the seawater layers which have different densities with creating forces that can come from air, tidal or even the ship movement. Internal waves generating needs a big forcing, generally internal waves is generated by strong tidal interaction, lower topography, and coating fluid. the case occurs in the Sulawesi Sea, where internal currents pass through very strong waters, especially on the Sangihe Chains Island section there is a sill with a depth of up to 1350 m [4]. Generating internal waves as a result of barotropic tide conversions passing through topography is an interesting topic to study.
The internal waves generation by using tidal has been a focus for recent research. Internal tide happens in the stratified fluid while the currents barotropic tidal propagation interact with topography of rough surface and has result in local internal pressure and vertical movement. This local troubles propagate as waves that are far from the generation center. Energetics of internal waves in the study area are estimated by calculating the internal energy budget of the energy conversion from barotropic to internal baroclinic tides which can propagate far from center of generation.

The important exertions have been done in the last decade in order to estimate the energy of internal wave using numerical model simulation. Using Hydrostatic Princeton Ocean Model (POM) (Blumberg dan Mellor 1987), investigations of energetics of internal tides have been done in the coast of British- North Columbia [5], in the Hawaii ridge [6-8], in the east China Sea [9], in the Monterey Bay region [10-12], and in the mid-Atlantic Ridge [13]. Numerical simulation of internal waves using Stanford Unstructured Non-hydrostatic Terrain-Following Adaptive Navier-Stokes Simulator (SUNTANS) [10, 14].

Estimates from barotropic to baroclinic energy have been analyzed with baroclinic energy divergence [5-7, 10], and also with the terms of conversion from the equation of barotropic and baroclinic energy [9, 15].

Recent research on Internal Waves in the Sulawesi Sea was conducted by [16], this study calculated the vertical diffusivity using a three-dimensional numerical model. Numerical experimental results show that the resulting higher internal M2 tidal energy occurs in parts with tide to baroclinic tide is found in the Near-Field area.

The aim of this research was to investigate the energetic and internal wave dynamics of the Sulawesi Sea, as well as to produce parametric models to estimate the conversion of barotropic-baroclinic tidal energy in the Sulawesi Sea. In this study an analysis of energetics of internal tidal waves in Sulawesi Sea will be estimated from various areas, namely deep, slope, and sill area especially along the area of Sangihe-Talaud Ridge (STR) using hydrostatic model of Regional Ocean Modeling System (ROMS) [17-20].

2. Methods
2.1. The area of study
Model domain is located in eastern of Sulawesi Sea with coordinate boundary from latitude of 0.75°N to 5°N and longitude of 122°E to 127°E (Figure 1). The model domain is situated in the Sangihe-Talaud ridge which is expected to be strong internal tidal wave dynamics.

![Image](image_url)
2.2. Numerical Model Configuration

This model simulation was carried out by ROMS-AGRIF [21], which has advantages in nesting capabilities using AGRIF (Adaptative Grid Refinement in Fortran). ROMS has special characteristics, including the solving of primitive equations (Boussinesq equations and vertical hydrostatic momentum balance), free surface (short time step for barotropic dynamics and large time step for baroclinic dynamics), increased horizontal pressure gradient calculations, and sediment modules. ROM simulation require topography, surface forcing (surface hem flux, wind stress, freshwater flux), land mask, horizontal grid data (grid size, grid position), lateral boundary conditions (temperature, salinity, tides, current, sea surface height), initial conditions (temperature, salinity, currents, sea surface height).

This model is initiated by using data input for the model was acquired from the Research Center and World Database [22], including surface forcing (air-sea parameter, heat flux, fresh water flux) from COADS05, bathymetry from GEBCO 30', sea surface temperature from monthly AVHRR-Pathfinder satellite imagery from 1985-1997, monthly wind stress climatology from QuickScat, properties of seawater from the lateral boundary conditions from DRAKKAR INDO-ORCA05 simulation of climatology (1970-2003) and World Ocean Database and lateral boundary conditions from DRAKKAR INDO-ORCA05 climatology simulation (1970-2003). The barotropic tidal velocity component is extracted from The TPX07 global tidal model and is used to force lateral open boundaries. The global tidal model are obtained from Oregon State University OSU [23].

Domain model (Figure 1) is discretized with 1/48° horizontal resolution, containing 239x204 grid cells and with 32 vertical sigma level. Vertical grid is stretched to increase boundary layer resolution. Model simulation is performed for one year in order to achieve statistical balance. The model is run with time-step of 180 seconds and the result of simulation is saved every one-hour. The last month of simulation is analyzed for this study.

2.3. Model validation

The results of numerical model simulation is validated by comparing the sea surface temperature from ROMS output and from NOAA AVHRR sea surface temperature of 2003-2009 (Figure 2). Sea surface temperature values are averaged at the central Sulawesi Sea. The correlation coefficient is calculated to extract information about the relation between sea surface temperature values of output model of NOAA AVHRR surface temperature.

![Figure 2. Results of validation SST from ROMS model with satellite image NOAA AVHRR.](image)

The sea surface temperature (SST) of the ROMS model is averaged over a year. While the SST results of NOAA AVHRR image analysis is the monthly average in the period 2003-2009. The value of SST in NOAA AVHRR image shows contrasting fluctuations during the peaks of the Northwest Monsoon period (Dec-Feb) and the Southeast Monsoon period (Jul-Sep). The SST from the
satellite data looks to be fit with the model SST. Amplitude of satellite SST during the Northwest Monsoon period seems to be much higher compared to the model, in contrast to that during the Southeast Monsoon period. The high correlation is indicated by the pattern of the three graphs and has a correlation coefficient value of 0.96 for the correlation between satellite SST and model SST. The alleged model may represent 92% of each observation model. This can be interpreted that the model can represent the actual situation and can be applied to the modeling of the Sulawesi Sea.

3. Results and discussion

3.1. Generation characteristics of internal waves in sangihe-talaud sill

The internal wave generation region is classified using non-dimensional parameters [24]. The stepness critical parameters of the internal wave pack are defined as the ratio between the topographic slope and the slope of the internal wave characteristics ($\gamma$) given by the equation:

$$\varepsilon = \frac{\left| \nabla h \right|}{\gamma}$$

(1)

where:

$$\gamma = \left( \frac{\omega^2 - f^2}{N^2 - \omega^2} \right)^{0.5}$$

(2)

$\omega$ is the forcing frequency, $f$ the Coriolis frequency, and $N$ the buoyancy frequency, the topographic slope is given by $\left| \nabla h \right| = \sqrt{(\partial h/\partial x)^2 + (\partial h/\partial y)^2}$, where $h$ depth of the topography. Based on the value of the critical parameter, topography becomes “subcritical” while the topographic slope was smaller than internal wave slope ($\varepsilon < 1$), but while the topographic slope was greater than internal wave slope characteristics ($\varepsilon > 1$), the topography becomes “supercritical”. Topography is “critical” when its topographic slope was the same with the internal wave slope characteristics ($\varepsilon = 1$).

The topography features of Sulawesi Sea are very complex. Particularly the Sangihe-Talaud Islands sill section as shown in Figure 3, along these areas forms a steep topographic feature with a topographic slope more than 40% and even at the northern end of the archipelago there is a steep topographic feature with a slope of more than 50%. The internal waves in the Sulawesi Sea are raised through the Sangihe-Talaud Island Chains area, which is a region with complex topographic features and consists of several steep sill topography.
To calculate the internal wave characteristic slope, is given \( \omega = 1.4 \times 10^{-4} \text{rad s}^{-1}, N = 1 \times 10^{-3} \text{rad s}^{-1}, \) and \( f = 0.8 \times 10^{-3} \text{rad s}^{-1}. \) So that, the value of the slope of the internal wave characteristic \( \theta = 1.16 \times 10^{-1} \text{rad s}^{-1}. \) Based on the topographic slope and characteristic slope of the internal wave angle, it can be classified that the area along the Sangihe-Talaud Island Chains is formed by the “critical” (\( \varepsilon = 1 \)) and “supercritical” (\( \varepsilon > 1 \)) topography features because the topographic slope value is greater than with internal wave characteristic values, “critical” and “supercritical” topography more efficient in emitting baroclinic energy or internal wave radiation resulting from the energy conversion process. So with the topographical characteristics that cause the process of energy conversion, dissipation and vertical diffusivity that occurred in the area of Sangihe-Talaud Island Chains has a greater value compared to other areas in the Sulawesi sea. While in the Sulawesi Sea basin section is dominated by subcritical topographic features (\( \varepsilon < 1 \)) because the slope of the internal wave is greater than the topographic slope, this area acts as an energy absorber. So the propagation of the internal wave of dissipation from baroclinic energy travels into the Sulawesi Sea basin area.

3.2. Energetics
3.2.1. Generation and propagation of internal waves
Barotropic tidal conversion to baroclinic occurs mainly in Sangihe-Talaud Island Chains (Figure 6). In many areas away from the generation sites in this case the sill region (e.g., Sulawesi Sea basin), the energy conversion is very weak less than \( 10^{-3} \text{Wm}^{-2}. \) Note that the negative value of energy conversion rates in some locations indicates evidence of internal wave generation, which is the result of the phase difference between internal waves generated locally and from a distant area [13].
Figure 4. A snapshot of the depth-averaged baroclinic energy dissipation rates in the Sulawesi Sea [16]

Figure 5. Snapshot Vertical velocity at a depth of 1000 m

The depth-integrated baroclinic energy flux distribution is showed in Figure 7 (vector). The energy of strong baroclinic energy flow higher than 10kW/m comes from an area where the conversion of significant energy is identified in the Sangihe-Tauland Island Chains. Most of the baroclinic energy is discharged in the area near the coast, the energy flow then propagates away from the central sites of the generation area and into the Sulawesi Sea basin, and it looks like a radiation of internal wave packets that is leading to the Sulu Archipelago (Figure 4). An internal wave packet leading to the Sulu Archipelago have been detected by satellite observation [25], as well as the results of a study explains that dissipation processes area is far from the generation center and propagation [16]. It can be seen clearly in a snapshot of energy dissipation level of the depth which is integrated with the depth of baroclinic energy ini Sulawesi Sea (Figure 3). The internal wave dissipation energy derived from Sangihe-Talaud Island Chains becomes more significant as radiation leads to the Sulu Islands. That's because those internal waves evolved in solitary like wave gradually, while there are increasing of the number horizontal wave. These solitary-like internal wave packets emitted from Sangihe-Talaud Island appear to spread independently without interacting with other independently. Nevertheless, each of the internal wave packets stands from propagation away from the archipelago, it provides large amounts of energy for dissipation during propagation.
3.2.2. Spatial structure

Figure 6 is showed the horizontal distribution of the depth integrated barotropic to the rate of baroclinic conversion. The red colour explains the positive energy conversion rate, that the the generations of the internal tides and image exhibits that the generation occurs on 280-m and 3500-m isobaths implicitly. The blue colour or the negative energy conversion rate explained the energy transfer from baroclinic to barotropic tide. It is caused with the difference phase between generated local and and remote waves internally [13].

**Figure 6.** Model-predicted distributions of Depth-integrated, period-averaged barotropic-to-baroclinic conversion rate (near-field area is defined in the black color line)

Significant negative conversion occurs in Sangihe-Talaud Island Chains due to the high baroclinic energy generated in the region around the talaud islands and driven by bathymetry of the Sangihe-Talaud Archipelago (Figure 6). A large dissipation of baroclinic energy occurs near strong internal wave generating sites. Figure 7 shows the horizontal distribution of the depth-integrated baroclinic energy-flux (vector). Large fluxes are seen around the area of Sangihe-Talaud Island Chains. The energy budget in subdomain is discussed in the next section.
3.2.3. Energy Flux Budget

Total budget of energy flux in a region is obtained by using the following equation [26]:

\[
BT \text{ Input} = - \sum \left( \nabla_H \cdot (\mathbf{F}_b) \right) \Delta A
\]  
(3)

\[
\text{Conversion} = \sum \left( \langle \mathbf{c} \rangle \right) \Delta A
\]  
(4)

\[
\text{BC Radiation} = \sum \left( \nabla_H \cdot (\mathbf{F}_b) \right) \Delta A
\]  
(5)

\[
\text{BT Dissipation} = \sum \left( \nabla_H \cdot (\mathbf{F}_b) + (\mathbf{c}) \right) \Delta A
\]  
(6)

\[
\text{BC Dissipation} = \sum \left( \nabla_H \cdot (\mathbf{F}_b) - (\mathbf{c}) \right) \Delta A
\]  
(7)

\[
\text{Dissipation total} = \sum \left( \nabla_H \cdot (\mathbf{F}_b) + \nabla_H \cdot (\mathbf{F}) \right) \Delta A
\]  
(8)

where \( \sum \) is the summation from every grid cell in particular region \( \Delta A \) which is area from every grid cell. Equation (3) - (8) above is limited by following condition:

\[
\ell_z: -200(n - 1) \leq z \leq -200n, n = 1, \ldots, 32
\]  
(9)

Figure 7 comparing the model-predicted distributions of the depth-integrated baroclinic energy flux (vector).

Figure 8 comparing the inputs of barotropic energy, baroclinic energy radiation and barotropic-to-baroclinic energy conversion in the 124°E - 126°E areas. Figure 8 (bottom) compares the input of barotropic energy, baroclinic energy radiation (baroclinic input), and barotropic energy conversion to baroclinic, while the top compares its power cumulative.

At depths below 250 m only a small portion of the barotropic energy of the input is converted to baroclinic energy, and negative baroclinic energy radiation implies that baroclinic energy produced in the deeper region flows into this shallow region and then undergoes dissipation. In a deeper region of 2800 m, almost all of the barotropic input energy is converted to baroclinic energy and under goes
peak conversion at depths of 3200 m - 4000 m. Radiation Baroclinic energy radiates greatly in the region between 3500-m and 3700-m isobaths, and much smaller in other regions.

Figure 8. Energy distribution as a function of depth, Equation (3) - (5)

Figure 9. The Distribution Energy as a depth function, Equation (6) - (8)
Figure 9 is contrasted with the baroclinic dissipation and barotropic dissipation. Common dissipation of barotropic energy happens in the deeper region of 3200m-4500m. However the dissipation energy of baroclinic happens in all depth with mount near 3300m and in 4000m. Figure 10 shows that the budget scheme energy for basin and peak areas that is limited to 350-m and 5500-m isobath depths. 9.45 GW Barotropic energy enters the slope area and about 76.11% of this energy is converted to baroclinic energy. Some of the resulting baroclinic energy is dissipated locally localized, while the remaining portion (57.37%) radiates to deeper and shallower areas. The basin region acts as a baroclinic energy absorber because of the good dissipation of locally generated energy and the part that flows into it from the slope region.

Figure 10. Schematic of the tidal energy budget for domain bounded by the 0-m, 350-m, and 4000-m isobaths.

Figure 11. Schematic of the tidal energy budget in percentages

Furthermore, detail of the resulting energy budget is presented in Table 1 for the 388.5 km × 83.25 km domain, which used to represent the Sangihe-Talaud Island Chains area as it covers all the typical topographic features in this area. For this area, approximately 7.19 GW (76.11%) of the barotropic energy with 9.45 GW is converted to baroclinic energy, and 4.13 GW (43.67%) of the resulting baroclinic energy is irradiated.
### Table 1. Tidal energy budget in Sangihe-Talaud Sill

| Energy Distribution       | Energy (MW)   |
|---------------------------|---------------|
| BT Input                  | 9,449.53 (100%) |
| BT-BC Conversion          | 7,192.32 (76%) |
| BC Radiation              | 412695 (44%)   |
| BT Dissipation            | -2,257.20 (24%) |
| BC Dissipation            | -3,065.38 (32%) |
| Total Dissipation         | -5,322.58 (56%) |

#### 3.2.4. Vertical diffusivity estimates in the sulawesi sea

Vertical diffusivity values at each depth $i$ are obtained using the Osborn equation [27], which given by the following equation:

$$K_{vl} = \Gamma \frac{\varepsilon_i}{N_i^2}$$  \hspace{1cm} (10)

Where $\Gamma$ assumed with the mixing efficiency to be 0.25 [28]. $N^2$ is Bunt-Vaisala frequency:

$$N_i^2 = -\frac{g}{\rho_0} \frac{\partial \rho_i^*}{\partial z}$$  \hspace{1cm} (11)

$g$ is gravity acceleration, $\rho_0$ is background density, and $\rho_i^*$ is the density because of the perturbation. The kinetic energy rate of the turbulent dissipation ($\varepsilon_i$) at each depth is obtained by the equation [29]:

$$\varepsilon_i = 7.5 \times \nu \left(\frac{\partial u}{\partial z}\right)^2$$  \hspace{1cm} (12)

$\nu$ is the kinematic seawater viscosity coefficient.

The distribution of vertical diffusivity can be seen in Figure 12 where strong mixing occurs in the near-field area around Sangihe-Talaud Island with the vertical diffusivity value $K_v \sim 10^{-2} \text{m}^2\text{s}^{-1}$. Even in far-field, from the generating sites we find vertical diffusivity $K_v \sim 10^{-4} \text{m}^2\text{s}^{-1}$. Outcome from propagating internal tides dissipation.

![Figure 12. Model-predicted distribution of the depth-averaged vertical diffusivities.](image-url)
The representation of the distribution sectional cross estimated diffusivity vertical using equation (10) that is shown in Figure 13, which than can be seen that the diffusivity vertical is far field less than $10^{-3}$m$^2$s$^{-1}$ above ~ 1000m, up to $10^{-1}$ to $10^{-2}$ m$^2$s$^{-1}$ to the bottom. Thus, the presence of a sill in the Sulawesi Sea with rough topography features is an important factor in increasing the value of vertical diffusivity in the Sulawesi Sea. The increase is due to the powerful interaction between topography around the sill area and barotropic tidal.

![Figure 13](image)

*Figure 13. Model-predicted cross-sectional snapshots of the vertical diffusivities in the Sangihe-Talaud Island Chains Domain*

### 4. Conclusion

The investigation of the dynamics and energetic of internal tide in this study used the model of numerical approach of Regional Ocean Modeling System (ROMS). The result obtained in this research indicate that the barotropic tides conversion to baroclinic occurs mainly in Sangihe-Talaud Island Chains. In some areas away from the generation sites in this case the sill region (eg, the Sulawesi Sea basin), the energy conversion is very weak i.e. less than $10^{-2}$Wm$^{-2}$. The energy of strong baroclinic flow higher than 10kW/m comes from areas where significant energy conversion is identified that is in the area around Sangihe-Talaud Island Chains. For the 388.5 km x 83.25 km domain including the typical topographic features in the Sangihe-Talaud Island Chains area, about 7.19 GW (76%) of the barotropic energy of 9.45 GW is converted to baroclinic energy, and 4.13 GW (44%) of the resulting baroclinic energy is radiated away from the generating area.

Distribution of vertical diffusivity indicates that the area where strong mixing occurs around Sangihe-Talaud Island with vertical diffusivity value $K_v \sim 10^{-2}$m$^2$s$^{-1}$. Even in area far from the generating center the model shows vertical diffusivity $K_v \sim 10^{-4}$m$^2$s$^{-1}$, as a result of internal propagation tides dissipation. The dissipation of internal wave energy from the Sangihe-Talaud Island Chain becomes more significant as radiation leads to the Sulawesi Sea basin. This is because these internal waves gradually evolve into solitary-like waves while increasing the number of horizontal waves.

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