ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Modelling explicit tides in the Indonesian seas: An important process for surface sea water properties

Dwiyoga Nugroho[a,b,*], Ariane Koch-Larrouy[a,c], Philippe Gaspar[d], Florent Lyard[a], Guillaume Reffray[c], Benoit Tranchant[d]

[a] Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Université de Toulouse, CNRS, IRD, CNES, UPS, 14 avenue Edouard-Belin, 31400 Toulouse, France
[b] Agency of Research and Development for Marine and Fisheries, MMAF, Jakarta, Indonesia
[c] Mercator-Ocean, 10 Rue Hermès, 31520 Ramonville-Saint-Agne, France
[d] Collecte Localisation Spatiale, CLS, 11 Rue Hermès, 31520 Ramonville-Saint-Agne, France

ARTICLE INFO

Keywords:
INDESO
ITF
Internal tides
Vertical mixing
Explicit tides
Ocean Physical General Circulation Model (OGCM)

ABSTRACT

Very intense internal tides take place in Indonesian seas. They dissipate and affect the vertical distribution of temperature and currents, which in turn influence the survival rates and transports of most planktonic organisms at the base of the whole marine ecosystem. This study uses the INDESO physical model to characterize the internal tides spatio-temporal patterns in the Indonesian Seas. The model reproduced internal tide dissipation in agreement with previous fine structure and microstructure observed in-situ in the sites of generation. The model also produced similar water mass transformation as the previous parameterization of Koch-Larrouy et al. (2007), and show good agreement with observations. The resulting cooling at the surface is 0.3 °C, with maxima of 0.8 °C at the location of internal tides energy, with stronger cooling in austral winter. The cycle of spring tides and neap tides modulates this impact by 0.1 °C to 0.3 °C. These results suggest that mixing due to internal tides might also upwell nutrients at the surface at a frequency similar to the tidal frequencies. Implications for biogeochemical modelling are important.

1. Introduction

The Indonesian archipelago, with its estimated 17,000 islands is a unique region in the world. It contains much of the world's marine biodiversity and is part of the “Coral Triangle”, the global hotspot of marine biodiversity (Allen and Werner, 2002; Mora et al., 2003; Allen, 2007; Veron et al., 2009). In addition to biodiversity, the physical oceanography of this region is remarkable by several aspects. Among them, the large tidal currents coming either from the Indian Ocean or the Pacific Oceans interact with the rough topography and create strong internal wave at the tidal frequency, called internal tides (Fig. 1). These internal tides are generated on the slope of sharp topography and eventually propagate in the interior of the ocean. When an internal tide gets instable, it breaks, resulting in a strong mixing. This mixing upwells cold, salty and nutrient-rich water from below and downwells warm and fresh water from the surface to deeper depth. This mixing, and the upwelling of cold nutrient-rich waters at the surface, could be critical for the climate system and for marine resources. Second, Indonesia also has the warmest oceanic waters on earth. These waters feed the most powerful atmospheric convective activity. The resulting large tropical atmospheric circulation affects, via teleconnexion, the global system. In such an energetic atmospheric region, any modulation of the ocean heat surface content by oceanic processes can have a large impact on local and tropical climate (Koch-Larrouy et al., 2010; Sprintall et al., 2014). Lastly, the Indonesian seas offer the only low latitude passage in the world for water flowing from the Pacific Ocean to the Indian Ocean, which is referred to as the Indonesian throughflow (ITF) (Murray and Arief, 1988; Fieux et al., 1994; Gordon and Fine, 1996; Hautala et al., 2001; Molcard et al., 2001).

In fine, Indonesian islands and their surrounding waters provide several billion dollars of annual revenue through fisheries, aquaculture and tourism. Tuna fisheries are a major economical sector in Indonesia, and fishing and aquaculture employ almost 6.4 million people (source from Fisheries and Aquaculture Department, http://www.fao.org/fishery/facp/IDN/en#CountrySector-Overview).

An accurate monitoring and forecasting system for the ocean is certainly vital to manage Indonesia waters and its resources. To help meeting these challenging objectives the INDESO (Infrastructure

* Corresponding author at: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Université de Toulouse, CNRS, IRD, CNES, UPS, 14 avenue Edouard-Belin, 31400 Toulouse, France.
E-mail address: dwi.yoga.nogroho@legos.obs-mip.fr (D. Nugroho).

http://dx.doi.org/10.1016/j.marpolbul.2017.06.033
Received 16 December 2016; Received in revised form 7 June 2017; Accepted 9 June 2017

Please cite this article as: Nugroho, D., Marine Pollution Bulletin (2017), http://dx.doi.org/10.1016/j.marpolbul.2017.06.033

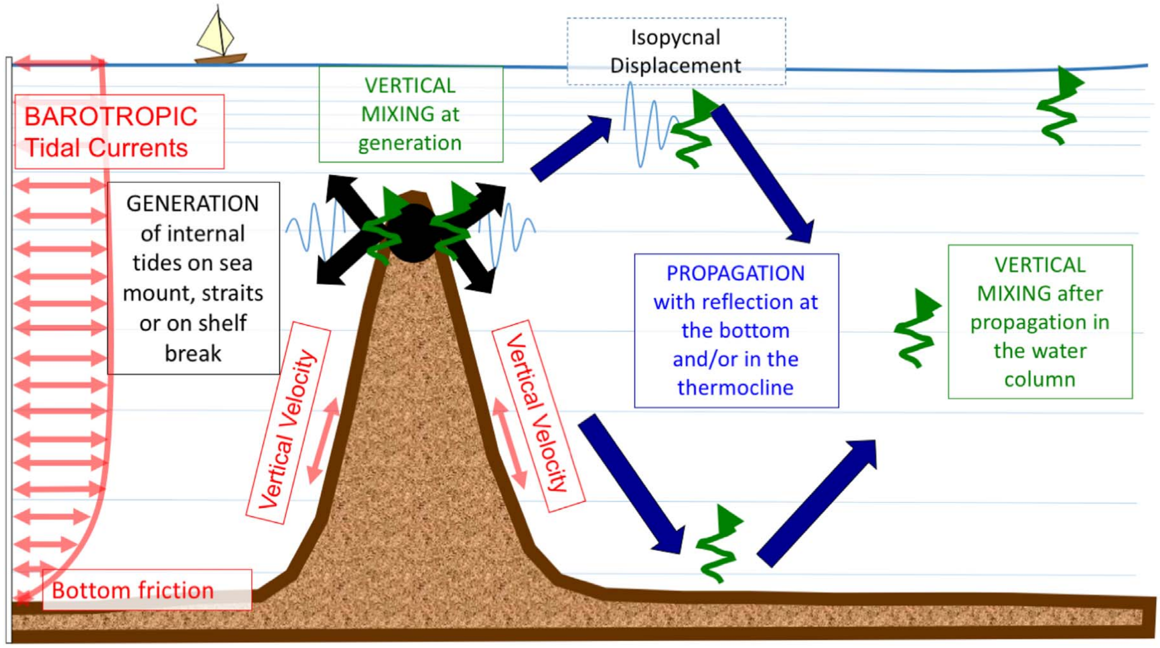

Fig. 1. Schematic of internal tides generation, propagation and dissipation. The barotropic (or surface) tides oscillate horizontally in the plain ocean (red arrow). It loses part of its energy at the bottom due to bottom friction (red arrow) or when internal tides are generated (black arrow). When the tidal currents encounter the topography feature (brown) it creates vertical currents on its sides (red arrows). This vertical motion in a stratified ocean acts as a vertical generator of waves at tidal frequency. Part of internal tides will dissipate and produce vertical mixing (green arrow) locally just after generation, or later after propagation. When internal tides propagate it can be seen isopycnal displacements (blue line) in the interior sea, and if the internal tides are very strong vertical displacement signature can also be seen at the surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Development of Space Oceanography) project was developed for the Government of Indonesia. With this project, Indonesia has implemented a new system for the monitoring and management of its tuna resources. Within INDESO, physical and biogeochemical coupled models are used to constrain a dynamical tuna population model SEAPODYM (Lehodey et al., 2008). In this study, we use for the first time the physical model to study the impact on surface properties of internal tides mixing and discuss the spatio-temporal patterns in the Indonesia Seas.

1.1. Background information on internal tides in the Indonesian region.

Internal tides are generated when barotropic (or surface) tides oscillate over a topography feature (Fig. 1). Barotropic horizontal motions are converted into vertical velocities (red arrow, Fig. 1) over the topography. As the ocean is a stratified fluid (thin horizontal blue line representing the isopycnal layers, Fig. 1), the vertical velocity will act as a vertical generator of wave at the tidal frequency. Part of the internal tides can dissipate and produce vertical mixing (green arrow, Fig. 1) locally just after generation, or later after propagation. The fate of internal tides can be traced using satellite and Radar images as it has been done in the Lombok strait for example (Mitnik et al., 2000; Sari Ningsih, 2008; Aiki et al., 2011; Matthews et al., 2011; Astawa Karang et al., 2012; Ray and Susanto, 2016) or in the Sulawesi Sea (Nagai and Hibiya, 2015). Signature of internal tides are also found in in-situ data. For instance, direct yo-yo station measurement in Lifamatola (Ffield and Gordon, 1996) and in Labani channel (Purwandana, 2014) shows the oscillation of isopycnal in the thermocline over the tidal period.

The Indonesian archipelago is the only region of the world with strong internal tides generation in a semi-enclosed area. Therefore, all of the internal (or baroclinic) tidal energy remains trapped locally inside the archipelago and is available for dissipation, and the archipelago has the largest internal tide generation value (10% of the global value). As a result, water mass is transformed when entering the archipelago, producing colder and fresher thermocline water and saltier and cooler surface water (Ffield and Gordon, 1996; Hautala et al., 2001; Koch-Larrouy et al., 2007). A vertical diffusivity of $1–2 \cdot 10^{-4}\ m^2/s$ has been estimated from observations in order to explain the water mass transformation in the archipelago (Ffield and Gordon, 1992).

Recently, the INDOMIX cruise (Koch-Larrouy et al., 2015) provided direct estimates of internal tide mixing with higher values ($10^{-2}\ m^2/s$) in the shallow and narrow passage between Ombai Strait and Halmahera, in comparison to lower values in the inner Halmahera Sea ($10^{-4}\ m^2/s$) or further away from generation sites ($10^{-6}\ m^2/s$) in the Banda Sea. These new results showed that the mixing induced by internal tides in the Indonesian archipelago is highly heterogeneous in space, with high values within straits. In addition, it demonstrated that internal tide mixing is also strong at the surface.

Modelling in the region is quite challenging because of the numerous processes at play and the very complex bathymetry. Koch-Larrouy et al. (2007), implemented a tidal parameterization adapted to the specificities of the Indonesian archipelago. Introduced in an Oceanic General Circulation Model (OGCM), this parameterization allowed the model to better represent the properties of the water mass evolution in each sub-basin, in good agreement with the observations (Koch-Larrouy et al., 2007). This model produced heterogeneous vertical diffusivity as large as $10 \cdot 10^{-4}\ m^2/s$, with an average of $1.5 \cdot 10^{-4}\ m^2/s$. This suggested that the total energy input provided by the tidal parameterization had the right order of magnitude. The tidal mixing parameterization resulted in the cooling of the sea surface by 0.5 °C in annual average, which reduced the deep convection, and the rain activity (by ~20%) (Koch-Larrouy et al., 2010; Sprintall et al., 2014). The impact on biological activity has not yet been studied, but it could be guessed from these results that the vertical mixing would have a significant impact on blooms of phytoplankton by upwelling water richer in nutrients at the surface. However this tidal mixing parameterization did not take into account the propagation of internal tides and thus the mixing that could occur further away from generation sites. It also does not take into account the upwelling of the base of the mixed layer associated to the isopycnal displacement of the wave when it propagates away from generation zones (Fig. 1).

Recently, with the increase of model resolution, a larger number of studies now includes the explicit forcing by the tides (Castruccio et al.,