J. Ind. Geophys. Union (April 2007)
Vol.11, No.2, pp.117-122

Turbulent kinetic energy and its dissipation rate of the Indonesian throughflow region via Lombok and Savu Straits

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ABSTRACT
Turbulent kinetic energy (TKE) and its dissipation rate are estimated at Lombok (115° 50′E, 8° 30¢ S) and Savu (122°E, 9° 30¢ S) strait of Indonesian Throughflow (ITF), in the upper and middle layers. It is the region having most complicated geometry of the world ocean. TKE is of the order of 10^{-3} m^2s^{-2} in the upper layer whereas it is 10^{-4} m^2s^{-2} in the middle layer. Corresponding values of TKE dissipation rate are of the order of 10^{-6} m^2s^{-3} and $10^{-8}m^2s^{-3}$.

INTRODUCTION

The model study is an important and significant step towards understanding the dynamics of the Ocean. The passages in Indonesian throughflow (ITF) region have key significance in the study of interconnection between Indian and Pacific Ocean. Numerical modeling also provides a tool for the study of mechanism for the better understanding of the role played by ITF in the climate system. The effects of the ITF on the upper thermocline circulation and surface heatflux over the Indian Ocean are presented for 3-D ocean model forced by two different monthly wind-stress climatologies (Pandey et al., 2007), as they show interesting differences, which could have implications for long term variability in Indian and Australian monsoon. The estimates of heat transport, reported in studies have based their conclusion on other models (Vranes, Garden & Ffield 2002) and POM (Pandey & Pandey 2006), found effective in the study of narrow passages/estuarine geometry. The effects are determined by contrasting a control run with a run in which the throughflow is blocked by an artificial land bridge across the exit channels into the Indian Ocean (Wajsowicz 2002; Pandey et al., 2007).

Turbulent kinetic energy is generated from fluctuation in velocity of the ocean system and a fraction of TKE is dissipated and remainder is used to increase the potential energy. According to classical turbulence theory (Lindborg 1996) the energy contained in large-scale "eddies" cascades to smaller scale eddies. This cascade of energy to smaller scales occurs on all spatial scales down to a dissipative scale, at which point the turbulent energy is converted into thermal energy via some dissipation mechanism. The dissipation rate is proportional to energy contained in the turbulence is treated as thermal heating.

Han et al., (2000) conservation is used to unify the treatment of heating and TKE dissipation (Businger & Businger 2001). The wave breaking reveals a greatly enhanced dissipation rate of kinetic energy close to the air water interface and upper layer. TKE dissipation takes important role in the near surface layer.

The (Garrett & Munk 1972, 1975) description of the internal wave field is a widely accepted baseline for waves in the ocean interior (away from boundaries and regions of forcing and localized dissipation). Interactions of waves in this environment lead to an up-vertical-wave number flux of energy and eventually to wave breaking and dissipation. A model for wave-induced dissipation at Garrett-Munk wave energy levels, verified by observations spanning more than two orders of magnitude of N^2 , predicts that $\varepsilon \sim N^2$.

We have $K_p = \Gamma\varepsilon / N^2$, where K_p is molecular diffusivity, ε is TKE dissipation rate, Γ is mixing efficiency, N^2 is buoyancy frequency squared. and $\varepsilon = q^3 / B_1 l$, where 2TKE=$q^2$=Q2, Second Order Closure, (Mellor &Yamada 1982; Mellor 1989)
Low-frequency internal wave may be trapped to regions of negative relative vorticity associated with the mesoscale flow field. If baroclinic, these flows may present critical layers to the waves (at the level where the wave frequency equals the effective Coriolis frequency). As wave energy accumulates on approach to such critical layers, breaking and dissipation result. This suggests a K_p (molecular diffusivity) dependence on the relative vorticity of the background flow field, though no formal effort has yet been made to parameterize this effect.

Observations clearly document enhanced internal wave energy density and turbulent dissipation adjacent to rough, sloping bathymetry. (Eriksen 1985; Garrett & Gilbert 1988) have thought about what turbulent dissipation and mixing may result from near-critical wave reflection from sloping bathymetry. Wave reflection may be in part responsible for this, but bottom generated waves have also been implicated.

Recently there is some effort to relate flow over bathymetry to wave generation, and in turn, the vertical propagation of these waves and eventual dissipation to the vertical profile of turbulent dissipation and diapycnal diffusivity. The work is beginning with the early models of (Bell 1975a, b) of internal tidal and internal lee wave generation, and the wave-wave interaction work demonstrated above to have skill predicting dissipation. This early results show promise that, given finescale bathymetric information and an estimate of bottom tidal and/or mesoscale currents, a prediction for K (z) may eventually be had. Lastly the boundary layers at the top and bottom of the ocean constitute the dominant sites of turbulent dissipation.

The Indonesian Archipelago consisting of about 1370 islands separate the seas of southwest Pacific from the equatorial Indian Ocean and these islands form a leaky boundary through which Pacific Ocean waters pass into the Indian Ocean. Now we want to apply the above TKE parameterisation theory for Lombok and Savu straits of ITF region having complex topography for an average order of the TKE and its dissipation rate values. The calculation in the present study provides a new way of quantitative estimate, which can be validated with the availability of dataset as the significant development in observation system is achieved.

In the following sections we shall describe in brief the model configuration and properties used, different phases of model run, which will be followed by the results along with their physical interpretation.

The effort employs a relatively simple model run to get the output of TKE and turbulence length scale in the region in order to calculate the average TKE dissipation rate. This is done using three dimensional 14 layer ocean circulation Princeton Ocean Model (POM) (Blumberg & Mellor 1987) run for Indonesian domain (100°E –150°E and 40°S - 0°N) with an open Pacific and Indian Ocean (PACIO) region. Model is forced with realistic seasonal and yearly varying monthly wind data sets da Silva, Young & Levitus 1994), initialized with *Levitus94* annual temperature (Levitus & Boyer 1994) and salinity (Levitus, Burgett & Boyer 1994) climatology.

MODEL CONFIGURATION AND EXPERIMENTS

The numerical model POM (Blumberg & Mellor 1987; Mellor 2004) used in this study is based on a three dimensional primitive equation, time dependent, sigma coordinate, free surface, estuarine and coastal ocean circulation model along with turbulence closure sub model (Mellor & Yamada 1982) that yields realistic Ekman surface and bottom layers. It is a sigma coordinate (terrain-following) model, meaning that the water column is divided into an equal number of proportional vertical layers regardless of the local depth. Curvilinear orthogonal coordinates define the horizontal grid and staggered "Arakawa C" differencing scheme is used for the grid. An explicit time step is used for the horizontal differencing and an implicit scheme for the vertical differencing, which enables the use of fine vertical resolution in the surface and shallow layers. The model employs a split time step. The external mode is two-dimensional and uses a short time step based on the Courant-Friedrich-Lewy (CFL) condition and the external wave speed. The internal mode is three-dimensional and uses a long time step based on the CFL condition and internal wave speed. The model contains an imbedded second momentum turbulence closure scheme to provide vertical mixing coefficients (Mellor & Yamada 1982). The transformation of the coordinates to the sigma coordinates is accomplished. The governing equations are the continuity equation, the momentum equations, the temperature and salinity equations, the turbulence closure equations, and the equation of state (Mellor & Yamada 1982; Blumberg & Mellor 1987; Mellor 2004) The model topography is generated from Extended Topography at 5¢ (ETOPO5) terrain *base* (Lee & David 1988) data set. In the topography the westernmost Lombok Strait are found to near 115° 50¢ E, 8° 30¢ S and Savu Strait is near 122° E and 9° 30¢ S. A curvilinear orthogonal system with a fixed resolution of 0.5^{o} x 0.5^{o} has been used as horizontal model grid in the model and staggered, Arakawa C-grid type of finite difference scheme has been used for numerical implementation. The vertical grid was fragmented in the 14 sigma layers with higher resolution in the upper mixed layer and lower resolution in the deep ocean. The horizontal mixing coefficients for momentum (viscosity) and tracers (diffusivity) were calculated by a Smagorinsky-type formulation (Smagorinsky, Manabe & Holloway 1965). In the sigma coordinate system, the number of levels is the same everywhere in the ocean, irrespective of the depth of the water column. It is, therefore, possible to resolve the bottom boundary layer wherever needed and hence best suited to shallow coastal regions (Kantha & Clayson 2000).

The OGCM was "spun up" for 10 years from a motionless, initial state of annual-average temperature and salinity climatology of Levitus 1994. During the spin-up, the OGCM was forced by monthly wind stress climatology from da-Silva 1994 wind. Since the model was forced by monthly wind so one-year time series of output has been obtained after spun up. We have run the POM in its general boundary condition for coastal region i.e. open boundary condition

Two different sets of numerical experiments are performed as follows:

a) Model run with open channel without forcing.
b) Model run with open channel with wind forcing.

In the first experiment the model simulation has been done with open channel of Indonesian throughflow (100°E-150°E and 40°S- 0°S) straits under consideration for ten years and complete flow field is generated. In the second experiment the model has been run for the same domain & time period but forced by realistic time-varying monthly wind field of da *Silva* SMD94. The model-produced fields such as transport, temperature, salinity and currents are retained for every one-month interval for the analysis. TKE dissipation rate (Ezer 2000) is calculated by multiplying an empirical constant (1/16.6) to $Q2^{3/2}L^{-1}$ where L is turbulence length scale and Q2 is 2TKE. We assume that construction and destruction of turbulence are closely balanced.

RESULTS

One-year time series of TKE and TKE dissipation rates through Lombok and Savu Straits are calculated from the model run with open PACIO geometry, with and without winds forcing. The average values of TKE and TKE dissipation rate are higher at upper layer through Lombok and Savu Strait, which clearly shows that wind forcing affects the rate whereas at lower levels for both the cases rates are almost same. TKE and its dissipation rate decreases with depth while the turbulence length scale increases with depth. Turbulence length scale is almost constant in the upper layer for the entire duration whereas there is monthly variation in lower level. Another point to notice is that the TKE and its dissipation rate are different in the case of Lombok strait than Savu strait, which shows topographic variation of the straits under consideration.

As clear from Fig.1, TKE of Lombok and Savu Strait at 2nd layer is varying on application of wind forcing. According to Fig.2, TKE values at 7th layer of the Lombok and Savu Strait are lower than 2nd layer and there is no significant change in the results on inclusion of wind forcing. It shows that the effect of wind forcing remains restricted upto upper ocean only. TKE dissipation rate without forcing at 2nd layer of the Lombok and Savu Strait is higher than with forcing except in February and April (Fig.3). At the 7th layer of the Lombok and Savu Strait TKE dissipation rate without and with wind forcing is almost the same and these are decreasing from January to December (Fig.4)

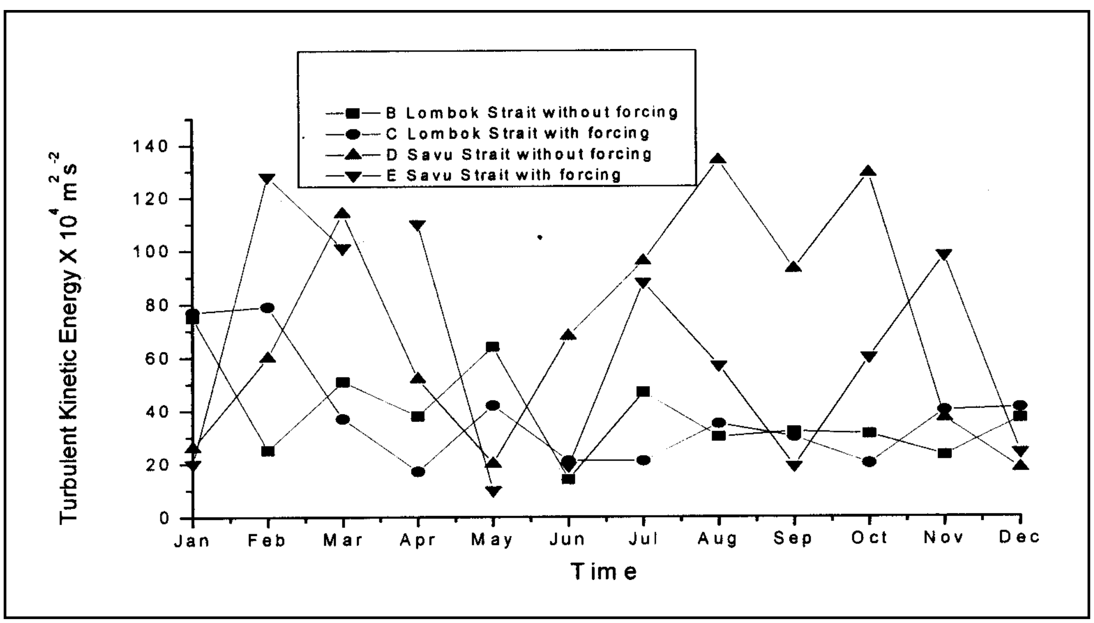

Figure 1. TKE of Lombok and Savu Strait at 2nd sigma layer

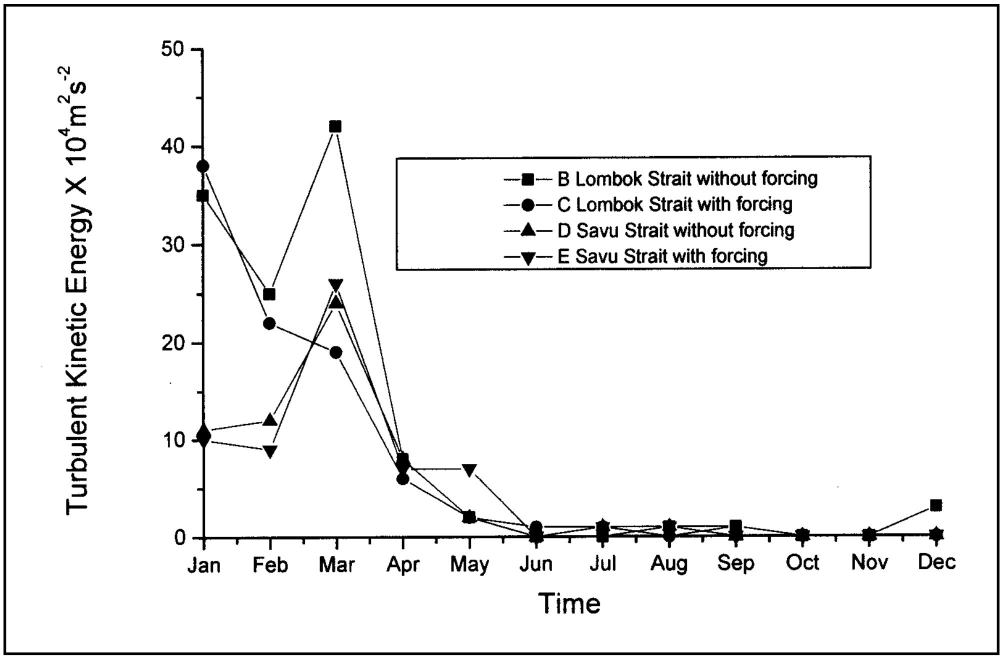

Figure 2. TKE of Lombok and Savu Strait at 7th sigma layer

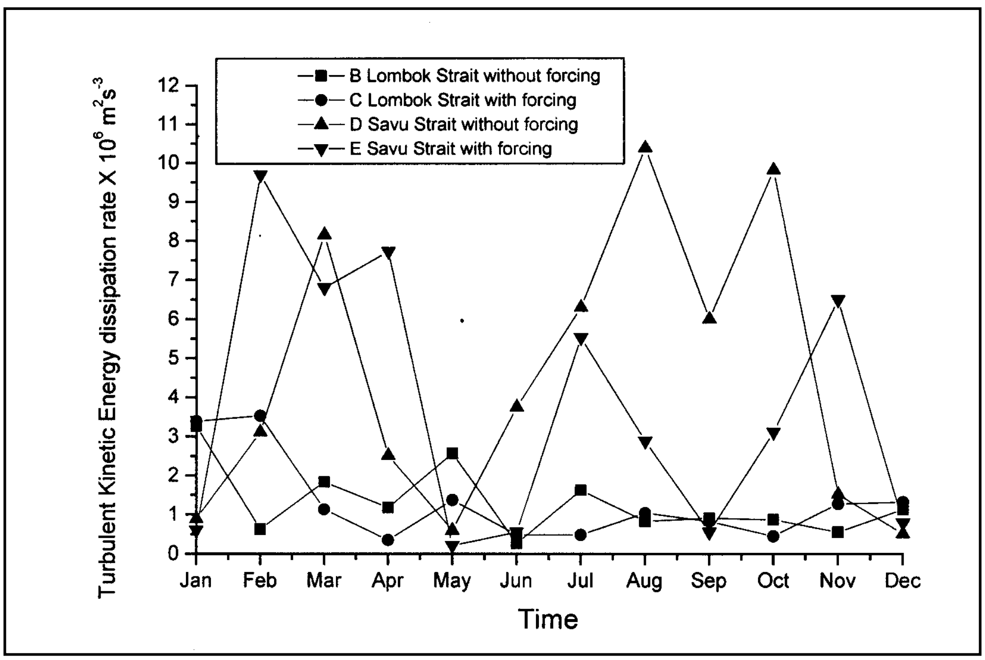

Figure 3. TKE dissipation rate of Lombok and Savu Strait at 2nd sigma layer

DISCUSSION

Model has been used to investigate the temporal and spatial variations in the magnitude of the TKE and its dissipation rate in the upper and middle layer of the PACIO region. Monthly variation in TKE associated with changes in its dissipation rate varies from region to region and also with the depth. A change in TKE in the region affects its dissipation rate and thus a consequent change in heating of the region is noticed. TKE dissipation rate plays an important role in raising and lowering of temperature of the ocean layer. In 7th layer of the ocean the dissipation rate is not much affected with wind forcing. The magnitude of TKE decreases with depth while turbulence length scale increases. Air –sea interaction

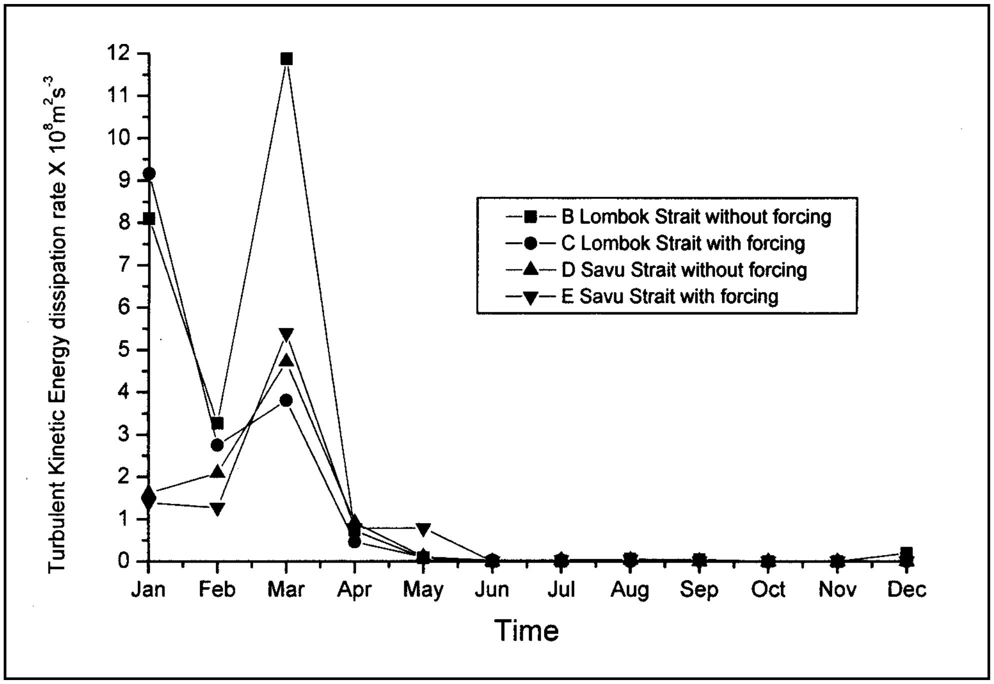

Figure 4. TKE dissipation rate of Lombok and Savu Strait at 7[th] sigma layer

plays an important role in such a phenomenon as is evident from the comparison between the results of model run with and without forcing.

High TKE and its dissipation rate in the upper ocean show that breaking of wave is dominant phenomenon in the upper ocean and due to this the TKE dissipation rate is enhanced. Monthly variation shows that TKE and its dissipation rate are time and space dependent

ACKNOWLEDGEMENTS

We thank Dr. Tal Ezer, Princeton University, Princeton and Dr. I.M.L. Das for their valuable suggestions. Authors also thank NCAOR/MoOD for the financial assistance.

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(Accepted 2007 March 25. Received 2007 February 22; in original form 2006 September 10)

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