A numerical study on larval dispersal around the Southeast Asia and West Pacific (SEA-WP) regions using an Indo-Pacific ocean circulation model

Aditya R. Kartadikaria[1], Kazuo Nadaoka[2] and Yasumasa Miyazawa[3]

[1]Dept. of Mechanical and Environmental Informatics, Tokyo Institute of Technology, kartadikaria.aa@m.titech.ac.jp
[2]Dept. of Mechanical and Environmental Informatics, Tokyo Institute of Technology, nadaoka@mei.titech.ac.jp
[3]Research Institute for Global Change/JAMSTEC, Yokohama, Kanagawa, Japan. miyazawa@jamstec.go.jp

The South East Asia and West Pacific (SEA-WP) region is a significant reservoir of the world's richest marine biodiversity especially in coral reef ecosystems. It is of vital importance to identify and explain reef connectivity due to larval dispersal by surface ocean currents. Moreover, coral reefs in this region are now severely threatened by numerous environmental factors. In order to reach effective conservation management purposes, we are trying to detect 'key areas' as candidate sites for MPAs (Marine Protected Areas) by developing a high-resolution numerical simulation model in Indo-Pacific Ocean. We examined the larval dispersal processes in detail by conducting advection-diffusion simulations based on the simulated ocean currents. Inside Indonesian archipelago, larval clouds do not merely move along with Indonesian Throughflow's (ITF) pathway. Eddy activities strongly influence the results of the larval dispersal process and their role is important in revealing the dynamics of connectivity.

Key Words **:** *Indo-Pacific ocean model, larval dispersal, connectivity*

1. INTRODUCTION

Almost 32% of the world total coral reefs are spanning around The Philippines, Indonesia, Papua New Genie, Australia and Solomon islands (Tun, et al., 2004). These regions contain nearly 100,000 km^2 of coral reef, with more than 600 of the almost 800 reef-building coral species (Burke et al., 2002). However, coral reef ecosystems in these regions are now severely threatened by numerous environmental factors; local anthropogenic disturbances, climate change effects, various kinds of illnesses and others (Glynn, 1996 and Burke et. al., 2002). These environmental threats may cause collapse of the ecosystems in few decades (Cropley, 2001). World Resources Institute’s study showed that the survival of at least 350 million people, particularly who live in South-East Asia and the Pacific Islands will be threatened due to the massive and extensive deterioration of coral reef ecosystems.

A coastal ecosystem is connected ecologically with other distant coastal ecosystems by larval dispersal and recruitment processes. The source-sink relationship based on larval dispersal and recruitment processes may exist for various pairs of coastal habitats in various spatial scales, forming so-called reef connectivity or coastal ecosystem networks. Larval recruitment of marine organisms is significantly important for the recovery of damaged populations. Some reef areas may act as good sources of larvae to other distant reefs. If we can identify these reefs in the ecosystem network, we can propose that these reefs should be properly conserved as marine protected areas (MPAs). The proper setup of MPAs in the network is effective for enhancing the resilience of the ecosystem network and therefore for its conservation and restoration.

The present study aims at examining larval dispersal processes in the South East Asia and West Pacific (SEA-WP) region, which is a significant reservoir of the world's richest marine biodiversity especially in coral reef ecosystems, but is severely declining due to various environmental threats. The computational results of the dispersal process have been successfully applied to identify the MPA candidate sites in the middle part of Indonesian seas based on a connectivity matrix analysis.

2. MODEL DESCRIPTION

As dispersal process is governed by the ocean currents, precise numerical simulations of larval dispersal processes in SEA-WP region can be made by introducing an ocean current simulation model system which can well reproduce the complicated ocean currents in the region. For this reason, we have first developed a high resolution ocean current model, which can resolve even complicated eddying motions in the central parts of the SEA-WP region characterized by their island studded nature. The high resolution model system is a multiply nested system with a new Indo-Pacific Ocean Circulation model (hereafter referred to as IP model) as the largest domain model. The finer resolution models nested with the IP model are IP1 and IP2 model having the spatial resolution of $1/3^0$ and $1/9^0$, respectively. These models use a numerical modeling code developed by the JCOPE project of JAMSTEC (Kagimoto et al., 2008), which is based on Princeton Ocean Model (POM) with generalized sigma coordinate.

For larval dispersal analysis, a particle tracking simulation technique is usually used, but in this study we have introduced a different approach based on the following advection-dispersion equation including an additional term to express biological aspects of larvae as zoo plankton.

$$\frac{\partial C_i}{\partial t} = -\nabla.\left(uC_i\right) + \nabla.\left(K_h \nabla C_i\right) + sms\left(C_i\right) \qquad (1)$$

where C_i denotes the concentration of larvae released from the location *i*, *u* is the velocity vector, and *Kh* is the turbulent diffusion coefficient. The last term indicates the biological aspects described later. This approach has advantage that by using the advection and dispersion routines in the ocean current models, all the physical parameters such as turbulent viscosity and diffusivity coefficients, temperature, salinity can be directly utilized for Eq. (1) and the model can be easily extended with marine ecology models. The biological aspect to be implemented in Eq. (1) is treated as nearly similar to zooplankton module in general Nutrient - Phytoplankton - Zooplankton - Detritus (NPZD) model. The first and second term in the right hand side of Eq. (1) indicate advection and diffusion processes. The last term is the source-minus-sink (sms) term to explain the biological aspects of larvae as the balance of add-reduce processes. For coral larvae, the sms term may be given below:

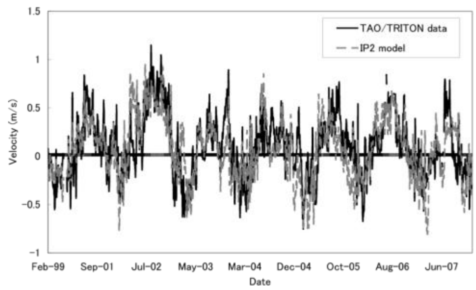
$$sms\left(C_i\right) = -dead \times C_i^2 - \left(1 - predation\right) \times C_i \quad (2)$$

where dead is coefficient for larval mortality (unit=day-1), while “predation” is removal rate by predator. The initial concentration of coral larvae, 0.05 mmol N/m3, was uniformly given to the release point grid, of which the size is $1/9^0$ x $1/9^0$. This advection and diffusion model was used to analyze the connectivity around Makassar Strait, the central part of Indonesian seas, which separates shallow Sunda and deep Sahul continental shelf.

3. MODEL VALIDATION

Figs. 1 (a) and (b) show the model validation results in long-term time series of zonal current for IP1 and IP2 model, respectively. The velocity fluctuations computed with IP1 and IP2 model were compared with the observed data by ADCP and eight additional TAO/ TRITON (http://www.pmel.noaa.gov/tao/), respectively. The correlation coefficients between the model results and observation data especially at 147^0E,0^0; 157^0E,0^0; and 165^0E,0^0 indicated that the performance of IP2 model increases by 2-7% compared with that of IP1.

(a) W-E velocity component in IP1 model



(b) W-E velocity component in IP2 model

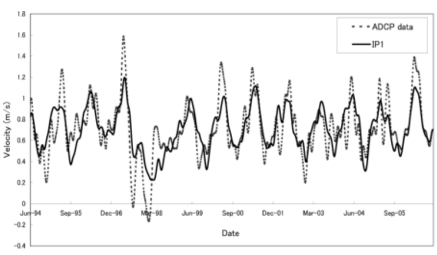


Fig 1. Examples of validation results for W-E velocity component for (a) IP1 model (0^0,110^0W) and (b) IP2 model (2^0N,147^0W).

4. RESULTS

One important physical point related with larval transport processes which has not been well discussed by many other researchers is the role of eddies in larval dispersal process. In this study, we have discussed two main topics related with the eddies as below based on the high resolution ocean current and dispersal simulations.

In general, W-E velocity component has longer periods of variability compared with N-S component, although N-S component is not indicated here due to the space constraint. Equatorial current and North equatorial counter current affect the domination of W-E component. Inter-annual variation appears at 137^0E;2^0N, 156^0E;2^0S and 165^0E;0^0. At the observation points in the open sea, like 147^0E;2^0N, 156^0E;0^0, 156^0E;2^0N and 156^0E;5^0N, annual variation of the zonal velocity can be found. But the 12 years observation data at point 156^0E;0^0 indicates that the annual variation is superimposed with a decadal variation. Strong seasonal variation is observed at the point 147^0E;0^0 and since there is a long missing data at this point, long period variations also might be superimposed at this point..

(1) Major eddies in the center of SEA-WP region

During three-year intensive ITF joint-research in INSTANT project, the appearance of eddies inside the Indonesian seas did not draw so much intention. The three year measurement of ITF did not provide any report regarding the eddy feature in this area. Whereas the climatology of temperature from World Ocean Atlas 2001 (WOA01) and XBT data showed a definite down-welling dome pattern in that area in February (Kartadikaria et al., in revision, 2011) and model results from Tozuka et al. (2001, in their Figure 4b) showed that real time forcing data produced increased temperature in the south of Makassar Strait, while Burnett et al. (2003) depicted a circular velocity flow between the Java and Flores Seas (in their Figure 5).

In our model, the feature of cyclonic eddies in February (**Fig.2**) is consistent with WOA01 and XBT data**.** From a vector plot, these eddies are warm cyclonic eddy with positive anomaly of Sea Surface Height (SSH) (not shown). Since these eddies are found in the southern hemisphere, the cyclonic type of eddy will lift SSH because Ekman transport bends a vector current to left of reference by following the left hand rule. Then it is creating surface water accumulation at surface in the eddy, indicated by positive SSH. This mass accumulation at surface then pushes the water column and creating a concave dome.

The eddy is located in the north of Lombok Islands with its center near 117^0E; 6^0S. Hereafter, the eddy is named as Lombok eddy. It has an inter-seasonal variation with different characteristic in its life span during boreal winter and autumn. It is stronger during late northwest (winter) monsoon with a long life span (2-4 months) than that during late southeast (autumn) monsoon with only 1-2 months of life span (not shown). In winter monsoon, it is strong in February, and in autumn monsoon it is strong in October. During La Niña year, 1998, in almost the entire year the Lombok eddy appeared in this area. We did not see good correlations between this eddy and positive IOD in 1994, 1997, 2006 and negative IOD in 1996, although during 1994 and 1996 the life span was longer than usual. This suggests that this eddy only responds to the ENSO variation in the Pacific, ITF and Asian-Australian monsoonal variations.

The complexity of the topography within the Indonesian seas is believed to trigger more complex ITF type flow there. Armed with those facts, it is difficult to believe that there are no types of mesoscale/basin eddy within Indonesian seas. In order to understand more about its mechanics, we need to calculate monthly heat budget and take into account the high influence of tidal mixing around the Indonesian archipelago.

(2) Reef connectivity analysis based on larval dispersal simulations

During strong eddy season, the existence of Lombok eddy train can last until April (monsoon transition period), and in April spawning of coral larvae occurs (Munasik, et al., 2008). In **Fig. 3** twenty five locations

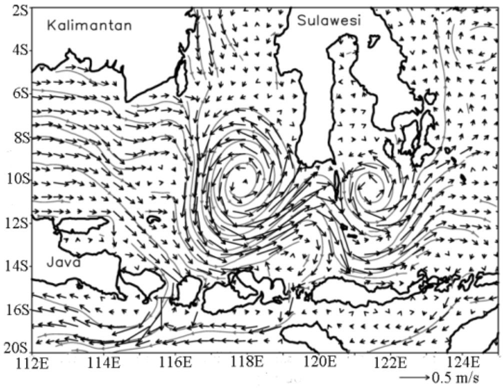


Fig.2 Surface current vectors showing pattern of eddies around Lombok-Flores Sea regions in February, 2006 (during positive Indian Dipole mode).

as MPA candidate sites were deployed to assess the connectivity in the area including Makassar Strait and Sunda and Sahul continental shelf. The simulation was made for April.

In **Figs. 4** and **5**, the matrix connectivity diagrams for 7 and 14 days after the release are plotted respectively. These diagrams explain how much larval cloud remained and entered one particular designated location after 7 days for the first or 14 days for the second diagram. In this case, we calculated the total amount of concentration of larvae that entered in the circle with the radius 0.25^0 at each designated point. Matrix connectivity can explain the degree of reef connectivity via larval dispersal process for all the possible combinations of the source-sink points among the designated locations. One designated point may release a larval cloud as a source and at the same time it may receive larval clouds from other points as a sink.

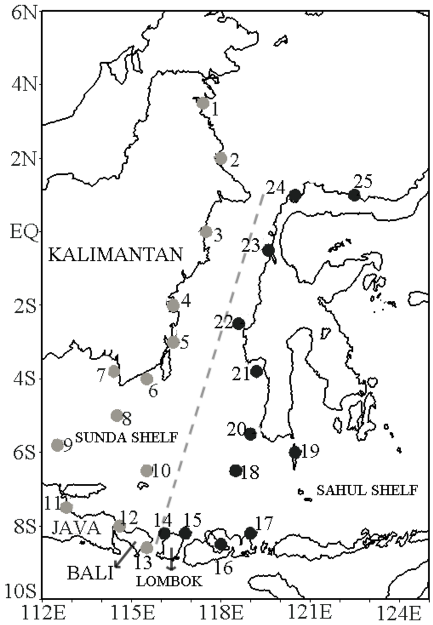


Fig.3 Larval clouds with the initial concentration of 0.05 mmol N m^{-3} were released at the 25 places around the central part of Indonesian seas. Points 1-13 are located in Sunda continental shelf, while points 14-25 are located in Sahul continental shelf. Dashed line represents the virtual "Wallace line"

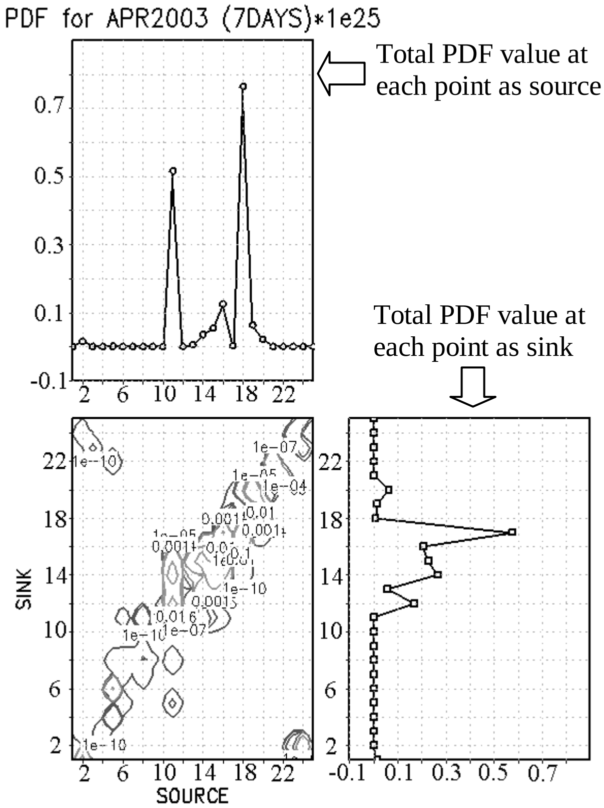


Fig.4 Matrix connectivity expressed in probability density function (PDF) (lower left panel) after 7 days released from April 1st, 2003. Upper and lower right panels show the total PDF values as source and sink, respectively, for each point.

Fig. 4 indicates that in Indonesian archipelago larval clouds do not merely move along with Indonesian Throughflow's (ITF) pathway, since ITF flow in April is relatively weak. Moreover, in April monsoon system is shifted from northwesterly wind to southeasterly wind. So, the configuration of the islands and the steep topography of the bathymetry highly influence the surface current pattern. Less connectivity found across the Makassar Strait and the Lombok Strait, while in the junction seas between Makassar and Java Seas or in Celebes basin, the connectivity appears stronger. A small eddy pattern appears in the north of Lombok during that time, suggesting the importance of the eddy in the connectivity mechanism in this area. This is also true for the connectivity in locations 1-2 to locations 24-25 in the Celebes Sea.

In the graph of the total PDF value as source, point 11 and 18 exhibit relatively high values, and the matrix PDF values show a certain wider distribution in the corresponding vertical column in the matrix. This implies that points 11 and 18 are good candidates as MPA sites because they may supply larvae to other locations more effectively than others. On the other hand, points 12-17 show relatively high values in the graph of the total PDF values as sink, and wide distributions in the corresponding horizontal rows in the matrix. This indicates that points 12-17 may be also good candidates of MPA sites as they have high potential of larval recruitment and hence high resilience from the damaged situation due to environmental disturbances.

High PDF values of diagonal elements explain the degree of self recruitment. If one location has strong larval source and sink in diagonal element then that area is indicated as a strong self recruitment site.

The matrix connectivity depends on the timing of larval clouds release, subsequent dispersal tracking periods, setting up of the designated points in the target area and others. **Fig. 5** shows the matrix connectivity and associated total PDF values as source and sink after 14 days. It indicates that almost similar arguments on the MPA candidate sites as those for **Fig.4** are possible, although slight change arises in the total PDF values as source, i.e., after 14 days, point 11 supplies larger amount of larvae than point 18. Besides, at point 17, the total PDF values as sink dramatically reduced to the level less than that at point 16. As another outstanding difference from the results of **Fig.4**, the larval clouds released in Sunda shelf are completely dispersed, and connectivity pattern between Sunda and Sahul is converged in the Northern part of Sunda Islands chain (Bali, Lombok and Nusa Tenggara Islands) and self recruitment in Sahul shelf’s side is still strong a

Fig.5 Similar to **Fig. 4**, but after 14 days released.

5. CONCLUSIONS

Using a new high-resolution ocean model, which we have developed based on a nesting approach, we have clarified the existence of characteristic eddies named as Lombok Eddies in the crossroad between Makassar Strait and Java Sea. We then validated our model performance in the comparison with long term ADCP and TAO/TRITON data. We found various multi-scale variations in the SEA-WP region ranging from intra-seasonal to biennial variations. The model results were consistent with various long-term observation data from ADCP and TAO/TRION instrument in terms of zonal and meridional velocity component, especially along the equatorial region of the Pacific Ocean. The Lombok eddy system can be found during the austral summer season, when the ITF transport is low.

We conducted larval dispersal simulation around the Makassar Strait and found that during spawning season the connectivity in the Strait is less prominent. On the contrary, the connectivity in the southern basin of the Makassar Strait is found stronger. The existence of eddy influences the larval connectivity pattern. The matrix connectivity analysis can be used for identifying good candidates of MPAs as effective source and/or sink sites in the larval dispersal processes.

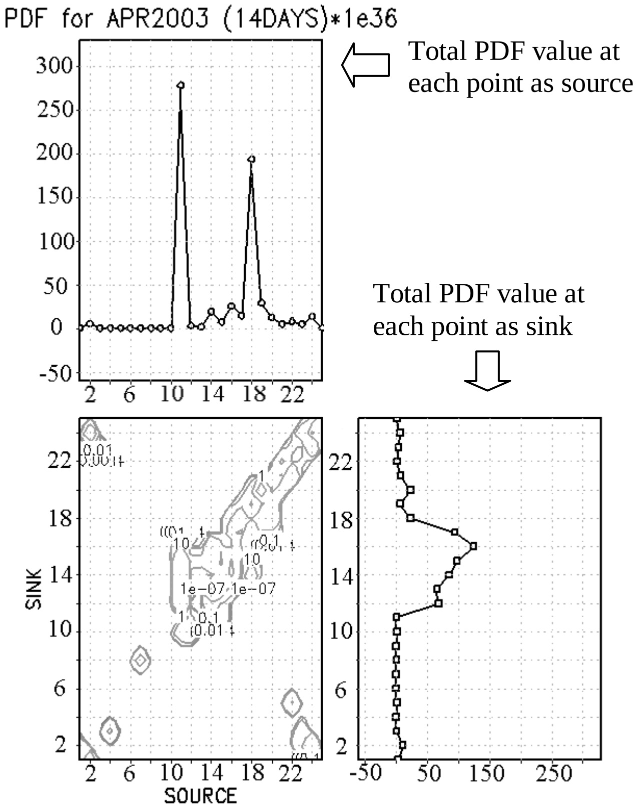


Fig.5 Similar to **Fig. 4**, but after 14 days released.

ACKNOWLEDGMENT: We would like to express our deep thanks to JAMSTEC Yokohama office for providing a set of code of JCOPE model and using SX-8R processors for the simulation work. This work was funded by the Global Environment Research Fund (F-082) of the Ministry of the Environment, Japan, and a Grant-in-Aid for Scientific Research (A) (No. 18254003 and No. 21254002) from JSPS (Japan Society for the Promotion of Science).

REFERENCES

Burke L., L. Selig, and M. Spalding (2002): *Reefs at Risk in Southeast Asia,* World Resources Institute, 72p

Burnett W. H.,V. M.Kamenkovich, A. L.Gordon, G. L. Mellor, 2003: The Pacific/Indian Ocean pressure difference and its influence on the Indonesian Seas circulation: Part I-The study with specified total transports, {¥em Journal of marine research},61 , 5, 577-611.

Cropley, E. (2001): *World Coral Reefs to Die by 2050,* Scientist Warns. Reuters.

Glynn, P. (1996): *Coral reef bleaching: facts, hypotheses and implications,* Global Change Biology 2, 495-509.

Kagimoto, T., Y. Miyazawa, X. Guo, and H. Kawajiri (2008): *High resolution Kuroshio forecast system -Description and its applications-, in High Resolution Numerical Modeling of the Atmosphere and Ocean,* W. Ohfuchi and K. Hamilton (eds), Springer, New York, 209-234.

Kartadikaria A. R, Y. Miyazawa, K. Nadaoka, A. Watanabe (2011), Existence of Eddies at Crossroad of the Indonesian seas, Ocean Dynamics, *in revision.*

Mellor, G. L., S. Hakkinen, T. Ezer and R. Patchen (2002): *A generalization of a sigma coordinate ocean model and an intercomparison of model vertical grids, In: Ocean Forecasting: Conceptual Basis and Applications*, N. Pinardi and J. D. Woods (Eds.), Springer, Berlin, 55-72.

Munasik, Suharsono, J. Situmorang, H.N. Kamiso (2008): *Timing of larval release by reef coral Pocillopora Damicornis at Panjang Island, Central Java,* Mar. Res. Indonesia Vol. 33, No. 1, 2008: 33-39.

Tozuka T., T. Kagomoto, Y. Masumoto, T. Yamagata (2001): *Simulated Multiscale Variations in the Western Tropical Pacific: The Mindanao Dome Revisited*, Journal of Physical Oceanography, Vol. 32, pp. 1338-1359.

Tun, K., L. M. Chou, A. Cabanban, T. Yeemin, PhilReefs, V. S. Tuan, K. Sour, Suharsono and D. Lane (2004): *Coral Reef Status Report for 2004: Southeast Asia,* Global coral reef monitoring Network Report.

(Received June 24, 2011)