USAID
FROM THE AMERICAN PEOPLE

PHILIPPINE ENVIRONMENTAL GOVERNANCE 2 PROJECT (ECOGOV 2)

Establishing Larval Exchange and Reef Connectivity Using Larval Dispersal Models

March 13, 2007

This publication was produced for review by the United States Agency for International Development. It was prepared by Development Alternatives, Inc.

The EcoGov 2 Project is an initiative of the Government of the Philippines, implemented in partnership with the Department of Environment and Natural Resources, Department of the Interior and Local Government, local government units and other stakeholders, funded by the United States Agency for International Development and managed by Development Alternatives, Inc. and its subcontractors:

Cesar Virata & Associates, Inc. ■
Deloitte Touche Tohmatsu Emerging Markets ■
The Marine Environment and Resources Foundation, Inc. ■
The Media Network ■
Orient Integrated Development Consultants, Inc. ■
Resources, Environment and Economics Center for Studies, Inc. ■

PHILIPPINE ENVIRONMENTAL GOVERNANCE 2 PROJECT (ECOGOV 2)

Establishing Larval Exchange and Reef Connectivity Using Larval Dispersal Models

March 13, 2007

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

ESTABLISHING LARVAL EXCHANGE AND REEF CONNECTIVITY USING LARVAL DISPERSAL MODELS

INTRODUCTION

A common tool used in coastal resource management in Philippine coastal waters is the marine protected area. Marine protected areas are areas where human activities are regulated (Sale et al., 2005). The use of marine protected areas in coastal resource management has been shown to increase the density, biomass and average size of target species within their borders (Halpern, 2003) and enhance fish yields to traditional fishers (Russ and Alcala, 2003). The elimination of fishing mortality within the MPA increases the biomass as well as the reproductive capacity of target populations increasing yield in neighboring areas through spillover and recruitment subsidy (Palumbi, 2004; Roberts, 2001).

The key elements to enhance effectivity of an MPA is to ensure that there is a net export of biomass and propagules, and at the same time have sufficient self-recruitment to replace the individuals being fished out. However, this is more easily said then done.

Marine populations are usually interconnected through larval dispersal (Botsford, et al, 2001) and the neighborhood scale of the adult members of the population may be different from the larval neighborhood scales because factors such as hydrodynamics, behavior and availability of suitable habitats are highly variable and highly site specific. The effectiveness of an MPA or MPA networks is a function of whether these neighborhood scales are consistent with the scales of an MPA or MPA network.

An MPA may very well be a good source of larvae because of the presence of protected broodstock population but if settlement of the larvae they produce is low, the potential benefits derived from the MPA may be limited (Sale, et al, 2005). This is the concept of MPA networks where several MPA’s may work collectively to act as both larval sources and settlement areas thereby increasing the benefits of individual MPAs, synergistically.

The estimation of the dispersal distance will therefore be very useful as it will determine the scales of management of these resources. This spatial distance will depend on ocean currents and their variability, the length of the planktonic larval duration (PLD) and larval behavior. Other complicating factors include the multi-species nature of municipal fisheries. Kinlan and Gaines (2003) estimated dispersal scales of different marine organisms can range from a few meters to a few hundreds of kilometers (**Error! Reference source not found.**). The dispersal scale and the fact that different species will have different PLDs and larval dispersal distances requiring management measures to be flexible enough to accommodate different species being managed at different scales.

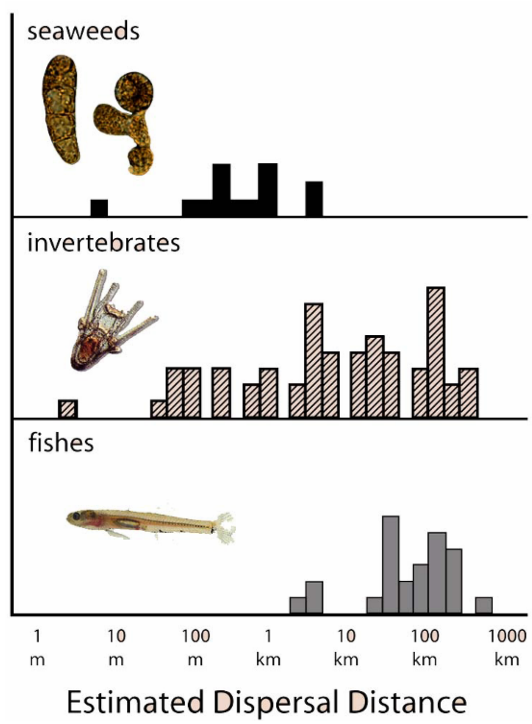

Figure 1. Estimates of dispersal distances for different groups of marine organisms (from Kinlan and Gaines, 2003)

Palumbi (2004) suggests that a conceptual framework in designing MPA networks is to set the reserve or MPA size based on adult neighborhood sizes of the highly fished species and determine spacing of a MPA network based on larval neighborhoods scales. This study will provide initial estimates of larval neighborhood scales for selected areas around the Philippines based on local hydrodynamics. The objective of this study is to characterize the oceanographic features in four different areas in the Philippines and to gain some insights as to how these processes might affect larval dispersal patterns and distances. The four sites are Baler Bay in Aurora, the Camotes Sea, Illana Bay and Sibugay Bay, both in the northern part of Moro Gulf. The study areas include Baler Bay in Aurora, Camotes Sea, Sibugay Bay and Illana Bay in the Moro Gulf (Figure 2). All of these areas are also EcoGov Sites where MPAs are being established or existing ones are being strengthened.

METHODS

Larval dispersal patterns can provide insights on connectivities between ecosystems or reef areas. In this study, we use Lagrangian dispersal models to simulate the dispersal of passive particles under different oceanographic conditions. Since the forcing for the circulation is dominated by the monsoonal winds, simulations were conducted for representative months for the northeast monsoon (January), southwest monsoon (August) and the transition during April.

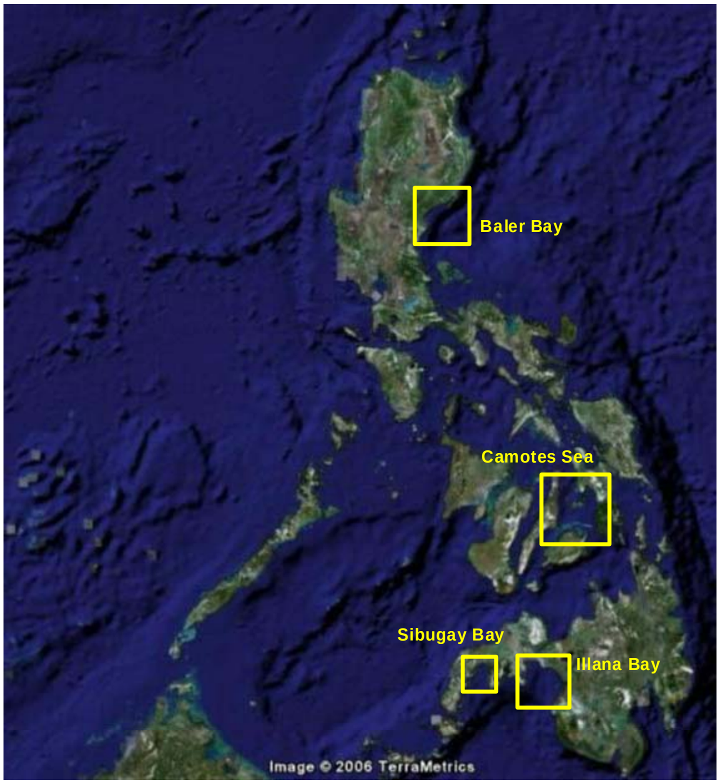

Figure 2. Map showing the 4 study areas

Hydrodynamic Modeling

The three-dimensional circulation of the waters in all four sites were modeled using the Princeton Ocean Model (Mellor, 2003). This model is a three-dimensional primitive-equation sigma coordinate model and is used in numerous applications ranging from estuarine to global ocean models. At the open boundaries, the model is forced by the tides and offshore currents and at the surface by the wind.

The tidal forcing prescribed at the open boundaries was derived from the Oregon State University Tidal Inversion Software (OTIS) model applied to Philippine waters by Magno (2005). Open ocean currents at the model open boundaries were obtained from the monthly mean barotropic velocities computed by the Pacific HYCOM Simulations (http://hycom.rsmas.miami.edu/data/information.html#pacific). Separate runs were made to represent seasonal circulation patterns. Each run was allowed to run for 30 days of model time for each seasonal boundary forcing. The model is also forced at the surface by winds derived from satellite altimetry (http://manati.orbit.nesdis.noaa.gov/hires/).

Lagrangian dispersal model

The dispersal model is adapted from the model of Polovina, et al. (1999). In this model, the larvae are represented as neutrally buoyant passive particles and their position over time is tracked using the following equations:

$$\begin{aligned} x_{t+\Delta t} &= x_t + \left(u_{x,y,t}\Delta t + \varepsilon\sqrt{D\Delta t}\right) \\ y_{t+\Delta t} &= y_t + \left(v_{x,y,t}\Delta t + \varepsilon\sqrt{D\Delta t}\right) \end{aligned} \tag{1}$$

where x and y are the coordinates of a particle; u and v are the advection velocities from the hydrodynamic model, Δt is the integration time step, ε is a randomly generated number ranging from –1 to 1, and D is the eddy diffusion rate (m^2s^{-1}). Each particle when released has attributes, which identifies it individually from the other particles. These attributes include age from release, location of release, date and time of release. These attributes will enable us to estimate the degree of exchange of simulated particles between areas based on the method used by Sauers et al. (2003) in analyzing drifter card data.

RESULTS

Oceanographic characterization

It is fortunate that the choice of the four study sites also represents different types of configurations. This presents an opportunity to compare dispersal patterns in areas that are influenced by different oceanographic processes. Baler Bay is a tear drop-shaped embayment along the eastern coast of Luzon. The bay itself is shallow with a maximum depth of about 300 m (Figure 3). The eastern edge of the bay is bounded by a ridge, beyond which the bottom drops off fairly rapidly to 2000 m. This rapid change in depth forms the natural boundary of the bay and is an important feature influencing the circulation of the Bay.

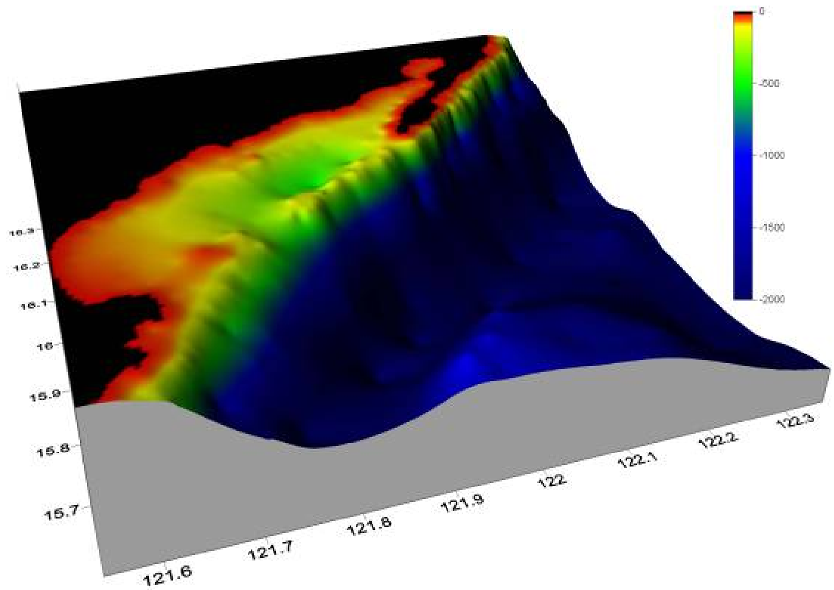

Figure 3. Bathymetry Map of Baler Bay

Illana Bay is a large embayment on the northeastern part of the Moro Gulf. It is a fairly large gulf, extending almost 40 nautical miles across and 30 nautical miles long. Maximum depths exceed 2500 m, making Illana Bay the deepest of the 4 sites. It is expected that the tidal component of the circulation will be very weak in Illana Bay because of the wide mouth and deep bathymetry.

In contrast, Sibugay Bay is much shallower with maximum depths not exceeding 100 m. The large surface area coupled with the shallow depths results in a stronger tidal component of the flow. The size of Sibugay Bay is slightly smaller than Illana Bay but both form the northern margin of Moro Gulf.

Unlike the other three sites, the Camotes Sea is characterized as having not one connection to neighboring seas but three. It is fairly deep but passages that connect it to the south are shallow are narrow (Figure 4). To the north, the channel between Cebu and Leyte is about 250 m deep. The channel to the south between Cebu and Bohol is also fairly deep at more than 250m but the channel between Bohol and Leyte to the south is very shallow (<20 m). The southern part of the Camotes Sea is composed of the Danahon Banks, a double barrier system characterized by shallow depths and numerous islands.

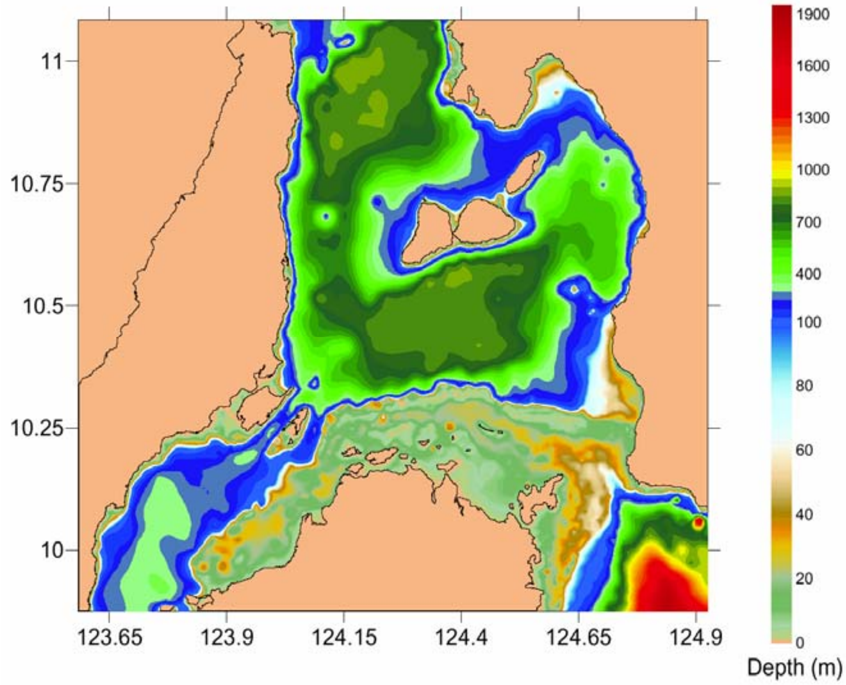

Figure 4. Bathymetry of the Camotes Sea

Circulation Patterns

Baler Bay

The dominant large scale current system off the eastern Luzon is the northward flowing Kuroshio Current (Qu et al., 1998) but off Baler Bay, the currents are generally southwards. There are no direct measurements of currents offshore of Baler but model results and satellite images show southward flow off Baler. Results from the Pacific HYCOM Model show a cyclonic eddy shed from the northward flowing Kuroshio Current (Figure 5). The eddy is usually found off Aurora and Quezon. This eddy can also be seen in satellite images of chlorophyll obtained using the Moderate Resolution Imaging Spectroradiometer (Figure 6). Daily satellite images show that this eddy is highly variable and may not be as distinct during other periods. However, despite the variability, flow patterns inferred from chlorophyll maps show a persistent southward flowing current almost throughout the year. Sometimes this current is a narrow jet while at other times, it may be a broad current. When the eddy is well developed, the southward flow off Baler bay forms the western part of the eddy. Otherwise, it appears as a narrow jet that terminates off Polillo. The effect of this persistent flow just off the mouth of the Bay will influence exchange processes between the open ocean and Baler Bay.

Currents adjacent to the coast follow the direction of wind forcing. During the southwest monsoon, coastal currents flow in the alongshore direction towards the north (Figure 7). Offshore, flow forced by large-scale currents is directed towards the southwest. At the mouth of Baler Bay along the ridge, a series of recirculating eddies are formed due to the current shear between flow inside and outside the bay mouth. It is apparent that the abrupt change in depth at the mouth of Baler Bay forms a natural boundary limiting the exchange between Baler Bay and the Philippine Sea. However it is not an impermeable barrier as some exchange still occurs. The strongest exchange into the Bay appears to be at the southern part of the Bay near the town of Baler. The coastal current direction reverses with the onset of the northeast monsoon (Figure 8). Even circulation in the Philippine Sea is also slightly different with the currents north of Cape San Ildefonso now flowing northwards. The circulation in the Philippine Sea near this area (off Aurora and Quezon) appears to be highly variable becoming less variable further offshore. The circulation patterns during April are similar to that during the southwest monsoon albeit with weaker currents (Figure 9).

During the northwest monsoon, the southward currents along the Pacific coast of Cape San Ildefonso cross the mouth of Casiguran Bay just after turning the bend at the Cape. Flow inside the bay is also more spatially variable compared to flow patterns outside the bay. At this stage it is difficult to get some estimates of uncertainty because of the absence of field measurements of sufficient coverage and quality to do a reliable calibration. Attempts to use satellite images will be done to infer current patterns based on temporal changes in chlorophyll patterns.

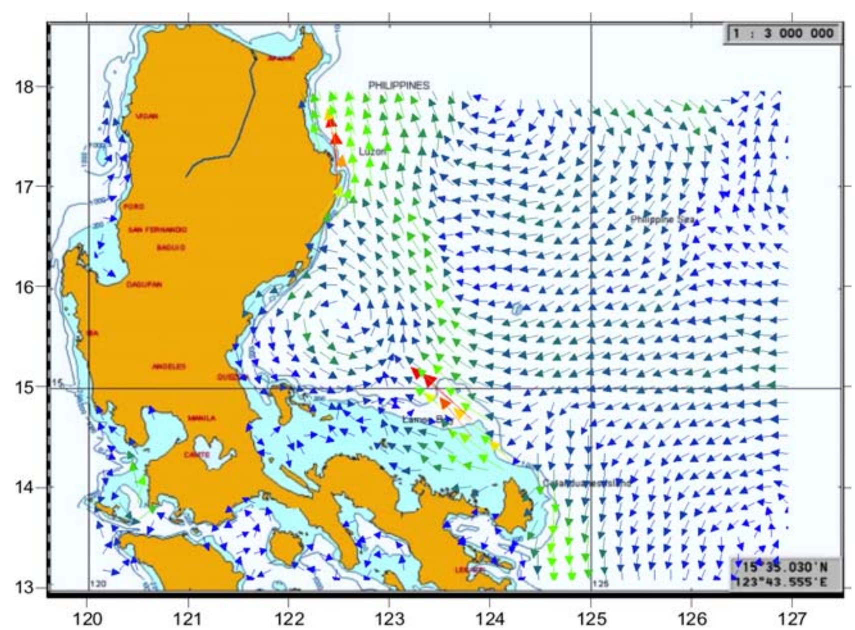

Figure 5. Currents off eastern Luzon from the Pacific HYCOM Model.

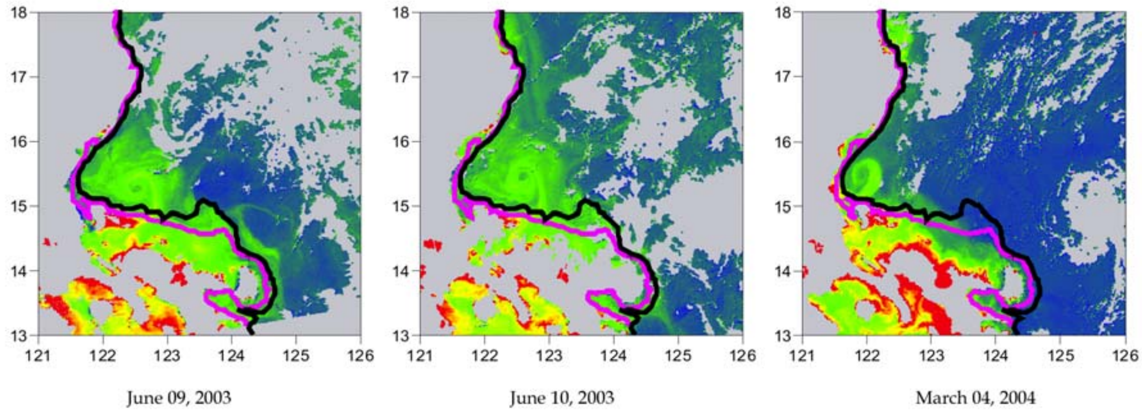

Figure 6. MODIS Chlorophyll distribution off Aurora and Quezon showing cyclonic eddy.

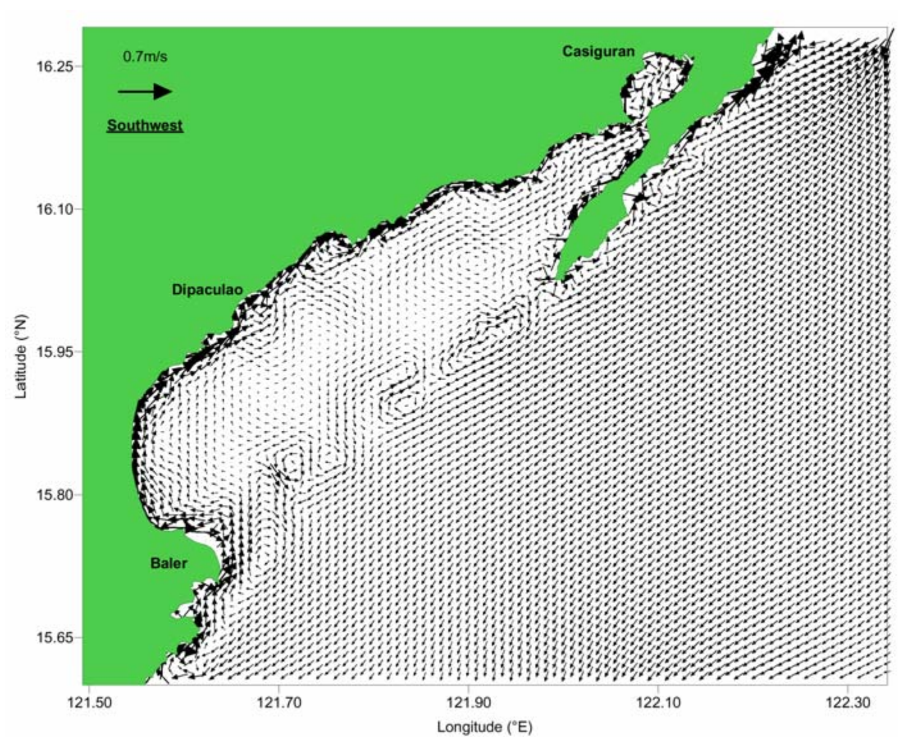

Figure 7. Surface currents in Baler Bay during the southwest monsoon

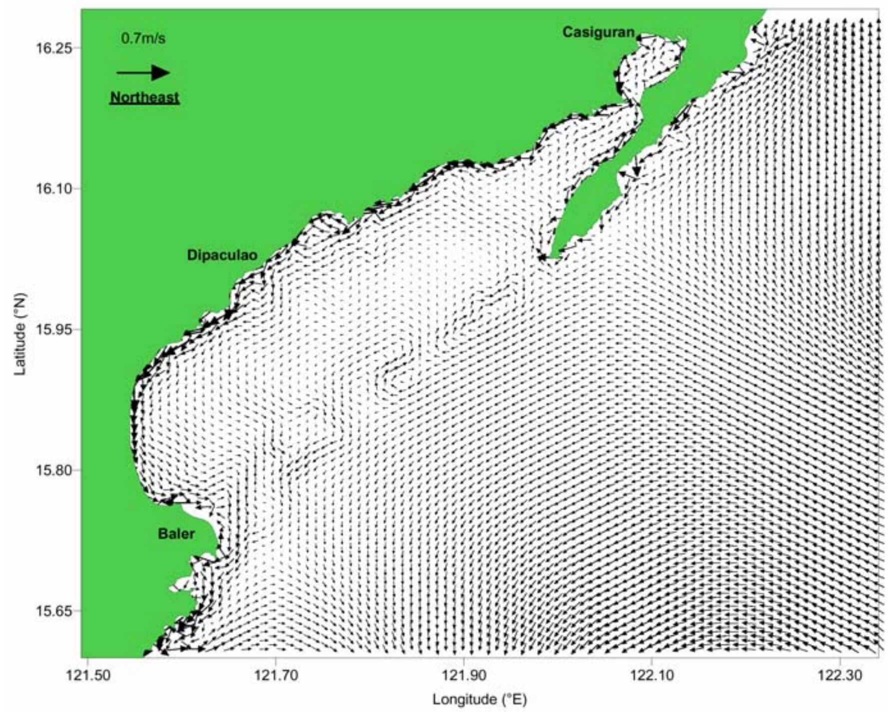

Figure 8. Surface currents in Baler Bay during the northeast monsoon

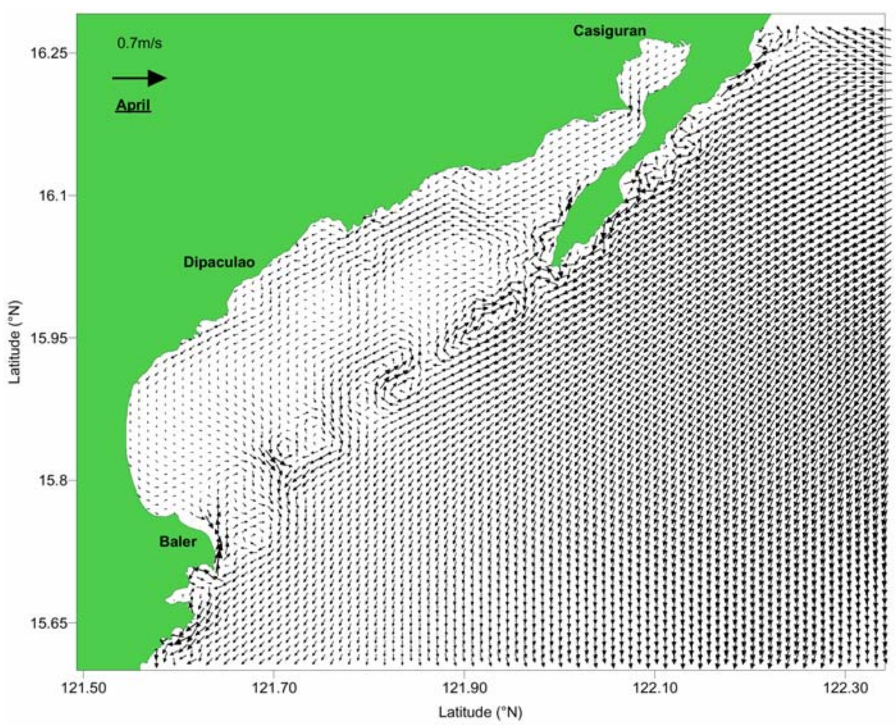

Figure 9. Surface currents in Baler Bay during April.

Illana Bay

Illana Bay forms the northern part of Moro Gulf. The flow in the Moro Gulf is dominated by the westward flow associated with the large-scale circulation in the Celebes Sea. The circulation in Celebes Sea is characterized by a branch of the Mindanao Current flowing westward then turning south, after which a portion returns to the east to form the North Equatorial Counter Current while the rest flows south through Makassar Strait and forms part of the Indonesian throughflow (Lukas et al., 1991). Despite the background westward velocities, the northern part of Moro Gulf consists of several embayments and interaction of capes and embayments may result in return flows into the embayments.

Flow into Illana Bay is mostly from the western part of the mouth and exiting on the eastern side, resulting in a slight clockwise pattern. However, the flow into the Bay may shift towards the east slightly and flow south of Tabina goes towards the west (Figure 10). During the southwest monsoon, flow south of Ganadian Peninsula is eastwards and is reversed during April and during the northeast monsoon (Figure 11). In the interior of the Bay, flow from the area south of the peninsula enters the Bay, turns and exits to the southeast during the southwest monsoon. The circulation is slightly similar during April except that outflow from the Bay occurs to the southeast as well as to the west. The circulation is practically reversed during the northeast monsoon.

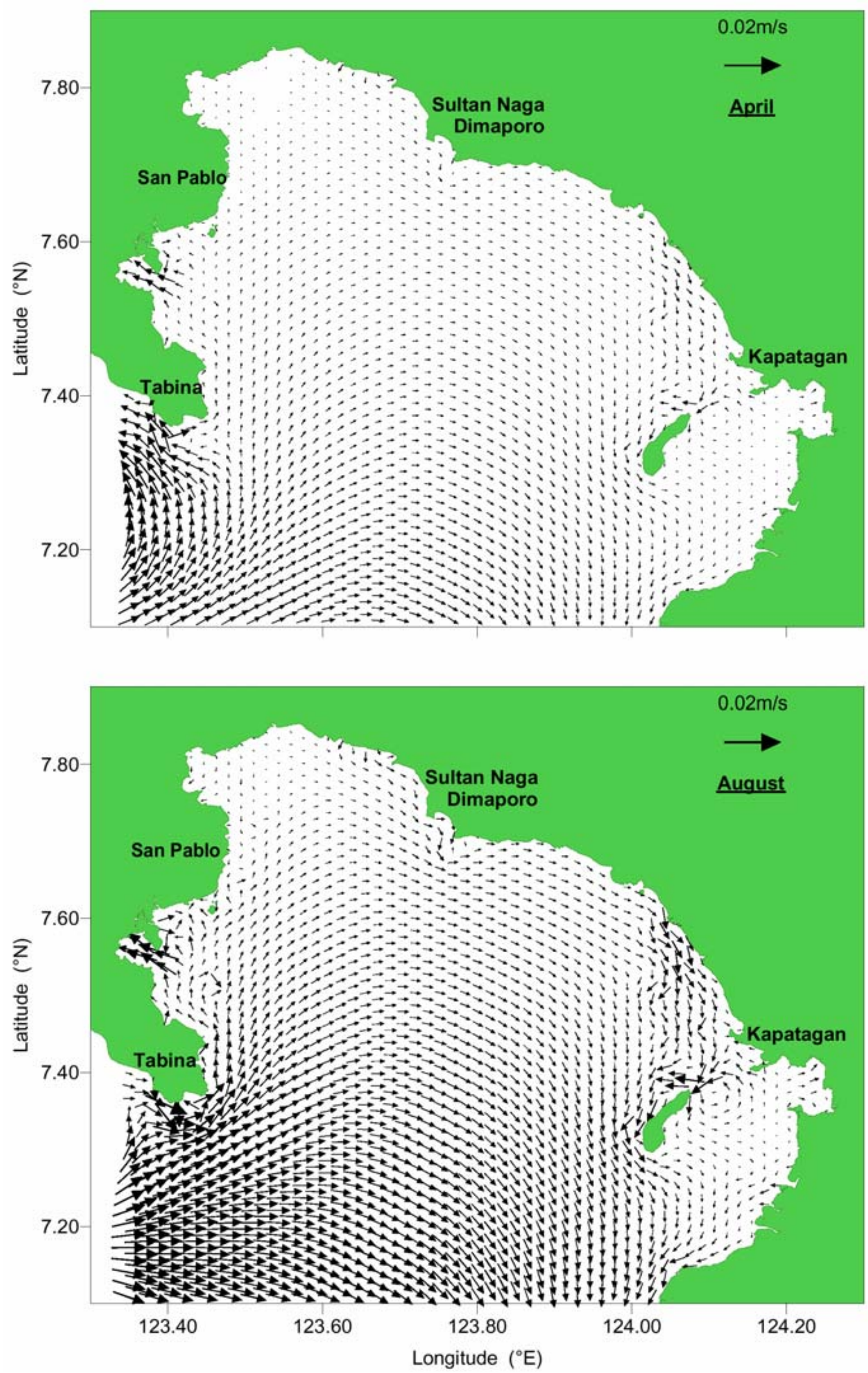

Figure 10. Surface circulation in Illana Bay forced by HYCOM velocities

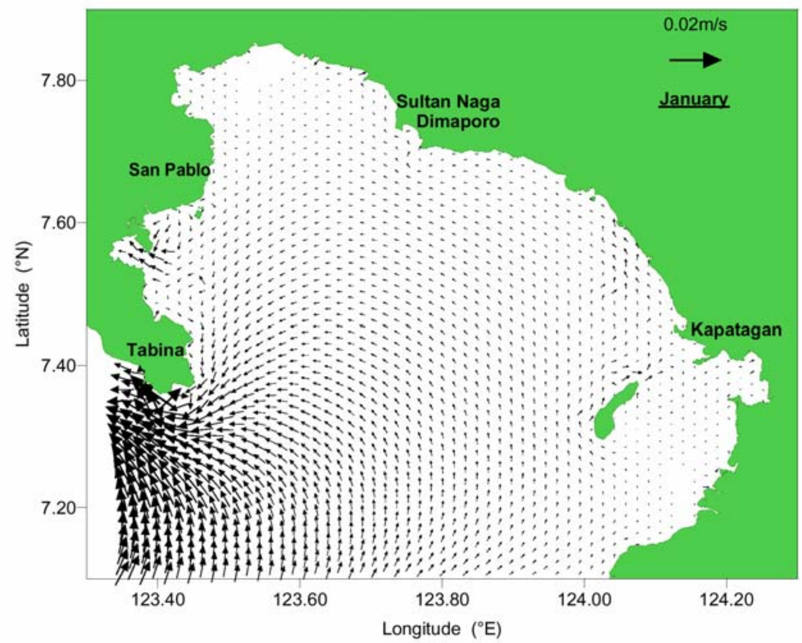

Figure 11. Surface current in Illana bay during the Northeast Monsoon

Sibugay Bay

The large surface area of the bay (about 25nm across and 30nm long) coupled with the shallow depth results (<100m) produces a large tidal volume which must move across the mouth at least twice a day. Such large volume of water passing through the relatively small cross-sectional area of the bay mouth produces a fairly strong tidal component. Near the mouth, the tidal component of the flow probably dominates the circulation (
Figure 12). The strongest tidal currents are found at the mouth and the magnitude decreases towards the bay head.
Figure 12 also shows the increasing tidal current speeds in the coves as a result of shallowing depths.

The wind-driven component of the circulation is shown in Figure 13. Forcing at the bay mouth is prescribed from the Pacific HYCOM Model and is generally similar between seasons with inflow into the bay on the eastern side of the bay mouth and outflow out of the bay in the western side of the bay mouth. This is consistent with the mean circulation patterns in the Moro Gulf. Currents close to the coast generally move in the same direction as the wind. Some recirculation occurs in the embayments along the bay such as in Tungawan. In the absence of wind forcing, the circulation is similar for the different seasons and is dominated by counter clockwise flow within the bay with inflow into the bay on the eastern side of the bay mouth and outflow on the western side of the bay mouth. Surface current measurements conducted in the head of Sibugay Bay were consistent with the westward flow simulated by the model. These measurements were conducted during a period of very weak winds and during slack times.

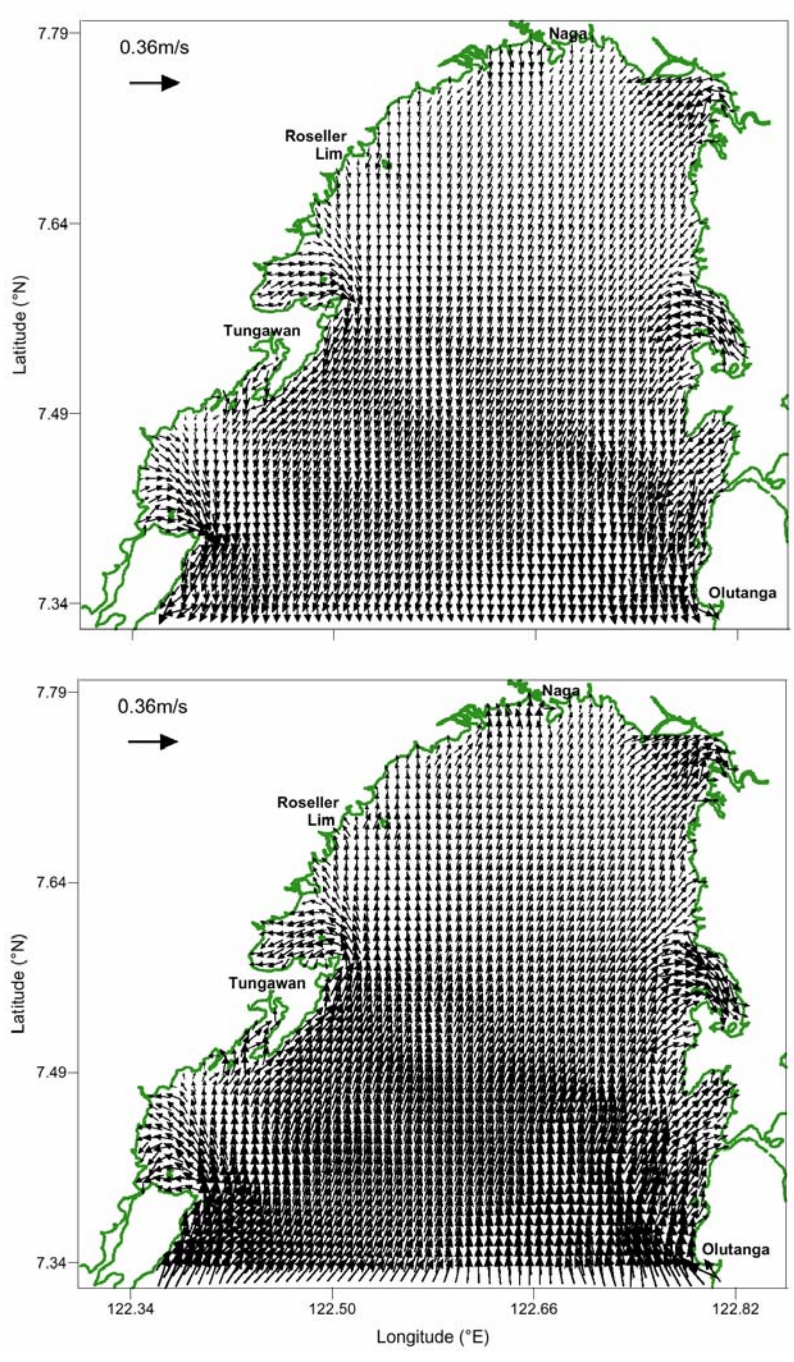

Figure 12. Tidal circulation in Sibugay Bay showing ebb (top) and flood (bottom) flow.

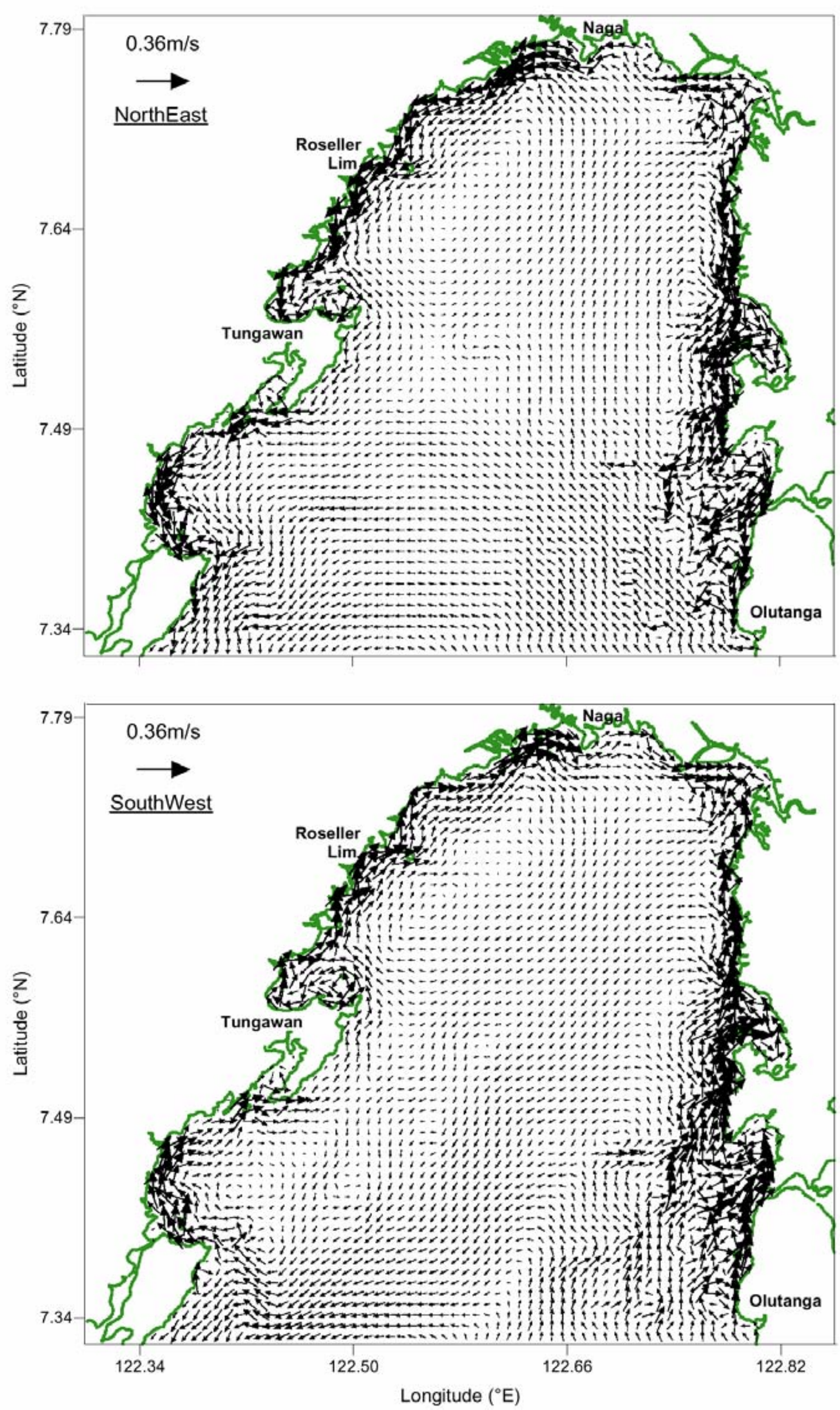

Figure 13. Wind driven circulation in Sibugay Bay

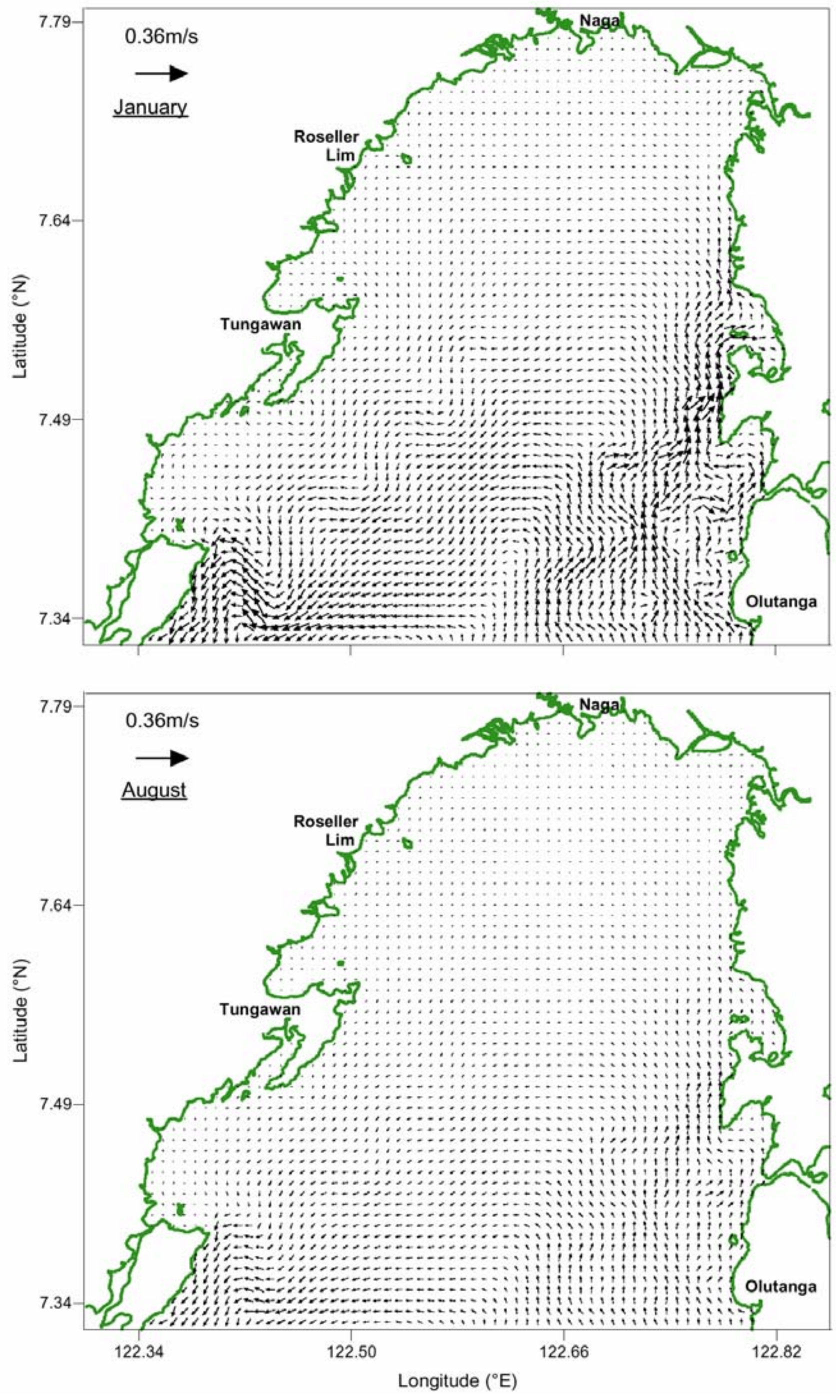

Figure 14. Sibugay Bay circulation forced by Pacific HYCOM velocities at the mouth

Camotes Sea

The HYCOM-forced current patterns are distinct and complex for the different seasons considered. Along Bohol/Cebu Strait, the flow is directed northward and continues into the Camotes Sea during January (Figure 17) and April (Figure 15) but reverses during August (Figure 16). For the two former months, these currents become deflected eastward as it approaches the shallow shelf south of the Olango Island located in the middle portion of the strait. It then continues eastward and moves parallel the barrier reefs but become further modified as it encounters the complex topography within the area. Along this area, currents moving eastward also come across the strong currents from the southwest. During August, this current pattern is reversed and the flow advances westward then southward through the Bohol/Cebu Strait.

It seems counterintuitive why barotropic currents along Cebu Strait move northwards during the northeast monsoon and southwards during the southward monsoon until the circulation in the whole Visayan Sea is examined. The Pacific HYCOM results show that most of the seas in the Visayas area flow along the direction of the wind except in the Camotes Sea, which appears to respond to the flow in the neighboring basins. It may have something to do with the fact that the Camotes Sea area is practically closed in the south except for the very narrow straits between Cebu and Bohol. This makes the Camotes Sea responsive to what is happening to the north. For instance, during the southwest monsoon, water from the Visayan Sea may pile up water in the northern part of the Camotes Sea. The presence of this meridional pressure gradient in the Camotes Sea may push the water southward, opposite the direction of the wind. It must be noted that the preceding statements were based on the results of the Pacific HYCOM Model and that no field observations have been made or is available to confirm such statements.

For all seasons, the strongest currents were consistently present in the shallow shelf along the Canigao Channel connecting the mainland Bohol and southern Leyte. Currents within this area are obviously influenced by the bottom topography as the currents generally follow its contour and increases in magnitude as water depths become shallower. Currents are also stronger in the shallow areas between Poro and Ponson Islands and along the west coast of Bohol.

The flow in the Danahon Banks in constrained by the presence of the double barrier system resulting in the dominance of the alongshore flow. The net flow appears to move towards the west and is consistent with the field measurements conducted. Landsat images of the Danahon Bank show island wakes formed in northwest sides of the islands suggesting flow is going into the Danahon Banks area. To the east, in the channel between Bohol and Leyte, flow reverses seasonally and since the flow in Danahon is always westward, the source waters for the Danahon area is from the Bohol Sea during the northeast monsoon and the monsoonal transition (April), and from the Camotes Sea during the southwest monsoon.

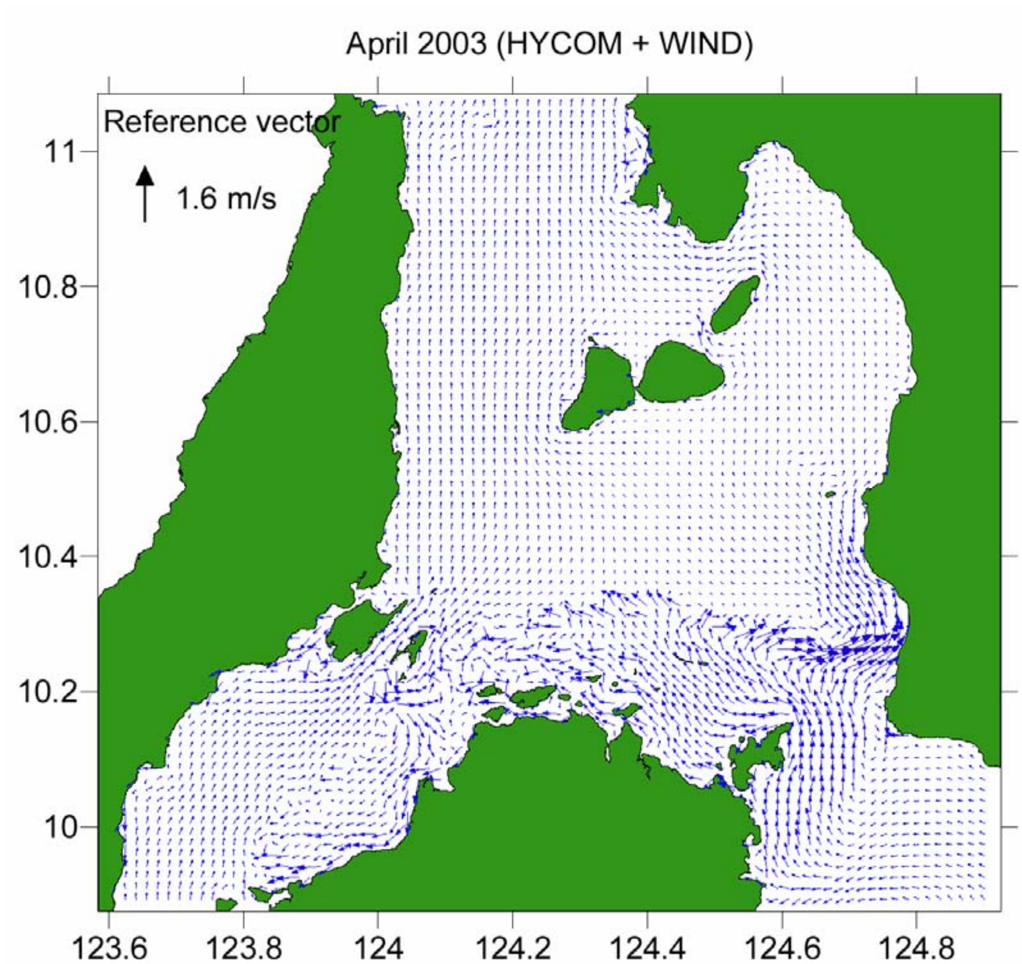

Figure 15. Circulation in the Camotes Sea forced by HYCOM velocities and wind during April

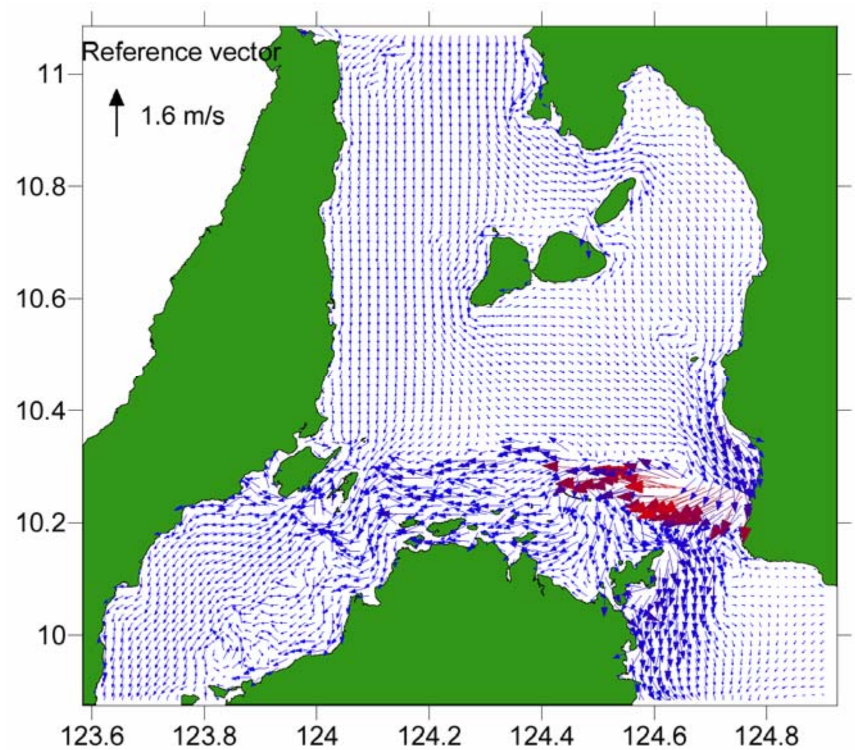

Figure 16. Circulation in the Camotes Sea forced by HYCOM velocities and wind during August

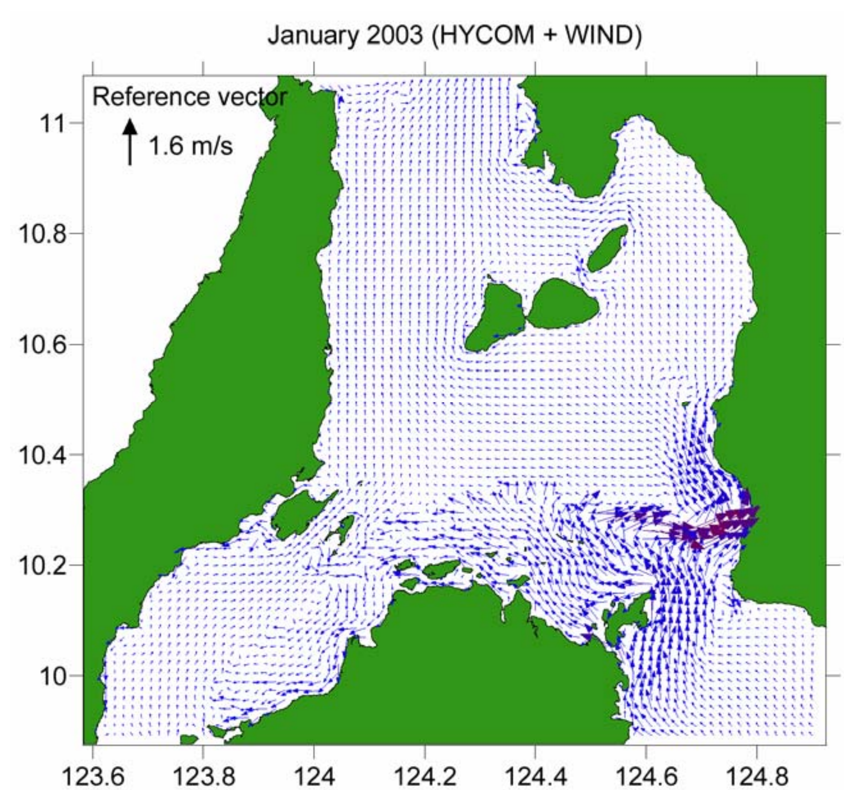

Figure 17. Circulation in the Camotes Sea forced by HYCOM velocities and wind during January

Dispersal Patterns

Baler Bay

Dispersal patterns in Baler Bay during the northeast monsoon are shown in Figure 18. The dispersal of particles from several locations around the bay is indicated by the different colored dots and their sources indicated by the box having the same color. Inside the bay, dispersal patterns show a general southward drift close to the coast. A similar dispersion pattern occurs for particles released along the coast north and south of Baler Bay. The only difference is for particles released in Cape San Ildefonso with particles directly crossing the mouth of Casiguran Bay and reaching the northwestern coast of Baler Bay. During the Southwest monsoon, most of the dispersed particles drift alongshore towards the northeast. Figure 19 shows the proportion of particles released that ended up within the boxes shown in Figure 18. The proportions are quite large and this is most likely due to the large areas assigned to each box. Future refinements for the larval dispersal model will make use of habitat maps to show potential areas of settlement and the use of smaller source and sink areas. The particle distribution shown in Figure 18 indicate that the particles released in areas along the coastlines outside Baler Bay are quickly carried away by currents in the alongshore direction and that no significant number of particles ended up in any of the boxes. Of course, this can also be due to the large spacing between boxes. Within Baler Bay and during the northeast monsoon, particles from different boxes appear to converge in the southern part near Baler Municipality and seen in the figure as part of the coast where the most number of different colors of particles are found.

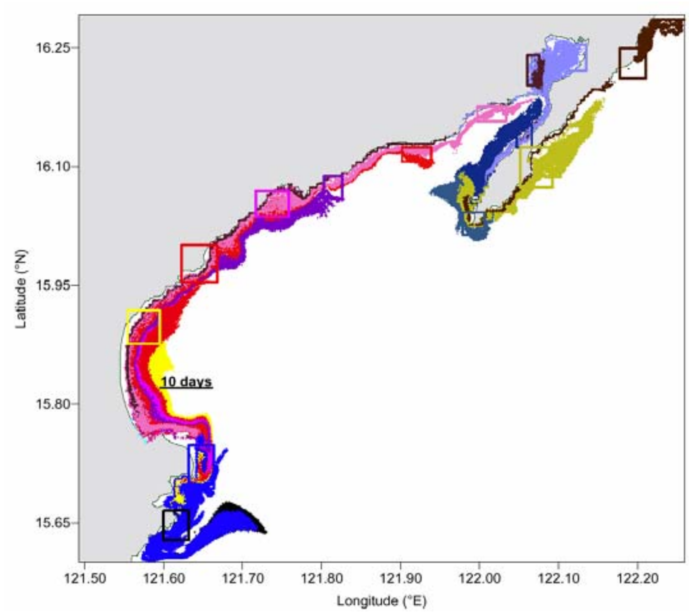

Figure 18. Dispersal of particles in Baler Bay released from locations indicated as boxes of the same color as the particles during the Northeast Monsoon.

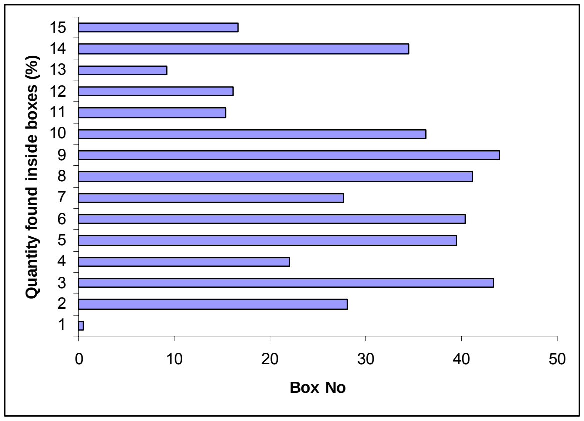

Figure 19. Proportion of particles settling within boxes in NE monsoon experiment.

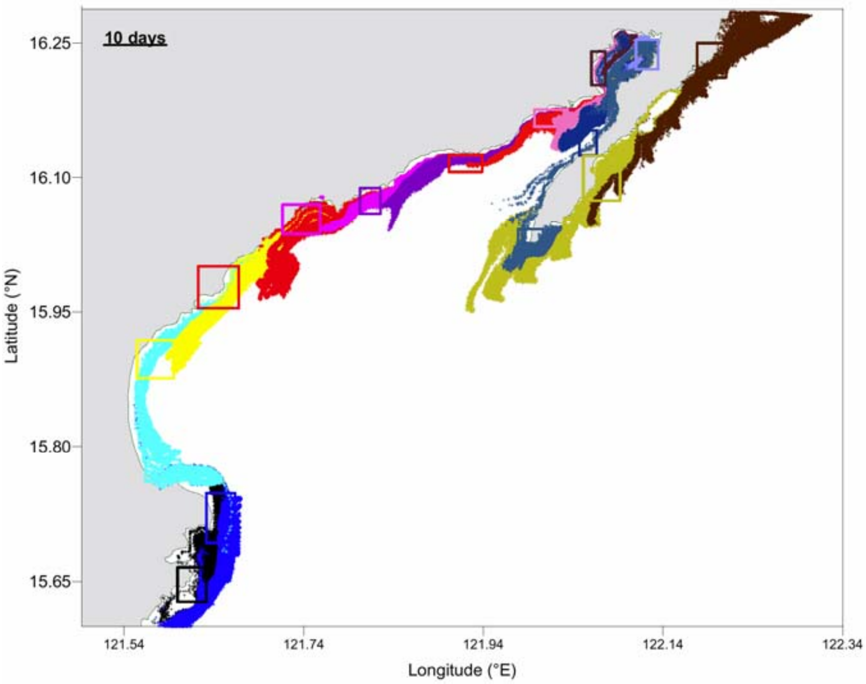

Figure 20. Dispersal patterns during southwest monsoon in Baler Bay

During the southwest monsoon season, dispersal of particles within the bay takes on a northward direction (Figure 20) and the convergence of particles from different areas around the Bay occurs in Casiguran Bay. Once particles enter Casiguran Bay, it becomes entrained there. Particles released on the eastern coast of Cape San Ildefonso tend to move southwards and some of it may enter the Casiguran Bay.

The proportion of particles released and ending up within the boundaries of any of the defined boxes is relatively high within Baler Bay and low for particles released directly along the Pacific coast. It is important to note however, that this is also dependent on the size of the sink areas. Nevertheless, this provides some initial insights on the probably dispersal patterns in Baler Bay.

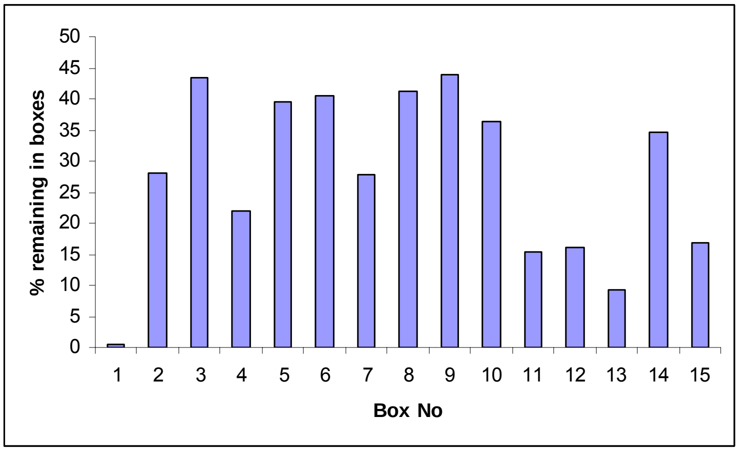

Figure 21. Proportion of particles settling within boxes in SW monsoon experiment.

Illana Bay

The deep bathymetry and wide configuration in Illana Bay result in relatively weak currents. As such, the dispersal distances are generally shorter as shown in Figure 22. For the simulation experiment conducted, no significant exchange between boxes was observed except in the western part of the Bay where the currents are relatively stronger. During the southwest monsoon, dispersal direction is in a clockwise fashion with particles released along the head of the bay directed slightly towards the east amd to the south along the eastern coast of the Bay. Seasonal difference in the dispersal patterns do not seem to be very significant and the common feature in both is the relatively large exchange between the areas along the western coast of the Bay.

Sibugay Bay

Dispersal patterns of particles released from different locations in Sibugay Bay driven by the tidal currents are shown in Figure 23. Particles released from the different locations are dispersed towards the mouth. In a purely tidal forcing, the strongest velocities are usually found close to the mouth and the weakest at the head of the bay. The dispersal patterns in Figure 23 show that the dispersal distances for particles released at the head of the bay are shorter than those released along the sides and those released closer to the mouth.

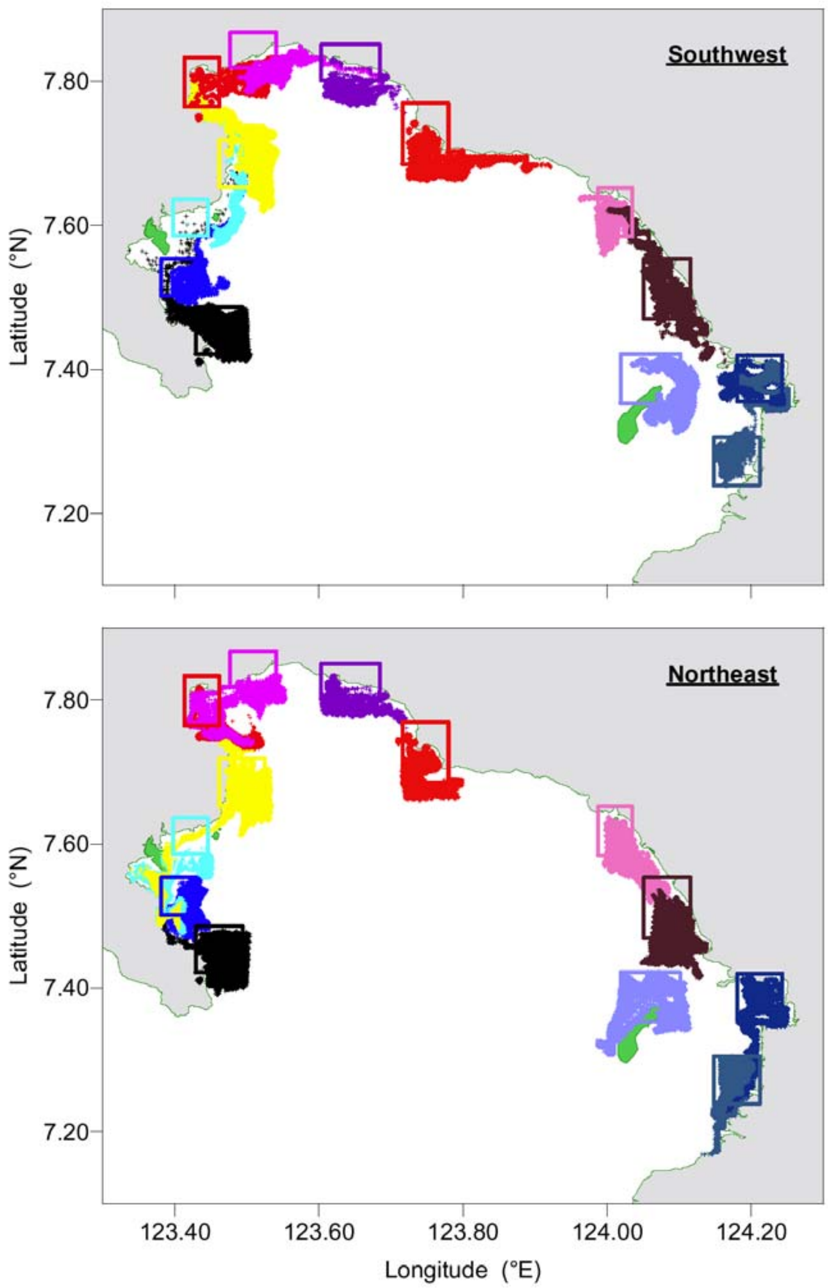

Figure 22. Dispersal patterns in Illana Bay during the southwest monsoon (top) and northeast monsoon (bottom).

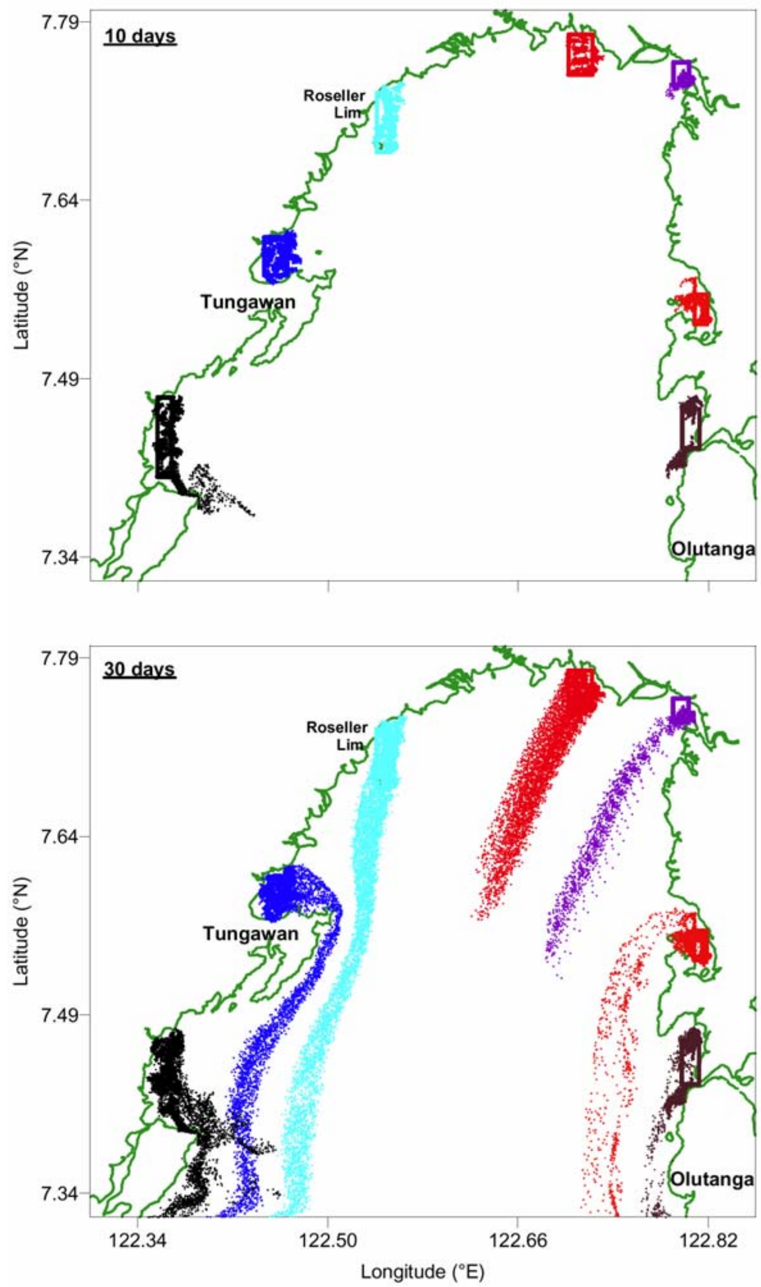

Figure 23. Dispersal due to tides in Sibugay Bay

Figure 24 shows the dispersal patterns during the southwest monsoon. Areas where particles are release are marked as boxes. Dispersal and scatter of particles on the western coast is broader compared to the particles of the eastern side of the Bay. This may be associated with the effect of Ekman drift during the southwest monsoon producing an offshore component of the flow. In the eastern coast, particles are much closer because Ekman drift will tend to push the water closer to the coast.

On both sides of the bay, alongshore transport is to the north converging in the head of the bay. Some retention occurs in Tungawan on the western coast of the bay and also along the northeast corner of the bay where convergence of the alongshore flow occurs. The proportion of particles settling within any of the boxes range from zero to around 20% (Figure 25). During the northeast monsoon, flow close to the coast reverses and flows towards the mouth. Dispersal on the western coast is much narrower again proably due to the slight onshore component due to Ekman drift. Surprisingly, Tungawan again shows up as receiving the highest number of particles compared to the other boxes. Almost 20% of the particles released settled in boxes (Figure 27), most of which were coming from the same box (e.g. self seeding).

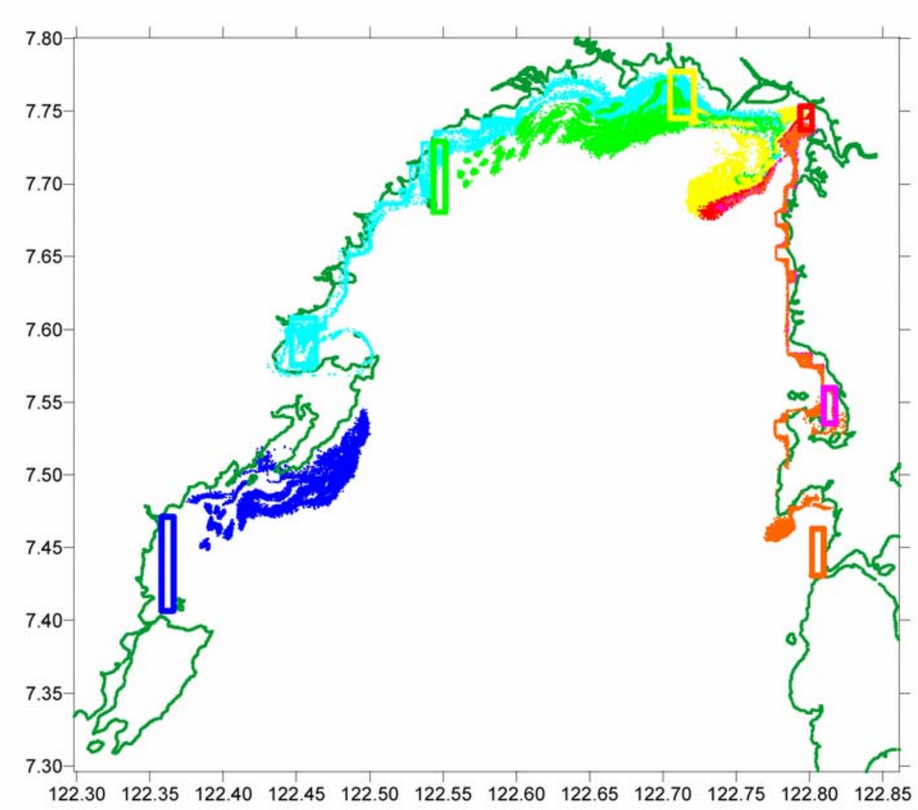

Figure 24. Dispersal during the southwest monsoon for Sibugay Bay

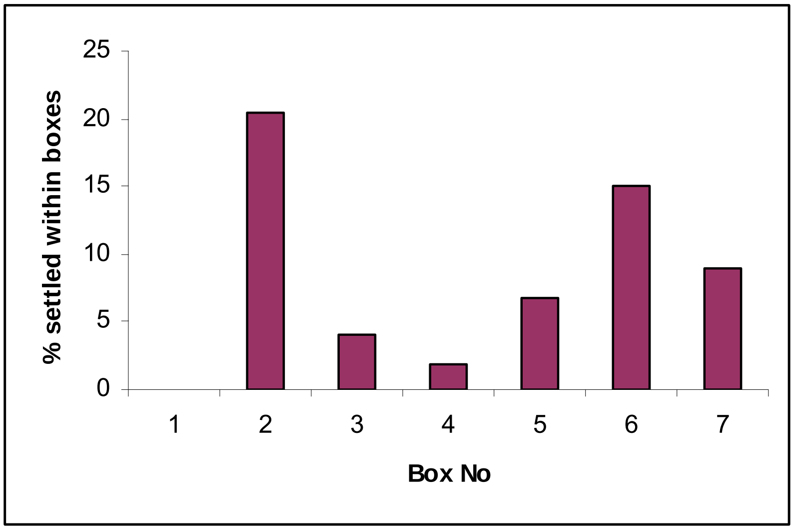

Figure 25. Proportion of released particles settling in boxes during the southwest monsoon

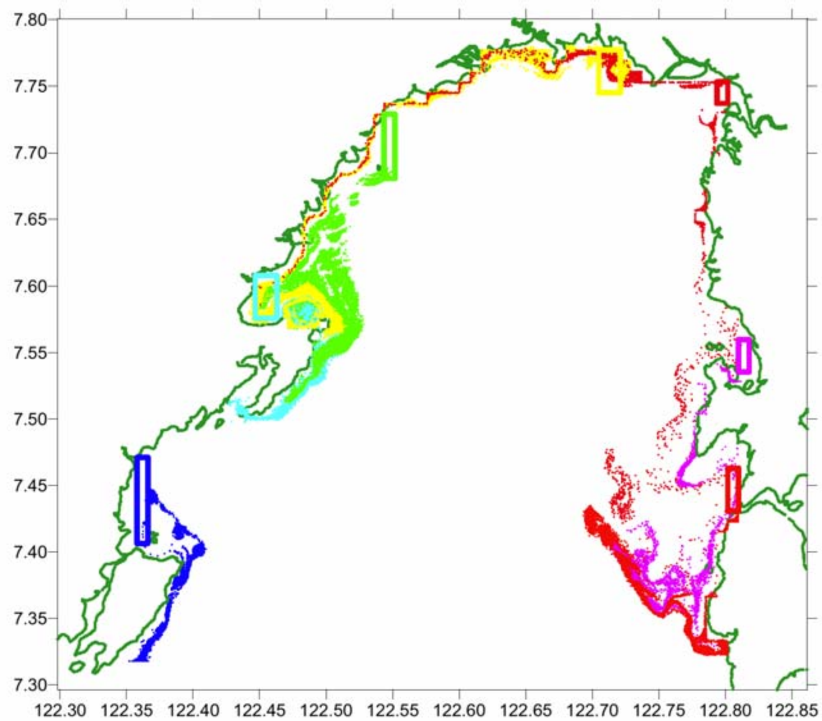

Figure 26. Dispersal of particles during the northeast monsoon for Sibugay Bay

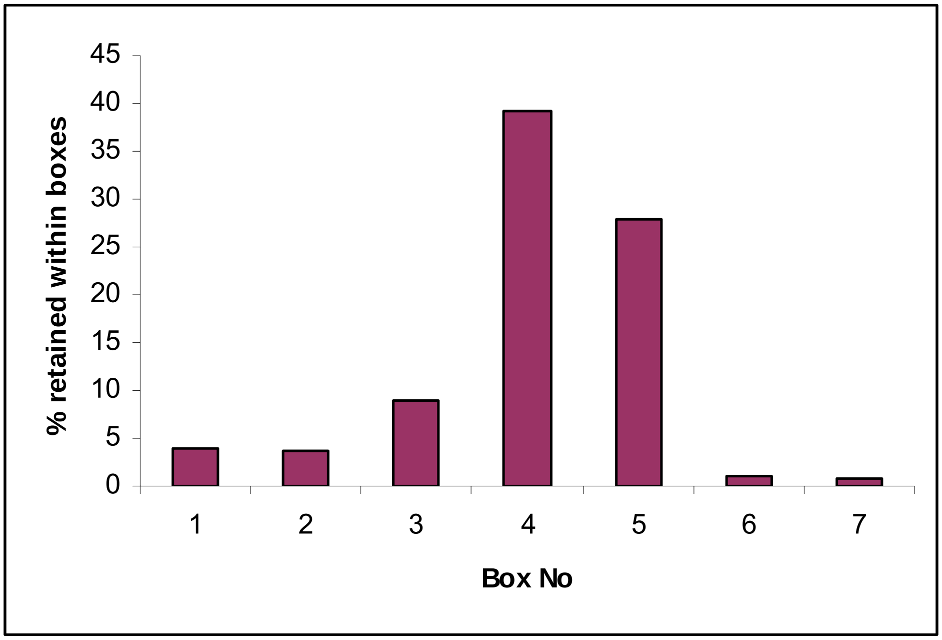

Figure 27. Proportion of released particles retained in boxes in Sibugay Bay during the northeast monsoon

Camotes Sea

The dispersal patterns in Camotes Sea for the months of April, January and August are shown in Figure 28, Figure 29 and Figure 30, respectively. It is clear from this figures that based on larval dispersal patterns, the Camotes Islands appear to be connected closer to Leyte rather than Cebu, while those particles on the eastern coast of Cebu generally flow along the coast. The deep connections of the Camotes Sea are found in the northern and southern part of Cebu so it is expected that flow between the northern channel and the southern channel will be the main route of water flowing through the Camotes Sea. The only way particles from either Camotes Islands or Cebu can reach the opposite coast are via diffusion or if the wind shifts direction. Besides, the distance between Camotes and Cebu is also farther away than the distance between Camotes Islands and Leyte. It is also likely that some exchange can occur between the Camotes Islands, Leyte and the eastern part of Bohol.

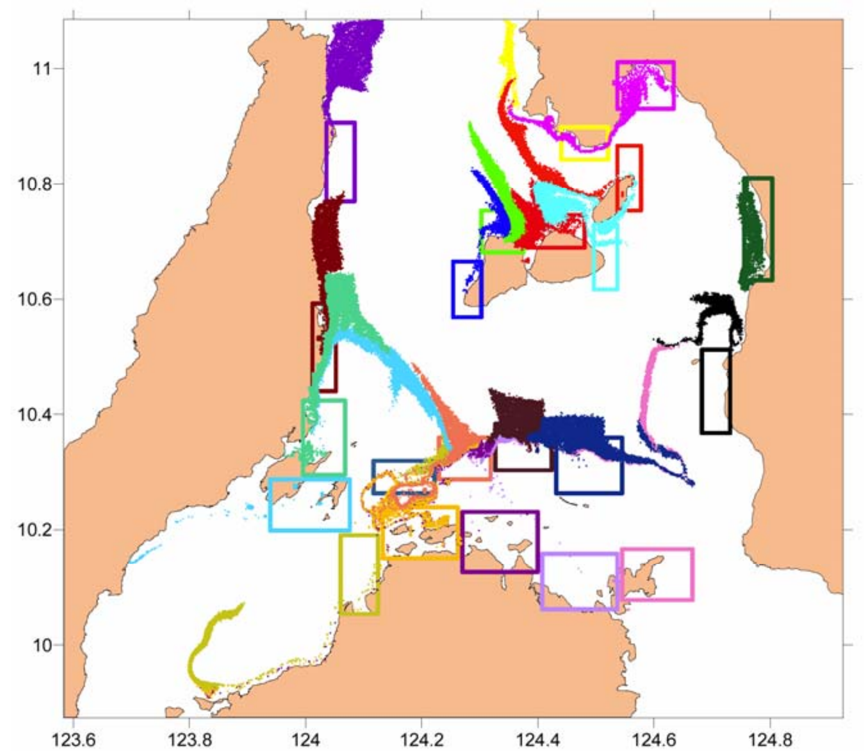

Figure 28. Camotes apr 30 days

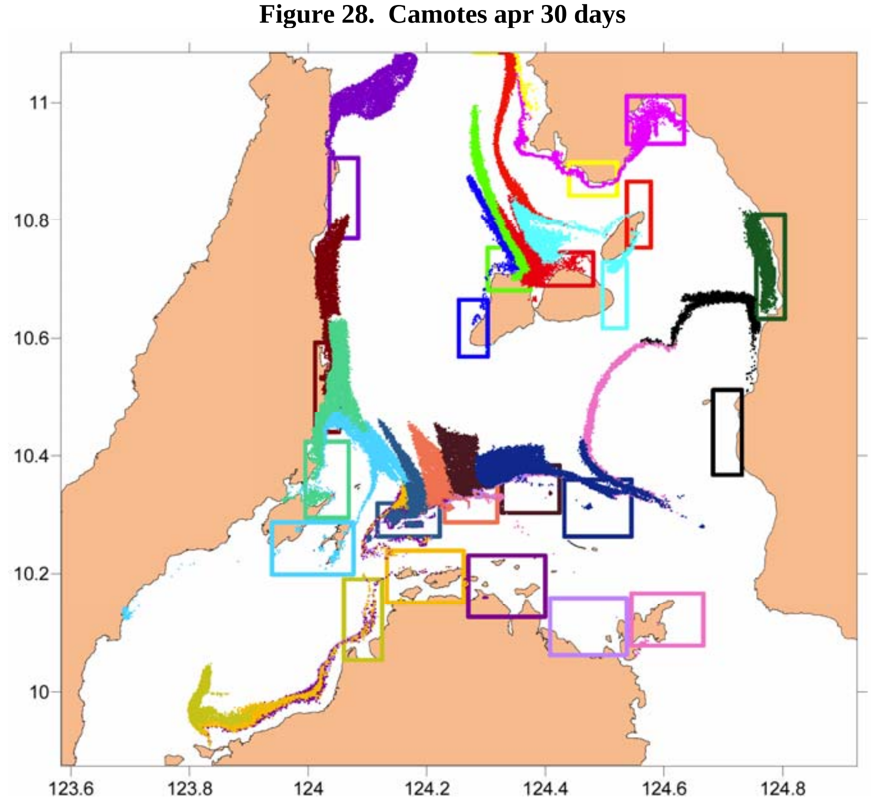

Figure 29. Dispersal Camotes Jan

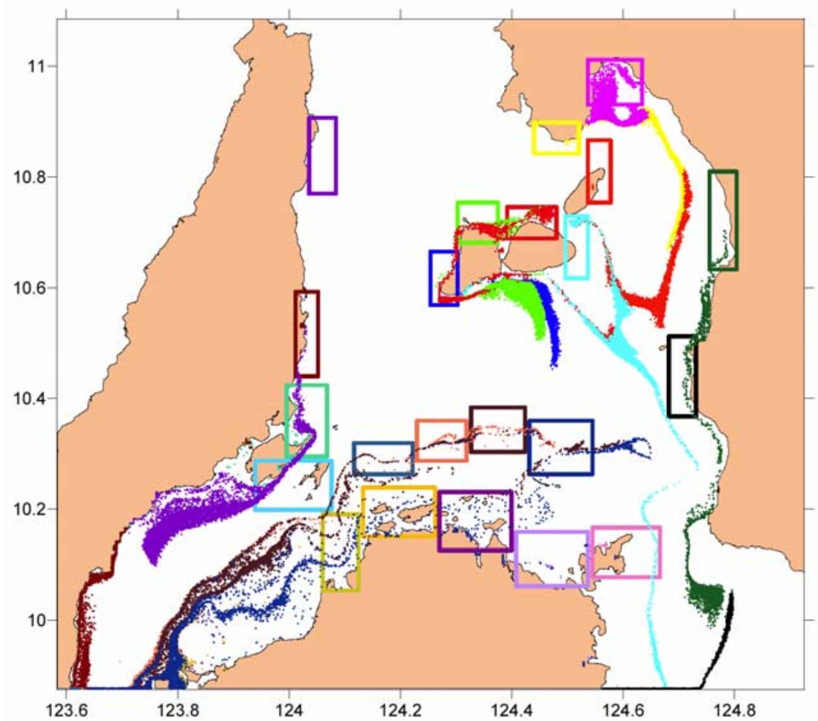

Figure 30. Dispersal Camotes Aug

DISCUSSION

Information on the potential of different areas to function as either a larval source or larval sink can be evaluated from the results of the dispersal model. Of course, this evaluation is based simply on the passive dispersal of simulated larvae. An area may be considered as a potential larval source if particles released from this site ends up in the neighboring areas that are identified as potential sink areas. The higher the proportion of particles found within boxes and the most number of boxes found to contain the particles indicates that the release area is a good larval source area. Even if the particles released from an area remain in the same area, it can still be a candidate as a potential larval source if the proportion of particles that settled within the area is high relative to the other larval sources. For example in the case of Baler Bay, most of the boxes within Baler Bay exhibited a high proportion of particles successfully settling in either the origin box or neighboring box. The boxes around Cape San Ildefonso in both the western coast facing Casiguran Bay and the eastern coast facing the Pacific exhibited lower larval settlement maybe due to stronger advection along the Pacific coast and the interruption of the coastal flow within Casiguran Bay by the sharp coastline curves.

The interaction between areas or boxes can be shown in the sink matrix shown in Table 1. The numbers in the first row and the first column represent the box numbers shown in Figure 31. The source boxes are represented in columns and the sink areas represented as rows. The numbers within a sink matrix represents the proportion of particles released from a source and distributed over 1 or more sink areas. The total of each column equals 100%. For instance in Table 1, particles released from Box 13 only settled in the same box thus in the source column, only one cell with a value of 100% is filled up corresponding to the row belonging to Box 13. In contrast, Box No 9 supplies particles to 9 Boxes from Box 2-9. In these examples, Box 13 appears to be a self-seeding area while Box 9 broadcasts over many areas. The percentage of particles from a box settling in another box can be used as a measure of connectivity between the two boxes.

One can also evaluate an area's potential as a larval sink using a similar matrix which is referred to in this study as a source matrix. This matrix will show the sources of all particles settling in a particular box. For example the source matrix in Table 2 shows that the particles found in Box 5 originated from Boxes 5 to 10 with 46.5 % coming from Box 5. Taking both the potential as a sink and as a source, the analysis seem to suggest that the connectivity between the boxes within Baler Bay is high with Boxes 2, 3 and 4 showing the greatest potential as sinks and Boxes 8, 9 and 10 showing the greatest potential as sources. Of course, this pattern will change with season and it is necessary to evaluate which season will dominate or when most of the spawning peaks are found for the majority of marine organisms.

For Illana Bay, the source and sink matrices reveal that the areas defined in the western part of the bay (e.g., Boxes 1-4 in Figure 32) show higher connectivity during the southwest monsoon compared to the northeast monsoon.

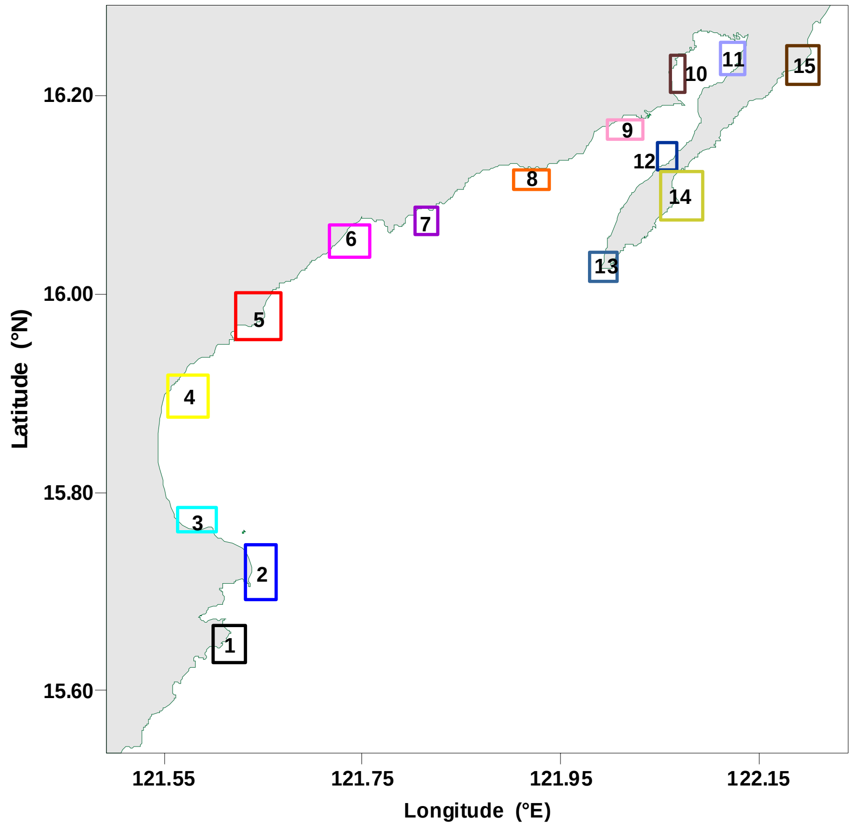

Figure 31. Areas used as both sinks and sources for dispersal experiments in Baler Bay

Table 1. Sink matrix during northeast monsoon in Baler Bay

Particle Sink \ Particle Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	100.0	34.4	25.7	2.4											
2		65.6	57.6	29.7	25.5	25.9	10.7	0.4	0.0						
3			16.7	40.4	26.9	27.3	22.9	16.6	15.7						
4				27.4	47.0	23.5	18.2	12.3	7.3	3.1					
5					0.6	17.4	28.6	16.3	14.1	4.5					
6						5.9	17.3	31.0	17.8	2.2					
7							2.3	15.1	11.7	3.5					
8								8.3	13.3	1.7					
9									20.1	2.8	2.8				
10										65.7	15.9				
11											47.8				
12										16.2	17.4	72.3			0.4
13										0.2	14.8	27.7	100.0	14.9	3.5
14											1.4			85.1	4.4
15															91.8

Table 2. Source matrix during the northeast monsoon in Baler Bay

Particle Source (columns); Particle Sink (rows)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.1	55.4	39.9	2.6											
2		33.1	28.0	10.0	14.5	11.4	2.9	0.1	0.0						
3			12.7	21.2	23.7	18.6	9.6	7.4	6.8						
4				16.1	46.5	18.0	8.6	6.1	3.6	1.2					
5					1.4	30.2	30.5	18.3	15.6	3.9					
6						12.0	21.7	41.0	23.1	2.2					
7							6.9	48.1	36.5	8.6					
8								36.7	57.5	5.8					
9									87.2	9.4	3.4				
10										92.0	8.0				
11											100.0				
12										23.5	9.0	66.9			0.6
13										0.2	5.1	17.2	34.2	39.9	3.5
14											0.2			97.9	1.9
15															100.0

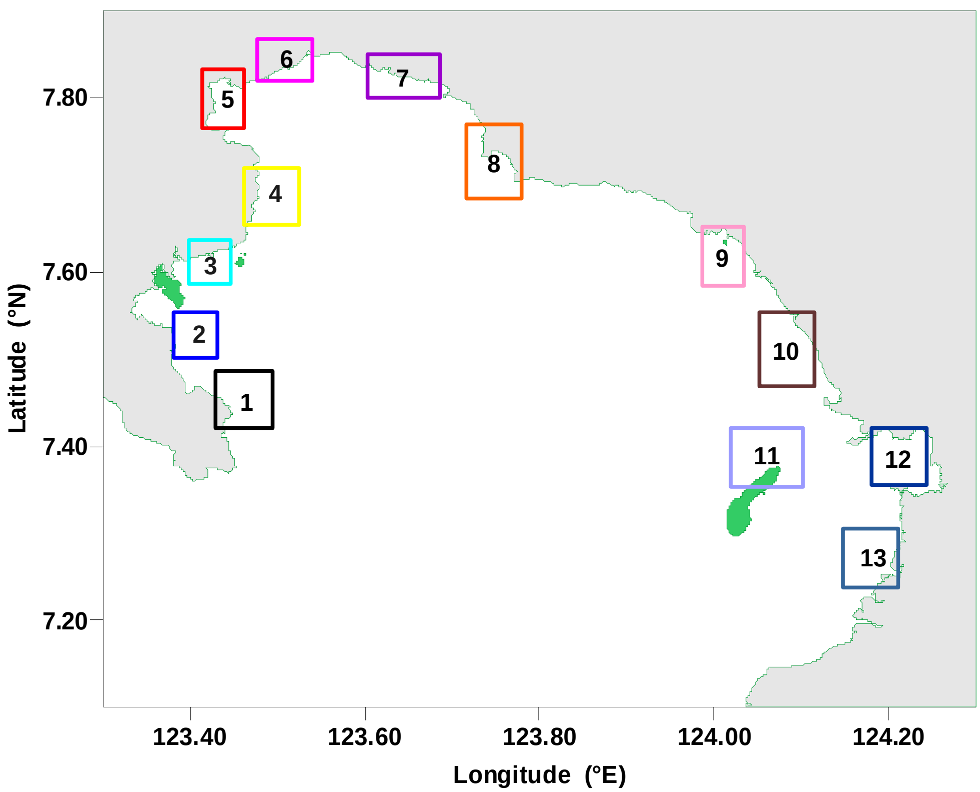

Figure 32. Areas used as both sinks and sources for dispersal experiments in Illana Bay.

Table 3. Sink matrix in Illana Bay for the northeast monsoon

Particle Sink \ Particle Source	1	2	3	4	5	6	7	8	9	10	11	12	13
1	99.8												
2	0.2	100.0	86.7	5.4									
3			13.3	0.7									
4				92.9									
5				1.0	100.0	45.4							
6						54.6							
7							100.0						
8								100.0					
9									89.9				
10									10.1	100.0			
11											100.0		
12												91.2	
13												8.8	100.0

Table 4. Sink matrix in Illana Bay for the southwest monsoon

Particle Sink \ Particle Source	1	2	3	4	5	6	7	8	9	10	11	12	13
1	97.5												
2	1.8	94.3											
3	0.7	2.2	1.6										
4	0.1	3.5	72.6	87.2									
5			19.3	8.7	18.6								
6			6.4	4.0	81.4	96.7							
7						3.3	100.0						
8								100.0					
9									100.0	8.5			
10										91.5			
11											100.0		
12												100.0	44.4
13													55.6

The Sibugay Bay dispersal results were analyzed in the same way and because of the smaller number of boxes and smaller sizes of boxes, it is expected that the proportion of particles settling within boxes is lower. During the southwest monsoon, Box 2 appears to be the best larval source with particles being supplied to three boxes (Table 5). However, during the northeast monsoon when dispersal patterns are reversed, it is Box 5 that is the better source area (Table 7). Potential sink areas include Box 4 and 5 during the southwest monsoon (Table 6) and Box 2, 3 and 7 during the northeast monsoon (Table 8). The boxes in this study have been arbitrarily chosen but it is very simple to define new areas and repeat the analysis.

For the Camotes Sea, the Boxes around Camotes Islands appear to have some degree of connectivity with Box 7 acting as a potential source during the northeast monsoon (

Table 9), and Box 2 and 3 during the southwest monsoon (Table 11). Similarly, potential sink areas include Box 2 and 4 during the northeast monsoon (Table 10) and Box 1-3 during the southwest monsoon (Table 12).

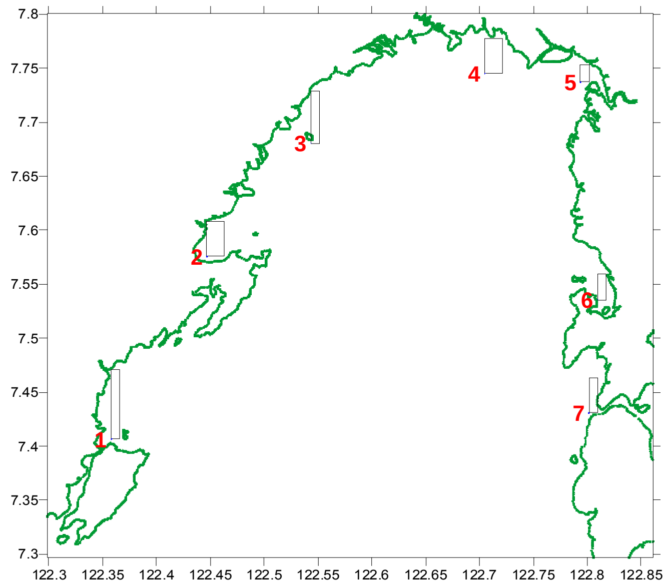

Figure 33. Areas used as both sinks and sources for dispersal expriments in Sibugay Bay

Table 5. Sink matrix in Sibugay Bay for the SW monsoon.

	1	2	3	4	5	6	7
1							
2		40.8					
3		15.6					
4		43.6	100.0	92.4			
5				7.6	100.0	100.0	77.9
6							22.1
7							

Table 6. Source matrix in Sibugay Bay for the SW monsoon

	1	2	3	4	5	6	7
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	100.0	0.0	0.0	0.0	0.0	0.0
3	0.0	100.0	0.0	0.0	0.0	0.0	0.0
4	0.0	60.6	29.2	10.2	0.0	0.0	0.0
5	0.0	0.0	0.0	1.3	16.4	48.4	33.9
6	0.0	0.0	0.0	0.0	0.0	0.0	100.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7. Sink matrix in Sibugay Bay for the NE monsoon

	1	2	3	4	5	6	7
1	100.0						
2		100.0	94.7	25.9	1.0		
3			5.3	9.6	4.4		
4				64.4	73.6		
5					20.5		
6					0.4		
7					0.1	100.0	100.0

Table 8. Source matrix in Sibugay Bay for the NE monsoon

	1	2	3	4	5	6	7
1	100.0						
2		17.3	42.4	40.0	0.3		
3			12.8	80.1	7.1		
4				81.9	18.1		
5					100.0		
6					100.0		
7					0.9	47.3	51.8

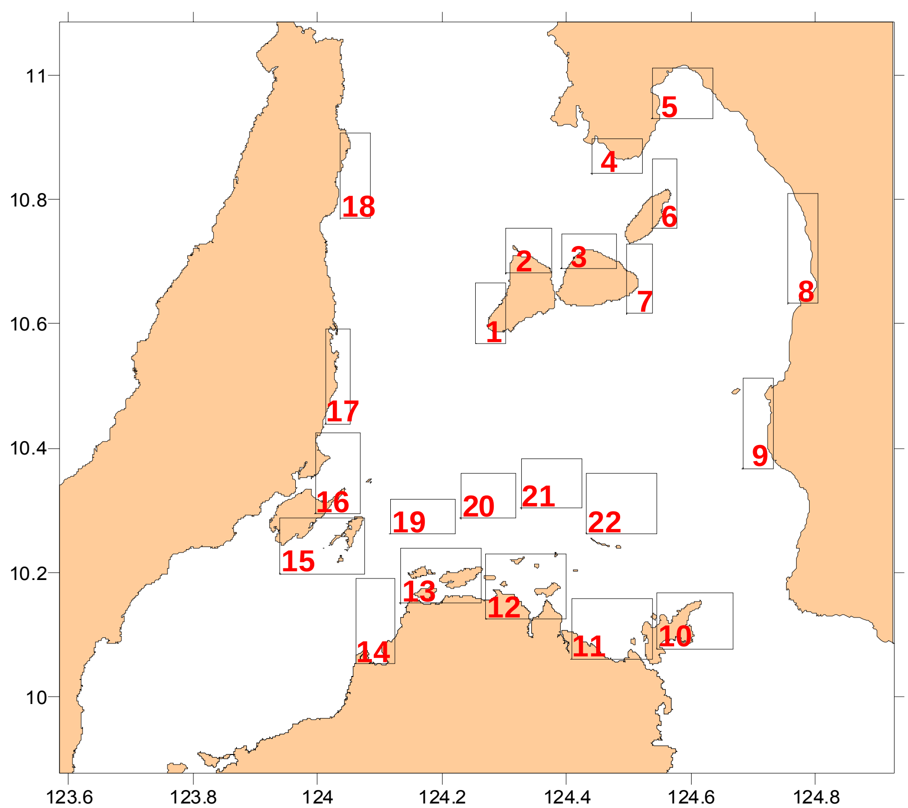

Figure 34. Areas used as both sinks and sources for dispersal experiments in Camotes Sea

Table 9. Sink matrix for camotes ne

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	16.9						0.0															
2	83.1	100.0	33.9				2.7															
3			66.1				52.7															
4				100.0	23.1	14.4																
5					76.9																	
6						85.6	4.5															
7							40.1															
8								100.0														
9									100.0													
10										1.9												
11										0.5												
12											0.0	0.9										
13											7.3	12.4	9.2									
14											4.8	21.6	58.6	86.0								
15												0.0			37.8							
16															42.7	51.6						
17															10.3	48.4	91.2					
18																	8.8	100.0				
19											30.8	58.9	32.3	14.0	9.2				100.0	15.8		
20										39.1	40.2	6.3								84.2	69.9	4.7
21										28.0	14.0										30.1	48.1
22										30.5	2.8										0.0	47.2

Table 10. Source matrix for camotes ne

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	99.9						0.1															
2	35.1	45.1	18.7				1.0															
3			65.0				35.0															
4				2.4	93.1	4.5																
5					100.0																	
6						74.3	25.7															
7							100.0															
8								100.0														
9									100.0													
10										100.0												
11										100.0												
12											6.1	93.9										
13											35.5	46.6	17.9									
14											9.3	32.7	46.1	11.9								
15												0.1			99.9							
16															32.2	67.8						
17															6.9	56.2	37.0					
18																	13.8	86.2				
19											20.3	30.2	8.6	0.7	2.4				33.3	4.6		
20										12.4	27.3	3.3								25.0	29.3	2.7
21										15.2	16.3										21.5	47.0
22										25.1	4.9										0.0	70.0

Table 11. Sink matrix southwest

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	100.0	67.2	20.3																			
2		18.9	25.8																			
3		13.7	52.0																			
4				100.0																		
5					100.0																	
6						21.0																
7		0.2	1.9			79.0	95.1															
8								82.4														
9								17.6														
10							4.9			100.0	0.2											0.3
11											19.5											2.4
12											46.5	17.3									0.7	22.4
13											33.7	82.4	100.0								0.8	29.7
14												0.3	0.0	100.0						1.9	3.7	12.5
15															100.0	23.9	14.2	7.9		1.9	1.5	0.1
16																76.1	81.7	45.5				
17																	4.1	46.6				
18																						
19																				27.6	6.5	3.1
20																				44.9	13.5	5.4
21																				21.4	26.3	0.6
22																				2.2	47.0	23.5

Table 12. Source matrix southwest

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	12.1	54.1	33.8																			
2		26.1	73.9																			
3		11.3	88.7																			
4				100.0																		
5					100.0																	
6						100.0																
7		0.4	8.6			34.5	56.5															
8								100.0														
9								100.0														
10							7.0			90.4	0.4											2.2
11											68.0											32.0
12											18.9	44.7									1.5	34.9
13											3.8	59.5	23.3								0.5	12.9
14												2.4	0.1	0.2						7.0	25.4	64.9
15															17.5	20.2	27.3	25.0		4.0	5.8	0.3
16																17.6	43.0	39.4				
17																	5.1	94.9				
18																						
19																				62.4	27.6	10.0
20																				57.7	32.6	9.7
21																				29.9	68.8	1.3
22																				1.8	71.5	26.7

Table 13. Sink matrixfor camoted during apr

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	29.2																					
2	70.8	100.0	15.8																			
3			84.2				45.2															
4				100.0	27.9	31.1																
5					72.1																	
6						68.9	2.3															
7							52.5															
8								100.0														
9									100.0													
10										0.0												
11										1.1	1.2											
12										4.4	2.3	0.2										
13											4.9	22.7	51.4	2.5	0.0				7.0			
14												1.4	4.1	22.6								
15															22.2							
16															36.8	44.3						
17															28.3	55.7	97.9					
18																	2.1	100.0				
19											1.6	5.8	20.4	52.4	7.7				30.0			
20										32.7	73.9	69.9	24.2	22.5	4.9				63.0	96.5	2.9	
21										27.6	16.1									3.5	97.1	23.9
22										34.1	0.0											76.1

Table 14. Source matrix for camotes during april

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	100.0																					
2	36.5	54.4	9.1																			
3			69.0				31.0															
4				6.0	82.2	11.8																
5					100.0																	
6						86.1	13.9															
7							100.0															
8								100.0														
9									100.0													
10										100.0												
11										32.4	67.6											
12										47.3	46.8	5.9										
13											6.1	34.1	53.4	1.2	0.0				5.1			
14												12.3	25.0	62.7								
15															100.0							
16															24.8	75.2						
17															11.0	54.5	34.5					
18																	2.4	97.6				
19											2.4	10.8	26.2	30.3	3.0				27.3			
20										5.7	24.4	27.9	6.7	2.8	0.4				12.2	19.1	0.8	
21										10.5	11.7									1.5	59.2	17.1
22										19.2	0.0											80.8

The use of the exchange matrices where one can see the potential of an area as a larval source and sink based on passive dispersal of particles can provide some information about dispersal length scales and the degree of connectivity between particular areas for a given set of oceanographic conditions. If applied to the potential of actual MPAs, the retention rates may be much smaller because the area of MPAs are also much smaller. There is a need to use more realistic source and sink areas that can be initially scaled to actual habitat areas present in an area. There is also a need to quantify the rate of larval production and initial estimates can be obtained from available fish visual census data together with fecundity data from the literature. With such information, together with dispersal estimates from modeling and planktonic larval durations, estimates as to the size of the larval neighborhood can be made for different types of organisms which have different planktonic larval durations.

SUMMARY AND CONCLUSIONS

Hydrodynamic and larval dispersal models were developed for 4 sites in the Philippines, namely; Baler Bay in Aurora, Camotes Sea in the Visayas, Illana Bay and Sibugay Bay, both in the Moro Gulf facing the Sulawesi Sea. The models reveal unique oceanographic characteristics for each site. Baler Bay for instance is influenced by a persistent southward current along it's Pacific coast but the sharp bathymetry step at the mouth of the bay serves as a natural boundary for the bay such that offshore features may be limited from influencing circulation within the bay. The two bays in the northern margin of Moro Gulf are similar in size but differ significantly in depth. Sibugay Bay is shallow with maximum depths of about 100m while Illana Bay can have depths > 2500m. Consequently, the tidal component of the flow is stronger in Sibugay Bay compared to Illana Bay.

A particle tracking Lagrangian model was used as a larval dispersal model. Several areas within each site were delineated as larval source areas and particles were released from these areas. The particles were allowed to drift around depending on the currents and a random walk model to simulate diffusion. The location of the particles after the simulation were noted and used as the basis for the exchange matrices where the interaction between the sources and sinks can be seen. Such matrices were also used to determine the potential of an area as a larval source or a larval sink solely on the basis of hydrodynamics. Further refinements are being planned on quantifying the larval production and using much more realistic size of sources or sink areas.

REFERENCES

Botsford et al, 1999. principles for the design of marine reserve. Eccol appl. 13:S25-31

Botsford et al., 2001. Dependence of sustainability of marine reserves and larval dispersal distance. Ecol. Lett. 4, 144-150

Halpern BS, 2003. The impact of marine reserves: do reserves work and does reserve size matter? Ecol. Appl. 13, S117-S137.

Kinlan BP, SD Gaines, 2003. Propagule dispersal in marine and terrestrial environments: A community perspective. Ecology 84(8):2007–2020.

Lukas R, Firing E, Hacker P, Richardson PL, Collins CA, Fine R, Gammon R, 1991. Observations of the Mindanao current during the Western Equatorial Pacific Ocean Circulation Study. Journal of Geophysical Research 96: 7089-7104.

Palumbi SR, 2004. Marine reserves and ocean neighborhoods: The spatial scale of marine populations and their management. Annu. Rev. Environ. Resour. 29:31-68.

Qu T, Mitsudera H, Yamagata T. 1998. On the western boundary currents in the Philippine Sea. JGR-Oceans 98JC00263 103(C4):7537

Roberts CM, Bohnsack JA, Gell F, Hawkins JP, Goodrifge R. 2001. Effects of marine reserves on adjacent fisheries. Science 294:1920-23

Russ GR et al (2004) Marine reserve benefits local fisheries. Ecol. Appl. 14, 597-606

Russ GR and Alcala AC, 2003. Marine reserves: rates and patterns of recovery and decline of predatory fish, 1983-2000. Ecol. Appl. 13: 1553-1565.

Sale PF, Cowen RK, Danilowicz BS, Jones GP, Kritzer JP, Lindeman KC, Planes S, Polunin NVC, Russ GR, Sadovy YJ, Steneck RS. 2005. Critical science gaps impede use of no-take fishery reserves. Trends in Ecology and Evolution 20(2), 74,80