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Residence Time Models and *Pyrodinium* Blooms in Matarinao and Murcielagos Bays, Philippines

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This is the first report on hydrodynamic models to determine current and water residence time patterns for Matarinao and Murcielagos bays in the Philippines, which have a long history of harmful algal blooms (HABs). Field surveys were conducted in Matarinao Bay in April and August 2010 and in Murcielagos Bay in February 2011. Hydrodynamic models of the bays were developed, and spatially explicit water residence times were estimated from the models based on rates of concentration decrease of a tracer within the bay. Both bays exhibited two distinct areas – the mouth with faster current flow and low residence time, and the head area with slower current flow and higher residence time. During the southwest monsoon, the residence time at Matarinao Bay was 5 d longer than that during the northeast monsoon. Phytoplankton sampling in both bays confirmed blooms of *Pyrodinium bahamense*, but the spatial distribution did not consistently correlate with the simulated residence time patterns. While residence time plays a significant role in algal blooms, extraneous factors may also influence the distribution of phytoplankton within embayments.

Keywords: harmful algal bloom, Matarinao Bay, Murcielagos Bay, *Pyrodinium bahamense*, residence time model

INTRODUCTION

Defining the hydrodynamic processes in embayment is critical to understanding the flow of dissolved and suspended particles in and out of the bay. Residence time refers to the average duration that water remains within the limits of a water system. It is a first-order metric describing the multiple and complex drivers of transport and is often used to study the spread of pollutants, dissolved nutrients, plankton, and HABs (Limoges *et al.* 2015; Du and Shen 2016).

Depending on the causative organism, HABs can inflict harm on both natural marine communities and human

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populations reliant on coastal resources. Algal blooms may deplete dissolved oxygen, suffocate aquatic life, prevent sunlight from reaching submerged vegetation, and spread toxins that are harmful to humans and other marine organisms. In the Philippines, HABs have been monitored and found to occur more frequently and in an increasing number of sites since the early 1990s (Yñiguez *et al.* 2021). The causative species have likewise diversified, widening the impacts that range from fatal neurotoxic problems to shellfish bans and fish kills that cause heavy economic losses among gleaners and farmers. The most common and widely distributed harmful alga in the country is the dinoflagellate *Pyrodinium bahamense* Plate (Azanza and Taylor 2001). This organism has been implicated in paralytic shellfish poisoning cases and deaths since 1983.

Despite the prevalence of HABs and the health and economic hazards they pose, only Manila Bay (Villanoy *et al.* 2006) and Sorsogon Bay (Yñiguez *et al.* 2018) have been thoroughly studied in the Philippines to determine the factors involved in the recurrence and sustenance of blooms. Among the coastal waters affected by HABs but poorly studied are Matarinao Bay in eastern Samar at the eastern side of the Philippines and Murcielagos Bay in northeastern Mindanao at the southern Philippines.

Matarinao Bay is a semi-enclosed embayment with a total water area of around 75 km^2. Except for 2014 and 2015, the bay experienced HABs every year since 2010, which led to the issuance of shellfish harvesting bans by the Bureau of Fisheries and Aquatic Resources of the Philippine government. The resulting shellfish bans adversely affect the livelihood of locals dependent on shellfish extraction and aquaculture of mussel and abalone. The bay has a coastline of around 46 km and has four major rivers plus several smaller rivers that drain into it. Matarinao Bay is surrounded by four municipalities, which include Salcedo, Quinapondan, Hernani, and McArthur.

Murcielagos Bay has a history of HABs resulting in shellfish bans, which persisted from 2009–2013 and recurred in 2021. Reports of fish kills in the bay have also been attributed to HABs. With a total water area of around 78.5 km^2, the bay is situated between the provinces of Misamis Occidental and Zamboanga del Norte with a coastline of around 50 km. There are 25 river systems that drain into the bay, which is dominated by a muddy substratum.

Since current published information on Matarinao and Murcielagos bays is still lacking, this study aims to provide baseline data on the analysis of the phytoplankton community, assessment of the residence time, and investigation of the relationship of *P. bahamense* abundances with residence time in both bays.

MATERIALS AND METHODS

Measurements of Physical Parameters

In situ measurements of salinity and temperature (from 1 m below the water surface to the bottom at 1-m intervals) and surface water current were obtained from 16 survey stations in both Matarinao (Figure 1A) and Murcielagos (Figure 1B) bays. Matarinao Bay survey was conducted on 21 Apr 2010, whereas Murcielagos was surveyed on 06 Feb 2011. Vertical salinity profiles were obtained using a Sea-Bird SBE 25 CTD (Sea-Bird Electronics, Inc., USA). Surface current profile measurements were made using a boat-mounted Teledyne RDI WHN Workhorse Sentinel Acoustic Doppler Current Profiler (ADCP) 300 khz (Teledyne, USA). Bathymetry was surveyed using a Garmin GPSMap 421s sounder (Garmin Ltd., Schaffhausen, Switzerland).

Sampling stations for Murcielagos Bay were not evenly distributed across the bay due to a very shallow bathymetry (< 1 m deep) in the middle area. The boats used could not pass through this area and alternative sampling station locations were necessary.

Modeling

A two-dimensional hydrodynamic model was developed using the DELFT3D-FLOW (Deltares, Rotterdamseweg 185, Delft, The Netherlands) software for Matarinao and Murcielagos bays due to observed weak stratification. Matarinao and Murcielagos Bay hydrodynamic models were set at a resolution of 100 m $\times$ 100 m. Model domains for both bays are presented in Figure 1. The models were forced either by tides prescribed at the mouth of the bay or by both tides and winds. All the tide data were taken from an implementation of the OSU Tidal Inversion Software or OTIS for the Philippine seas (Magno 2005). The wind data in the Guiuan weather station was used for Matarinao Bay, whereas the Dipolog weather station was used for Murcielagos Bay taken from the "weather underground" website (www.wunderground.com) as no PAGASA (Philippine Atmospheric, Geophysical, and Astronomical Services Administration) weather stations were located in the vicinity for both bays.

Spatially explicit residence times were also derived from the model based on the rates of decrease in the concentration of a hypothetical tracer due to flushing from outside the bay. For this study, the initial concentration of the hypothetical tracer was 1000 units inside the bay and zero for the water coming into the bay through the open boundary.

Residence times of waters near the open boundaries were highly influenced by the phase of the tide during the start of the simulation. To account for the time-varying flow, 24 simulations were conducted for each residence time

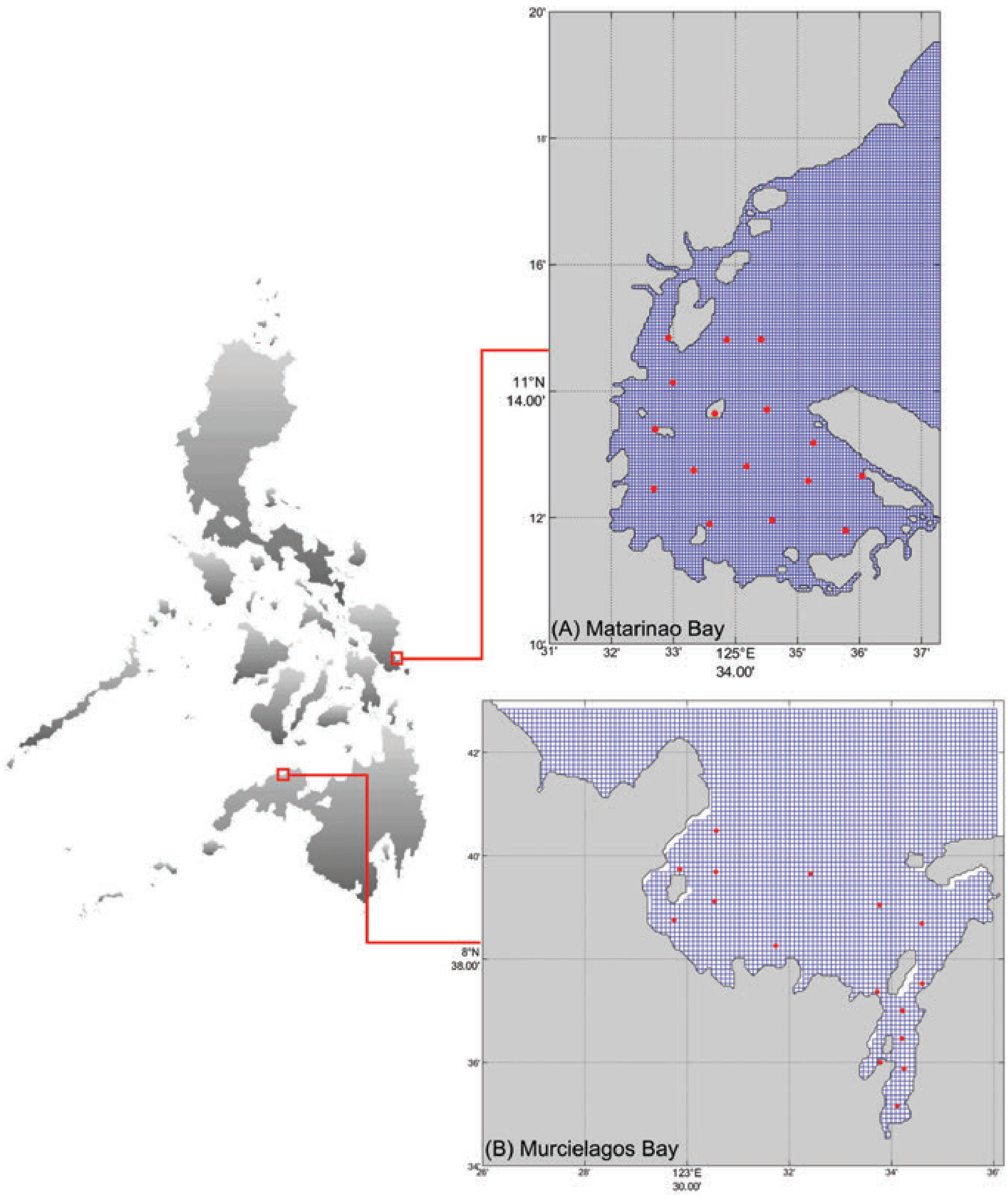

Figure 1. Model domains at 100 m x 100 m grid resolution with sampling stations in red circles of [A] Matarinao and [B] Murcielagos bays for *in situ* measurements of physical parameters (salinity, temperature, current, depth) and phytoplankton sampling.

calculation, each starting 1 h later than the previous one. The final residence time estimate was determined from the average of the 24 simulations.

For the purpose of this study, the residence time is defined as the time needed for the concentration at a given point within the bay to decrease 50% from its initial concentration. It is further categorized by short (0–7 d), intermediate (8–15 d), long (16–23 d), and very long (24–30 d).

Phytoplankton Sampling and Analysis

Phytoplankton sampling was conducted in Matarinao Bay and Murcielagos Bay. In Matarinao Bay, sampling was conducted on 20 Apr 2010 covering 12 stations (MTB2–9, 12, 14–16) and on 19 Aug 2010 covering 11 stations (MTB3–5, 7, 8, 10–14, 16) shown in Figure 2A. Murcielagos Bay sampling was conducted on 06 Feb 2011 covering 15 stations (MUR1–4, 6–16; Figure 2B). The location and the number of sampling stations were determined based on the size and topography of

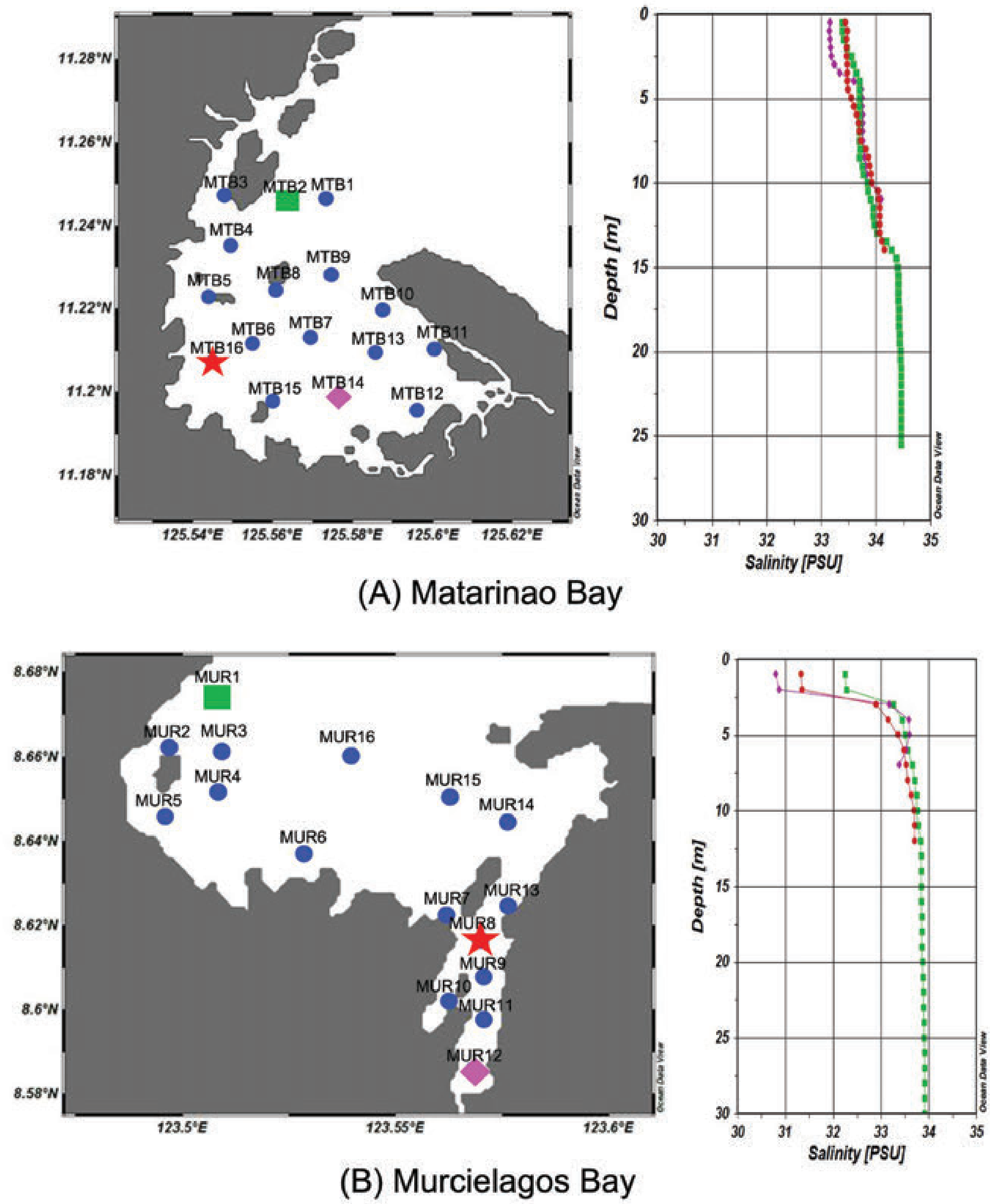

Figure 2. Sampling stations shown in blue circles with representative stations shown in green square, red star, and magenta diamond (left) plus salinity profiles (right) of [A] Matarinao and [B] Murcielagos bays.

each embayment. In each station, water samples were collected using a 20-µm mesh plankton net (qualitative) and a Niskin water sampler for quantification. Two replicates were collected at 1 m below the surface and at bottom depths. Samples were preserved with Lugol's solution, gravimetrically settled for 24 h for concentration, from which 1 mL aliquots were taken for quantitative and qualitative analysis using a Zeiss Axioskop II microscope. Identification of phytoplankters was based on the taxonomic guides of Yamaji (1979), Tomas (1997), and Omura *et al.* (2012). Cell counts (at least 200 cells) were made from a 1-mL aliquot using a Sedgewick Rafter counting chamber. Cell density expressed in cells per L was determined by multiplying the cell count by the concentrated volume of the sample and dividing the result by the original volume of the sample (1 L).

Phytoplankton enumeration was based on large phytoplankton groups – namely, dinoflagellates, diatoms, silicoflagellates, and cyanophytes. Other groups such as picoplankton and nanoplankton were not included in the analysis.

Correlation of Residence Time with the Spatial Distribution of *P. bahamense*

To determine the relationship between the residence time and relative abundance of *P. bahamense* for each survey, Pearson's product-moment correlation was calculated using the *cor.test* function in R software (version 4.1.1). The correlation was considered statistically significant at $p < 0.05$.

RESULTS

Bathymetry

Bathymetric surveys at Matarinao Bay showed that the embayment is shallow with 60% of surface area less than 10 m deep (Figure 3A). Meanwhile, Murcielagos Bay is even shallower with approximately 50% of surface area less than 5 m deep and with portions of its middle area measuring less than 1 m deep (Figure 3B). Towards the mouth of both bays, the depth goes down steeply to more than 30 m.

Salinity Distribution

Three representative stations – one from the mouth and two stations from the head of the bays – were used to compare vertical salinity profiles across each bay for Matarinao and Murcielagos (Figure 2). Plots showed that Matarinao Bay had a narrow salinity range (33.2–34.5 PSU). On the other hand, Murcielagos Bay showed a wider salinity range – from 30.8–34 PSU. Yet, when the water depth reached to 2.5 m, the vertical salinity range narrowed from 33–34 PSU. Both these bays showed high salinity values and narrow salinity ranges, suggesting that aside from the near-surface layer (< 3 m), water column stratification was weak and that the use of a two-dimensional hydrodynamic model was reasonable.

Current Patterns

The surface current pattern derived from ADCP in Matarinao Bay on 21 Apr 2010 (Figure 4A) showed that stronger currents situated at the bay mouth, whereas a weaker current was located at the head of the bay. During conditions where the model was only influenced by tides, the strong flow of water going inside the mouth of the bay was being circulated at the middle of the bay where strong eddies were formed. Weak current flow was observed as waters travel to the head of the bay (Figure 4B). The same scenario was seen when wind forcing was added in the model (Figure 4D). In Aug 2010, wind speed was at the maximum of 29 km/h, with an average of 11 km/h. Wind direction corresponded with the southwest monsoon (SWM), with the majority of the wind coming from the southwest.

On the other hand, April 2010 (Figure 4C) simulation showed stronger current flow compared to August 2010 (Figure 4D). Wind speed was at the maximum of 43 km/h and with an average of 19 km/h. Based on the simulation, it was evident that a strong current flow was going inside the bay as shown in the model. Consistent weaker current flow was forming at the head of the bay. Wind direction was influenced by the northeast monsoon (NEM), where most of the wind came from the east.

Weak current flow was also observed at the head of Murcielagos Bay, whereas strong current flow was

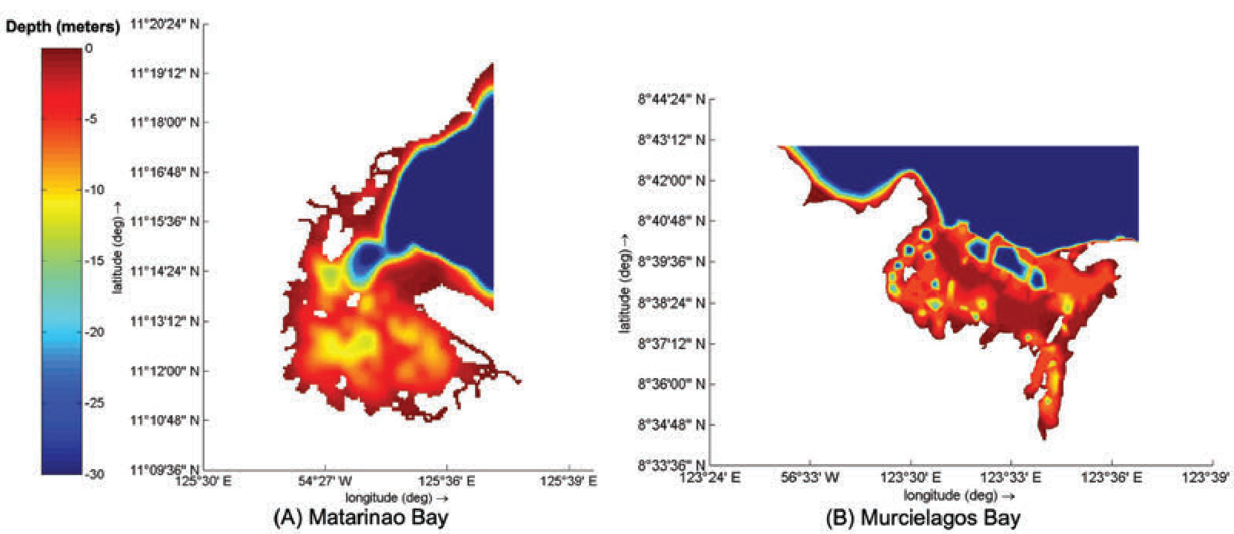

Figure 3. Spatial bathymetric maps of [A] Matarinao and [B] Murcielagos bays.

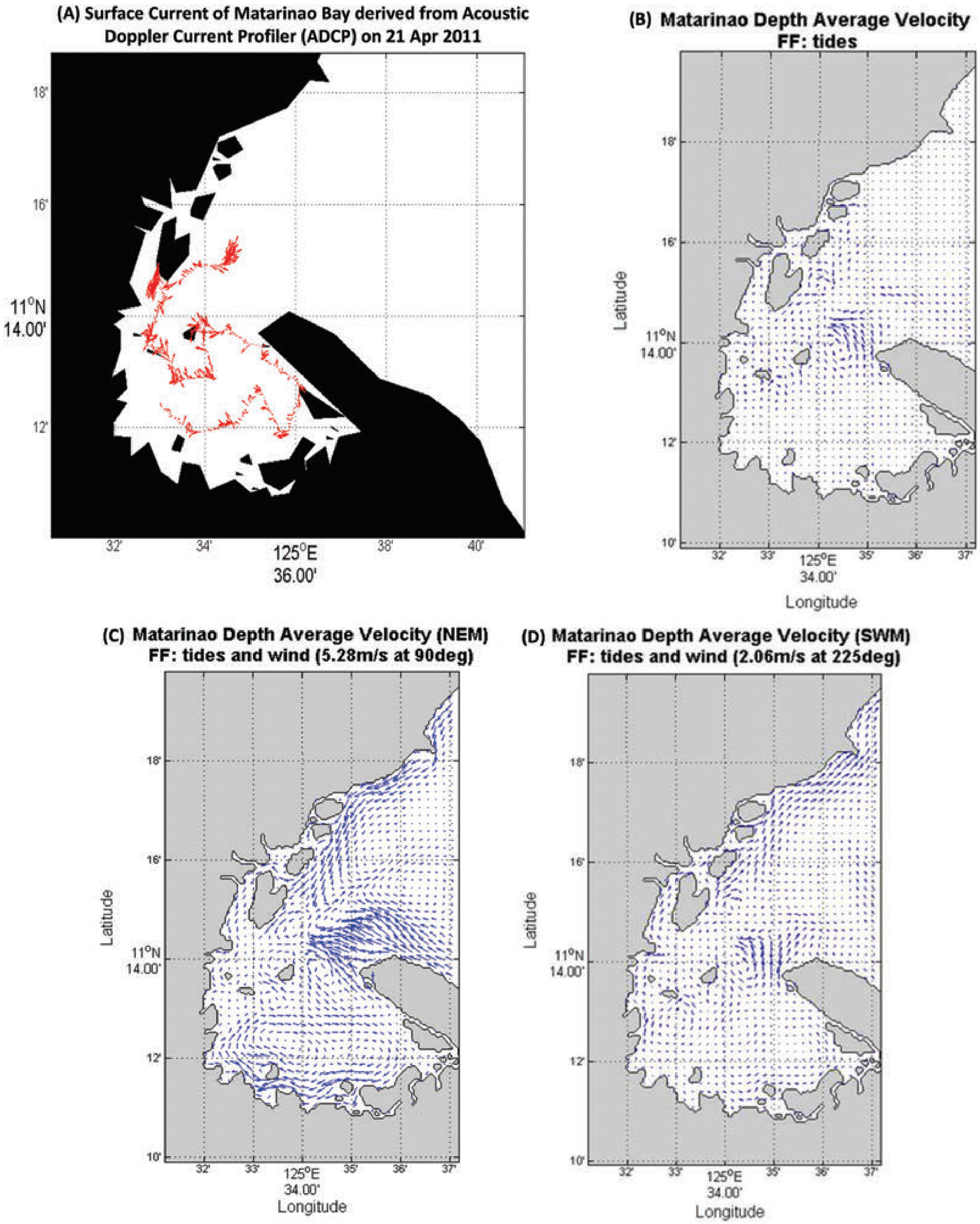

Figure 4. [A] Matarinao Bay surface current derived from ADCP on 21 Apr 2010 and monthly depth-averaged velocity field derived from the model forced by [B] tides alone and depth-average velocity field with the influence of tides and wind in [C] April 2010 (NEM – northeast monsoon) and [D] August 2010 (SWM – southwest monsoon).

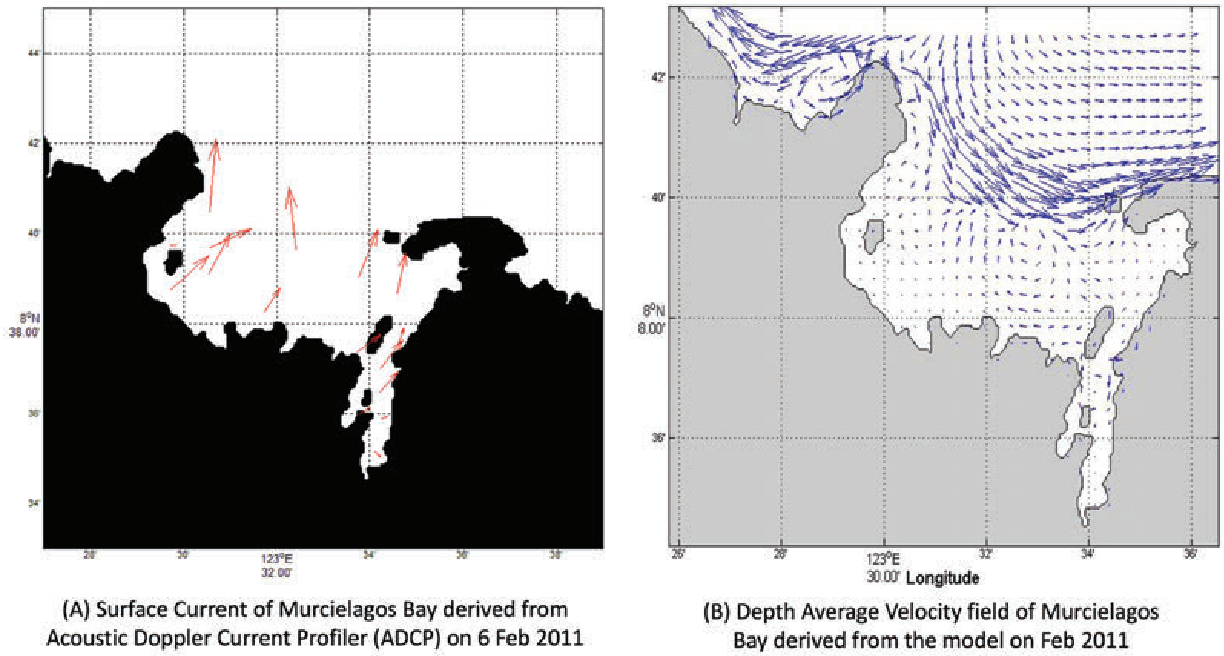

Figure 5. Murcielagos Bay surface current derived from ADCP on 06 Feb 2011 and monthly depth-averaged velocity field forced by tides and wind for the month of February 2011 derived from the model.

observed at the mouth of the bay (Figure 5A). Surface currents derived from the model forced by tides and wind in Figure 5B showed a similar scenario observed in ADCP data. Both surface currents derived from the ADCP and the depth-averaged velocity fields derived from the model illustrated that currents were stronger at the mouth of the bays and weaker at the head of the bays.

Residence Time of Hypothetical Tracer

When forced by tides or in combination with winds, the model-derived water residence time for both Matarinao and Murcielagos bays (Figure 6) showed shorter water residence time at the mouth and longer water residence time at the head of the bays. In Matarinao Bay, water residence time during April 2010 was 5 d shorter compared to August 2010, but both ranged from long (16–23 d) towards the head of the bay and intermediate (8–15 d) to short (0–7 d) at the mouth of the bay. The residence time of Murcielagos Bay in February 2011 was short, mostly with intermediate residence time only at the southernmost tip of the bay.

Pyrodinium bahamense Blooms

A bloom of *P. bahamense* was confirmed in a number of sampling locations in Matarinao Bay for both April and August 2010 samplings. In both sampling periods, high mean cell densities were quantified at the head portion of the bay (Figure 7). In April 2010, *Pyrodinium* cells (Figure 7A) were mostly found towards the western head of the bay; whereas in August 2010, they were found at higher cell densities at the eastern head of the bay (Figure 7B). Mean cell densities were higher in August 2010 at 2.2×10^4 cells/L when water residence time was comparatively longer compared to April 2010 at 8.2×10^3 cells/L. In Murcielagos Bay, a bloom of *P. bahamense* was confirmed during the February 2011 sampling with higher mean cell densities found towards the head of the bay (Figure 7C).

Phytoplankton Community and *Pyrodinium* Bloom in Matarinao Bay

In April 2010 sampling, 46 phytoplankton species were identified belonging to Bacillariophyceae (14 species), Dinophyceae (18 species), and Dictyochophyceae (one species). Dinoflagellates generally dominated in all sampling stations. *Pyrodinium bahamense* comprised approximately 54% of the phytoplankton total abundance, with a maximum cell density of 7.7×10^4 cells/L at the bay's western side. In each station, *Pyrodinium* cells were present at varying cell concentrations (Figure 8A). High cell densities of *Pyrodinium* were quantified in stations MTB16 and MTB5, which were located at the head of the bay (Figure 7A). Other major phytoplankters that contributed to the phytoplankton assemblage include *Protoperidinium* spp., *Ceratium* spp., *Skeletonema costatum* Cleve, *Thalassionema* spp., *Pleurosigma* spp., *Rhizosolenia* spp., and *Chaetoceros* spp.

In August 2010, a nearly monospecific bloom (90% of the phytoplankton assemblage) of *P. bahamense* was observed

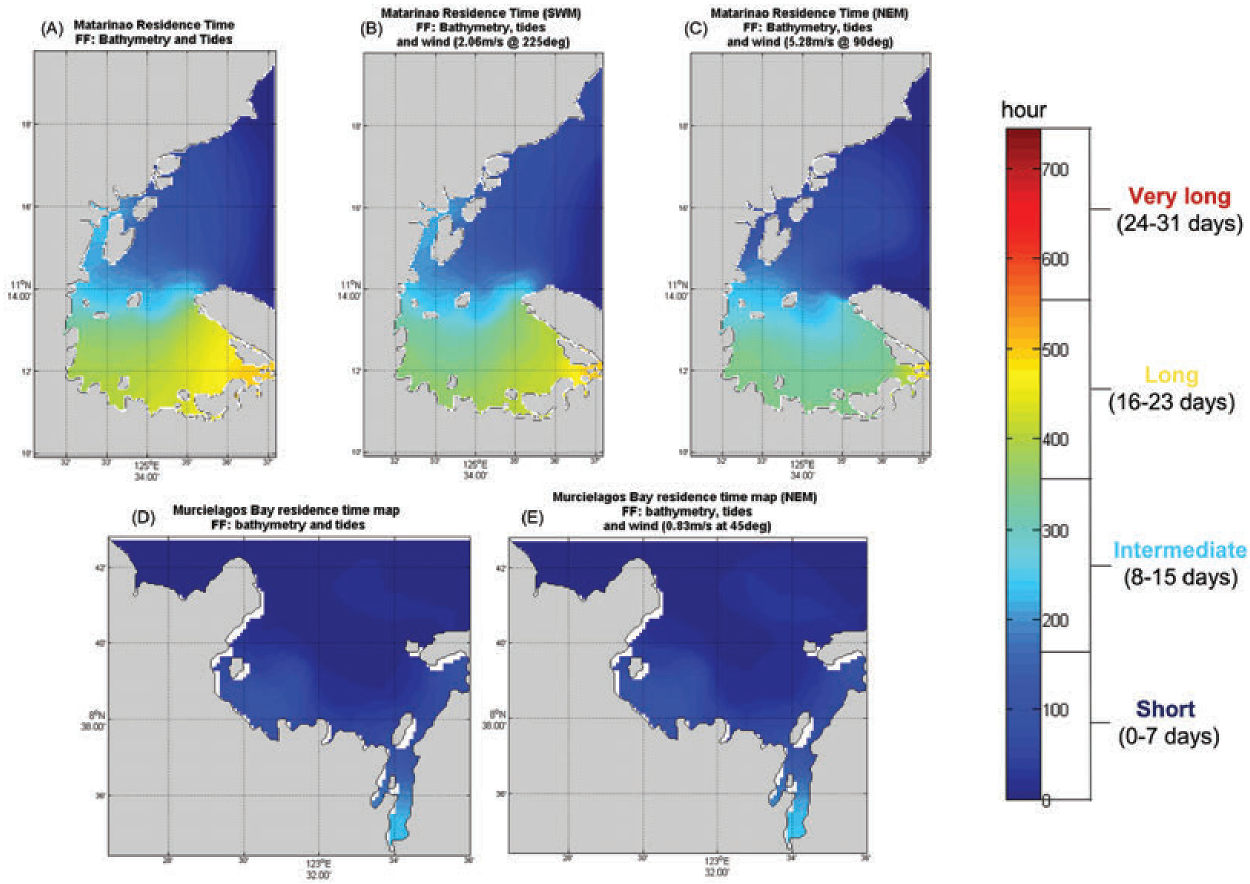

Figure 6. Map of monthly average water residence times in Matarinao Bay initially forced by tides alone (A), for April 2010 having a wind data of 5.28 m/s @90 deg (B), for August 2010 having a wind data of 2.06 m/s @225 deg (C) and in Murcielagos Bay initially forced by tides alone (D), and for February 2011 having a wind data of 0.83 m/s @45 deg (E). The residence time is further categorized by short (0–7 d), intermediate (8–15 d), long (16–23 d), and very long (24–30 d).

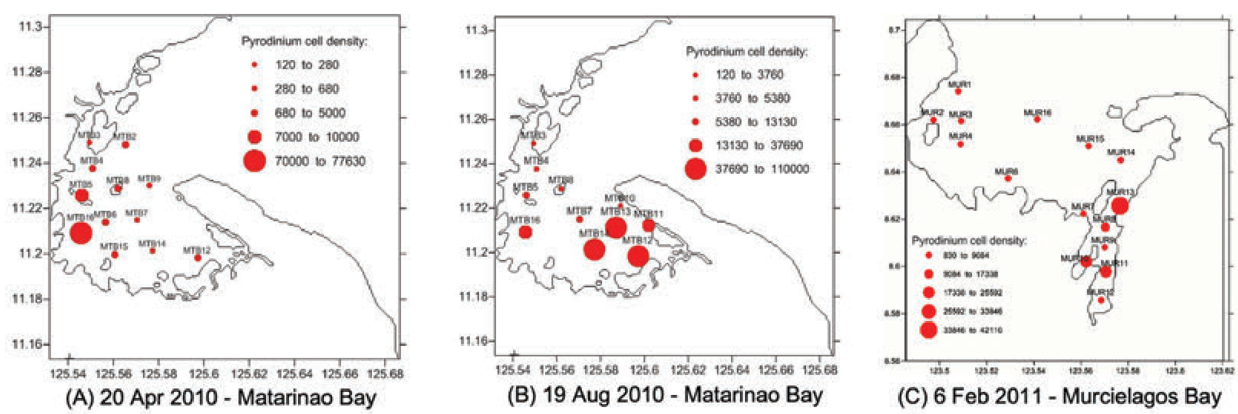

Figure 7. Sampling stations (in red circles) and spatial distribution of *Pyrodinium cells* in Matarinao Bay on (A) 20 Apr 2010 and (B) 19 Aug 2010, as well as in Murcielagos Bay on (C) 06 Feb 2011 at varying concentrations.

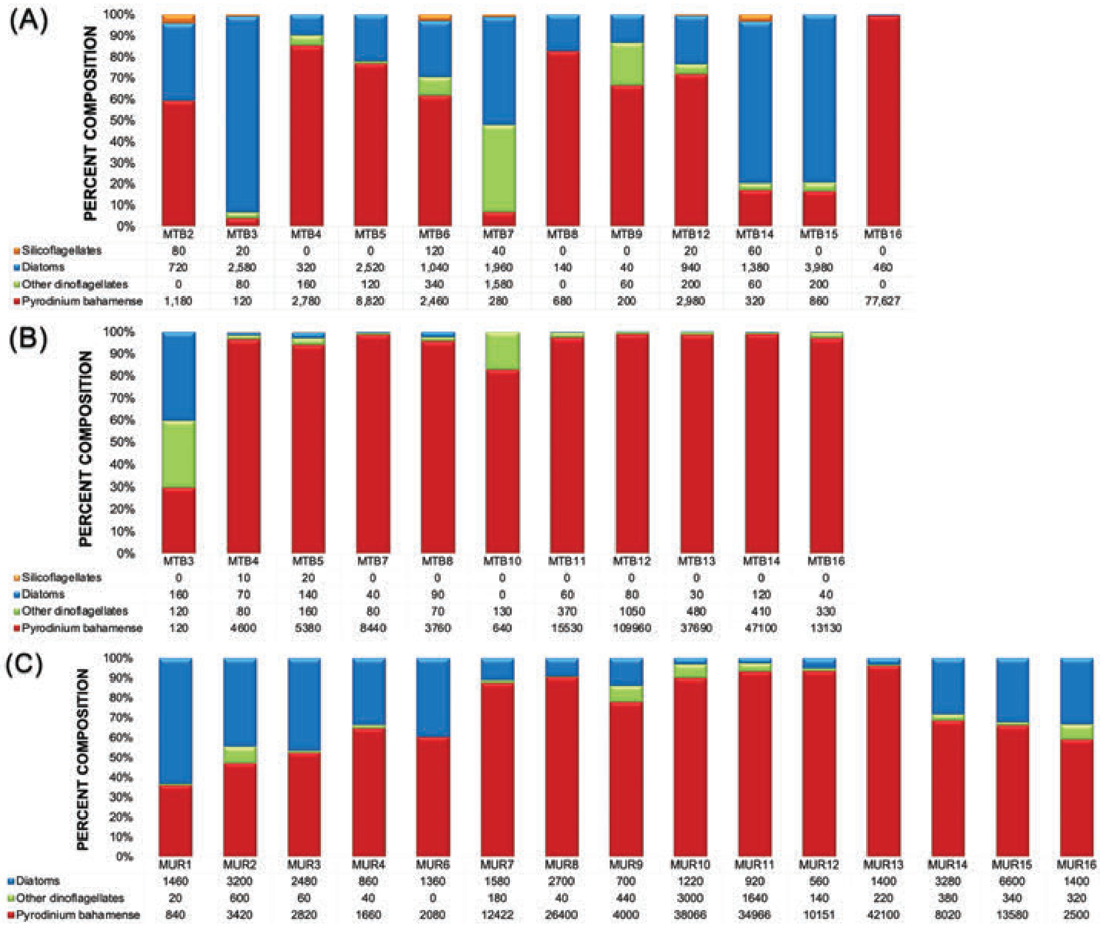

Figure 8. Percentage composition and cell density (cells/L) in Matarinao Bay during (A) 20 Apr 2010 and (B) 19 Aug 2010 samplings, as well as in Murcielagos Bay during (C) 06 Feb 2011 sampling.

in stations mainly in the innermost (head) part of the bay (Figure 8B). High concentrations of *P. bahamense* cells were recorded in stations MTB11, MTB12, MTB13, and MTB14. These stations were located at the innermost part of the bay (Figure 7B). The highest concentration of *Pyrodinium* vegetative cells was found in MTB12 with a cell density reaching 1.1×10^5 cells/L. Stations with low *Pyrodinium* cells were found towards the mouth of the bay. The remainder of the phytoplankters that contributed significantly to the phytoplankton assemblage includes *Protoperidinium* spp., *Ceratium* spp., *S. costatum*, *Thalassionema* spp., *Pleurosigma* spp., *Rhizosolenia* spp., and *Chaetoceros* spp.

Phytoplankton Community and *Pyrodinium* Bloom in Murcielagos Bay

Total phytoplankton cell density is shown in Figure 8C. The highest phytoplankton density was observed in MUR13. Dinoflagellates dominated the phytoplankton community in most stations during the sampling period. Of these groups, *P. bahamense* was the most dominant species accounting for 72% with a mean cell density at 1.3×10^4 cells/L. Although *Pyrodinium* cells were found in all stations, high cell densities were concentrated at the head of the bay (Figure 7C). *Pyrodinium bahamense* comprised more than 90% of the phytoplankton assemblage in this area, with cell densities ranging from 1.02×10^4 cells/L to 3.8×10^4 cells/L. The lowest concentration of *Pyrodinium* was observed in station MUR1 at 840 cells/L. Other potentially harmful phytoplankton found in the bay includes *Gymnodinium catenatum* Graham, *Noctiluca scintillans* Kofoid & Swezy, *Ceratium furca* Claparéde & Lachmann, and *Ceratium fusus* Dujardin.

Correlation of *P. bahamense* and Residence Time

No significant correlation (r = 0.302, $p > 0.05$, n = 12) between the distribution of *P. bahamense* cells and the residence time in Matarinao Bay was detected in April 2010, suggesting a minimal effect of the latter to the former. This was potentially because high counts of *P. bahamense* were at the western head of the bay. In contrast, the area with longer residence time was modeled to be at the southern head of the bay. However, a significant positive correlation (r = 0.713, $p < 0.05$, n = 11) was obtained for Matarinao Bay in August 2010. This implies the modest influence of residence time on the *P. bahamense* cell counts. In particular, a 1-d increase in the residence time in the area during this period will nearly double (1.71 times) the number of algal cell counts, highlighting a potential rapid increase in the toxicity and related risks under long residence time conditions. Indeed, dense *P. bahamense* counts were found in the eastern head of the bay, spatially corresponding to an area with a long residence time. For Murcielagos Bay in February 2011, a significant positive correlation (r = 0.729, $p < 0.05$, n = 15) was also derived, suggesting the potential effect of residence time to *P. bahamense* cell count in the area. Similarly, the dense *P. bahamense* counts were detected at the southernmost head of the bay, with a relatively longer residence time as predicted by the hydrodynamic model.

DISCUSSION

In the Philippines, HABs usually occur within embayments where water flow is restricted (Yñiguez and Ottong 2020). The retention of algal cells in areas of high residence time is a dominant factor controlling blooms of algae (Sastre *et al.* 2013; Ralston *et al.* 2015; Londe *et al.* 2016; Quin and Shen 2019), especially for *P. bahamense*, given its relatively slow growth compared to other algae (Phlips *et al.* 2006). This study highlights the potential role of residence time in allowing for bloom formation and in maintaining these blooms in particular types of embayment and areas within these bays. In both Matarinao and Murcielagos bays, areas with very short residence time – especially towards the mouth of the bays – corresponded well to low counts of *P. bahamense*. Conversely, the heads of the bays characterized by longer residence times generally harbored higher counts of *P. bahamense*. However, statistical correlation analyses do not always show this to be a consistent trend. Nonetheless, in Tampa Bay, Florida, USA, areas with blooms of *P. bahamense* were characterized by long residence times (Corcoran *et al.* 2017). The algae were largely absent in areas with high rates of tidal mixing and river flushing. Modeling the lower James River, Virginia, USA spatial differences in the density of *Cochlodinium polykrikoides* Margalef were also found to be mainly due to differential flushing, HABs were more likely to be initiated in areas with higher residence time (Quin and Shen 2019).

The August 2010 model of Matarinao Bay coincides with the SWM and contains a higher cell concentration of *P. bahamense* than the April 2010 model. This is consistent with observations in Sorsogon Bay, also in the Philippines, where a *Pyrodinium* bloom peak occurred with the onset of the SWM and resulted in a net current that recirculated cells around the bay rather than advecting them outward (Yñiguez *et al.* 2018). While rainfall and warmer temperatures associated with the SWM may contribute to cell proliferation, cell retention due to a longer residence time has a more immediate effect on cell abundance than on other environmental factors (Pannard *et al.* 2008). Current patterns for April 2010 in Matarinao Bay coincide with the NEM forced by stronger wind and current data, resulting in a generally shorter residence time. It shows the consistent circulation of the water within the bay, enabling enhanced flushing and mixing of the water. It is important to note that the R-value correlating the April 2010 residence time model of Matarinao Bay with the *P. bahamense* cell distribution showed no significant correlation, suggesting other factors were at play.

Strong vertical mixing is seen to be a factor in the resuspension of *P. bahamense* cysts (Villanoy *et al.* 2006), especially in shallow bays. Cyst density and location of cyst beds have been shown to play a significant role in the variability of *P. bahamense* abundance (Corcoran *et al.* 2017). In Manila Bay, areas with the highest cyst densities corresponded to the areas where blooms first occurred and were most persistent (Corrales and Crisostomo 1996). It must be noted, however, that for other HAB-causing algae such as *Alexandrium fundyense* Balech (Ralston *et al.* 2015) and *C. polykrikoides* (Quin and Shen 2019), cyst distribution was less of a factor in blooms, whereas cell retention was a more significant influence on bloom development. There is no available information on the presence or location of cyst beds at both Matarinao Bay and Murcielagos Bay. Thus, further studies on this matter will be needed to verify the relative roles of cyst beds and vertical mixing in local blooms within these two bays.

The prevailing wind direction in smaller embayments such as Matarinao Bay must also be considered as the concentration of *P. bahamense* cells towards the eastern head of the bay corresponds directly with the wind coming from the west (90 degrees). Bloom simulations in Manila Bay showed that cells were almost always advected along the wind direction (Villanoy *et al.* 2006). The direct and instantaneous effect of advection may have been a major factor during the phytoplankton sampling on 20 Apr 2010.

Previous studies conducted in other Philippine embayments showed that blooms of *Pyrodinium* were triggered by the transition from dry to rainy conditions, resulting in increased nutrient inputs and a more stratified water column (Villanoy *et al.* 2006; Yñiguez *et al.* 2018;

Yñiguez and Ottong 2020). For example, the broader dynamics of *Pyrodinium* blooms in Sorsogon Bay have been investigated by Yñiguez *et al.* (2018), considering both physical and biological factors. Further studies in Matarinao and Murcielagos bays should consider other environmental parameters such as rainfall, nutrient input, and the algae life cycle. It is further recommended that a time series analysis be done with frequent data sampling to account for the rapid replication rate of *P. bahamense* and possible changes in wind and current patterns.

CONCLUSION

This study provides a wealth of baseline information on the physical characteristics of two little-studied embayments in the Philippines that suffer from HABs. Detailed bathymetry for both Matarinao and Murcielagos bays has been established, along with snapshots of salinity profiles, current patterns, phytoplankton communities, and the distribution *of P. bahamense*. Using representative data, hydrodynamic models were derived, showing that Matarinao and Murcielagos bays are divided into two distinct areas – the mouth characterized with stronger current flow and the bay head area with slower current speeds. Based on the simulations, longer residence time was evident at the head of the bays, which corresponded to areas that showed higher concentrations of *P. bahamense*. While there is some correlation between residence time and the spatial distribution of *P. bahamense* cells, other factors such as cyst location and wind may also play a significant role. In Matarinao Bay, simulations also indicated longer residence times during the SWM. Advection of *Pyrodinium* cells out of the bay may decrease the potential for cells inside embayments to increase to bloom concentrations.

While it is very difficult to measure residence time directly, these hydrodynamic models provided simulated residence time information based on the best available data. Useful insights were also derived when residence time was correlated with field data on phytoplankton cell counts.

The utility of the hydrodynamic models extends beyond the field of HABs. The residence time maps are valuable tools for coastal zone management. Mariculture sites should consider both the retention of their generated nutrients and the flushing of pollutants from landward sources, depending on the culture system and commodity being reared. Domestic and industrial wastewater outfalls should ideally be situated away from areas with high residence time. Seasonal variations should also be considered to account for potential effects on local HABs.

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STATEMENT ON CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

AZANZA R, TAYLOR M. 2001. Are *Pyrodinum* Blooms in the Southeast Asian Region Recurring and Spreading? A View at the End of the Millennium. AMBIO: a Journal of the Human Environment 30: 356-364.

CORRALES AR, CRISOSTOMO R. 1996. Variation of *Pyrodinium* cyst density in Manila Bay, Philippines. In: Harmful and Toxic Algal Blooms. Yasumoto T, Oshima Y, Fukuyo Y eds. IOC of UNESCO, Paris. p. 181–184.

CORCORAN AA, WOLNY J, LEONE E, IVEY J, MURASKO S. 2017. Drivers of phytoplankton dynamics in old Tampa Bay, FL (USA), a sub estuary lagging in ecosystem recovery. Estuarine, Coastal and Shelf Science 185: 130–140.

DU J, SHEN J. 2016. Water residence time in Chesapeake Bay for 1980–2012. Journal of Marine Systems 164: 101–111.

LIMOGES A, DE VERNAL A, RUIZ-FERNÁNDEZ AC. 2015. Investigating the impact of land use and the potential for harmful algal blooms in a tropical lagoon of the Gulf of Mexico. Estuarine, Coastal and Shelf Science 167: 549–559.

LONDE LR, NOVO EMLM, BARBOS C, ARAUJO CAS. 2016. Water residence time affecting phytoplankton blooms: study case in Ibitinga Reservoir (São Paulo, Brazil) using Landsat/TM images. Brazilian Journal of Biology 76: 664–672.

MAGNO MM. 2005. Estimation of entrainment potential in Philippine coastal waters: the physical consequence of island wakes and eddies [MS Thesis]. University of the Philippines Diliman. Quezon City, Philippines. 136p.

OMURA T, IWATAKI M, BORJA VM, TAKAYAMA H, FUKUYO Y. 2012. Marine Phytoplankton of the Western Pacific. Kouseisha Kouseikaku Co., Ltd., Tokyo. 160p.

PANNARD A, CLAQUIN P, KLEIN C, LE ROY B, VÉRON B. 2008. Short-term variability of the phytoplankton community in coastal ecosystem in response to physical and chemical conditions' changes. Estuarine, Coastal and Shelf Science 80: 212–224.

PHLIPS EJ, BADYLAK S, BLEDSOE E, CICHRA M. 2006. Factors affecting the distribution of *Pyrodinium bahamense* var. *bahamense* in coastal waters of Florida. Marine Ecology Progress Series 322: 99–115.

QUIN Q, SHEN J. 2019. Physical transport processes affect the origins of harmful algal blooms in estuaries. Harmful Algae 84: 210–221.

RALSTON DK, BROSNAHAN ML, FOX SE, LEE K, ANDERSON DM. 2015. Temperature and residence time controls on an estuarine harmful algal bloom: Modeling hydrodynamics and *Alexandrium fundyense* in Nauset Estuary. Estuaries Coast 38: 2240–2258.

SASTRE MP, SÁNCHEZ E, FLORES M, ASTACIO S, RODRÍGUEZ J, SANTIAGO M, OLIVIERI K, FRANCIS V, NÚÑEZ J. 2013. Population fluctuations of *Pyrodinium bahamense* and *Ceratium furca* (Dinophyceae) in Laguna Grande, Puerto Rico, and environmental variables associated during a three-year period. Revista de Biología Tropica 61: 1799–1718.

TOMAS CR. 1997. Identifying marine phytoplankton. San Diego: Academic Press. 858p

VILLANOY CL, AZANZA RV, ALTEMERANO A, CASIL AL. 2006. Attempts to model the bloom dynamics of *Pyrodinium*, a tropical toxic dinoflagellate. Harmful Algae 5: 156–163.

YAMAJI I. 1979. Illustrations of marine plankton of Japan. Osaka: Hoikusha Publishing Company. 537p.

YÑIGUEZ AT, LIM PT, LEAW CP, JIPANIN SJ, IWATAKI M, BENICO G, AZANZA RV. 2021. Over 30 years of HABs in the Philippines and Malaysia: what have we learned? Harmful Algae 102: 101776.

YÑIGUEZ AT, MAISTER J, VILLANOY CL, DEAUNA JD, PEÑAFLOR E, ALMO A, DAVID LT, BENICO, GA, HIBAY E, MORA I, ARCAMO S, RELOX J, AZANZA RV. 2018. Insights into the dynamics of harmful algal blooms in a tropical estuary through an integrated hydrodynamic-*Pyrodinium*-shellfish model. Harmful Algae 80: 1–14.

YÑIGUEZ A, OTTONG Z. 2020. Predicting fish kills and toxic blooms in an intensive mariculture site in the Philippines using a machine learning model. Science of The Total Environment 707: 136–173.