THE RESIDENCE TIME OF SEAWATER IN THREE BAYS OF VIEQUES, PUERTO RICO

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INTRODUCTION

The residence time of a body of water plays an integral role in defining the presence or absence, and to a degree, population of the dinoflagellate *Pyrodinium bahamense* var. *bahamense* (Seliger et al, 1970; Monsen et al. 2002; Badylak et al.2004; Phlips et al, 2006). Bays with longer residence times (days and longer) can accumulate the bioluminescent organism *Pyrodinium* in high concentration. In this study I show that the residence time of Puerto Mosquito, Puerto Ferro and possibly Bahia Tapon are long enough to support *Pyrodinium* populations.

BACKGROUND

The three bays of this study are located on the south side of Vieques no more than two miles from one another. Vegetation, water temperature, salinity and numerous other factors are fairly similar between the bays. There are three critical parameters which vary between them: openness to the ocean, depth, and volume. Puerto Mosquito was the calmest of the three bays as a result of its long mouth which bent nearly 90 degrees before entering the main body of the bay, slowing any water entering. Depth varied from about 3 feet to 12-14 feet. Volume was 1.33 million cubic meters. Puerto Ferro was far more active, with a mouth that was hardly smaller than the bay itself, which directly faced the ocean. Within the confines of the bay, wave action occurred. Depth was the deepest of any of the bays going as deep as 30 feet. Volume was 2.14 million cubic meters. Bahia Tapon was the shallowest of the bays never exceeding 6 feet in depth. The mouth faced the ocean directly like PF but was significantly narrower than the bay itself. This caused great contrast in BT with the mouth and center of the bay far more turbulent than around the far perimeters. Volume was 0.20 million cubic meter.

METHODS

Tidal cycle and water temperature measurements were taken with Solinst Level Loggers (SLL) deployed in seven locations within the three bays in June 2006 (Fig. 1). YSI multiparameter long-term monitoring sondes were deployed between January and June 2006 in various points within the three bays. The sondes recorded tidal cycles, temperature, salinity, pH and dissolved O_2. Additional salinity and temperature measurements were taken the nights of June 26 and 27, 2006 at 11 locations within PM and PF, using a salinometer. The locations of the above measurements/instruments were recorded using a Thales MobileMapper Pro GPS.

Processing of SLL and Sonde data was accomplished using Microsoft Excel. GPS data was processed in ArcMap. There was no post processing of GPS data points.

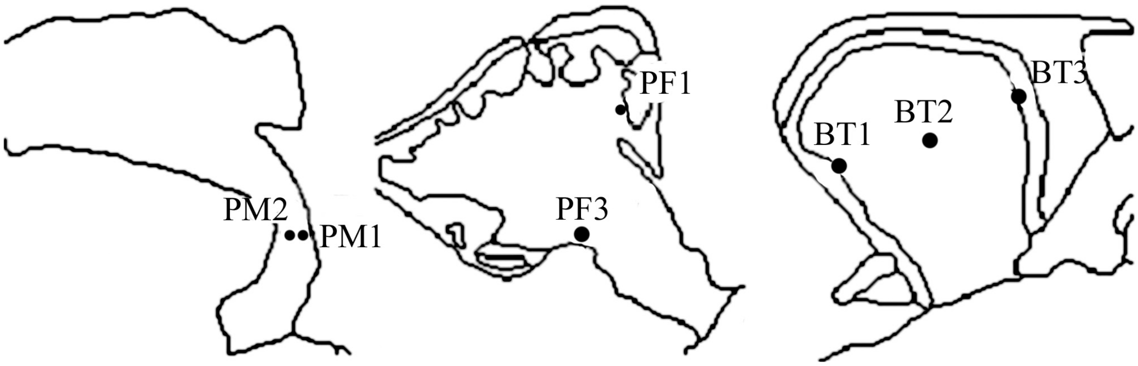

Figure1. Solinist Level Logger deployment points for tidal cycle and temperature measurements.

RESULTS

Tidal heights as measured by pressure transducers in SLL and YSI Sondes matched with less than a 0.5 inch deviation. Tidal cycles occurred once daily and with such cycling following longer 14 day lunar phases in which tidal ranges were as great as 18 inches on January 28 and as little as 4 inches on May 8th. The average tidal range over the period of January to June 2006 was 12 inches ±1 inch. The tidal range on a given day between the three bays were identical (Fig 2.)

Annual rainfall in the vicinity of the bays is 28.4 inches/year, based on USGS Camp Garcia rainfall data from 1992 to 2006, omitting the years 1997, 1998, and 2003 in which the data set was incomplete. Annual evaporation is approximately 70.9 inches (Soler-Lopez et al, 2005).

Salinity of the ocean, based on salinometer readings, averaged 34.6 ±0.1 ‰. Within Puerto Mosquito average salinity was 35.5‰ and within Puerto Ferro it matched the oceans salinity. Salinity data for Bahia Tapon did not exist.

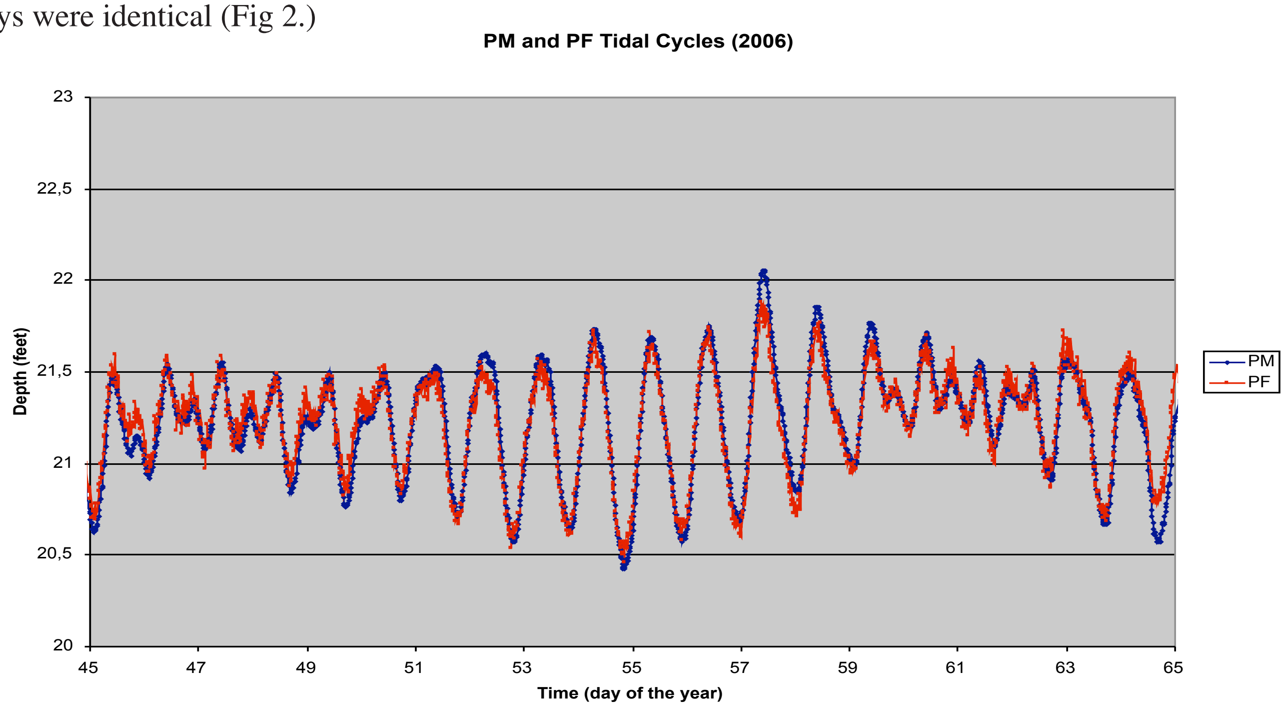

Figure 2. Tidal cycling of Puerto Mosquito and Puerto Ferro identical. Tides occur once daily and follow a longer 14 day lunar cycle.

DISCUSSION

Bay water residence times is based on the speed in which water is added and subtracted from a system. In the three bays of Puerto Rico the rise and fall of the tides is the main mechanism of exchanging water. Rain is less than 1% of the average 12 inch tidal rise such that direct rainwater input, overland, stream and groundwater flow is negligible when calculating residence times. Records of rainfall history, during times of significant rains storms, show that neither salinity nor temperature were visibly affected.

The efficiency in which tidal action flushes a bay ranges from 50% and less, which would mean that half or more of the flushed water or tidal prism reenters the bay in the following tidal cycle to up to 70% efficiency in which only 30% of the flushed water reenters or even greater (Garcon et al 1986). Factors which affect the efficiency rate include time between tides, i.e. once or twice/day, strength of currents outside bay mouth which transport flushed water away, and density stratification of flushed water. In table 1 calculated residence times based on 70% and 50% efficiency flushing rates are given.

The residence time can be better understood by comparing the elevated salinity of the bays to that of the surrounding ocean. As bay water evaporates salinity is elevated. For salinity to be in dynamic equilibrium the salinity increase due to evaporation must be equally offset by a salinity lowering resulting from less saline ocean water mixing with the bay. Bays with longer residence times will have greater salinity differences.

To use this technique, it is necessary to know the evaporation rate. I estimated the rate using the Soler-Lopez et al. (2005) formula. Their formula is based on evaporation rates in coastal areas of Puerto Rico, which exhibit a linear relationship inversely related to annual rainfall. With 28.4 inches of rain per year evaporation rate is estimated at 70.9 inches. Average daily evaporation minus precipitation is 0.1164 inches/day. Based on such an evaporation rate, the 0.9‰ salinity elevation in PM would occur with an approximately13.50 day residence time.

$S^*=[(S_1)(V_1)+(S_2)(V_2)]/(V_1+V_2)$
S^* is salinity of mixed water, S_1, V_1, S_2, V_2 corresponds to the salinity and volume of water bodies 1 and 2.
With a 0.1164 inches/day evaporation rate the total amount of PM water lost due to evaporation in one day is: (0.1164 inches)(1 meter/39.37 inches)(913236.24 m2)= 2700 m3
The new salinity would be: $S^*=[(0.0355)(1333747)+(0)(-2700)]/(1333747-2700)= 0.035572$. That is a salinity elevation of 0.07 ‰. For salinity to remain in a steady state, the tidal flushing with ocean water with its 34.6 ‰ salinity would have to act in the negative direction. The amount of sea water required to this is:

$0.0355=[(0.035572)(1333747)+(0.035572)(-X)+(0.0346)(X)]/(1333747-X+X)$
$X=98796 m^3$

This volume of sea water is 35.5% of the tidal cycle volume: 98796/278537=.355 This means that the tidal cycle is 35.5% efficient, giving a bay water residence time of 13.50 days: $1333747=(0.3048)(913236)(0.355)(X)$
$X=13.50$

	Volume (m^3)	Surface Area (m^2)	Res. Time, days (70%)	Res. Time, days (50%)
Puerto Mosquito	1333747,4	913236,2	6,8	9,6
Puerto Ferro	2143843,4	958739,9	10,5	14,7
Bahia Tapon	199428,1	334044,9	2,8	3,9

Table 1. Bay Water Residence Time based on tidal cycle as exclusive flushing mechanism.

The lack of salinity difference in PF indicates a rapid flushing in opposition to previous findings. The difference could be due a number of possible factors, such as the margin of error of the salinometer, the incoming tide which would bring in less saline water, or a possible build up of more saline surface waters in a calm area of Ferro like that observed by Seliger in Oyster Bay, Jamaica.

This salinity difference method to calculate bay water residence times is far more rudimentary than the simple tidal cycle method. It relies on average evaporation and precipitation rates, when the average rarely occurs. In the week leading up to the taking of salinity measurements, rain fell on five of the days with a total accumulation of nearly 3 inches. As such, residence times were skewed in the negative (shorter) direction. This technique with more control could give better results though effort would be much better focused on a dye tracing method to refine residence time further.

In a dye tracer residence time study, dye would be injected in the water and samples would be taken from various locations within the bay over a period following the original injection, which for these bays I would recommend two weeks. There are many tracer methods and ways of running such an examination. One such method is well outlined by Robert Houghton et al. 2002 of the Lamont-Doherty Earth Observatory, in "Dye Tracer Experiments in Jamaica Bay, which is accessible on their ldeo.columbia.edu website. In their study they found a relatively low, 50% flushing efficiency. One such cause is the twice daily tides, which decrease the time for flushed water to be removed from the area.

CONCLUSION

The residence time of the three bays are likely as short as if not shorter than the estimates based on 50% efficiency. Those residence times are: PM 9.6 days, PF 14.6 days and BT 3.9 days. The longer residence time of PF compared to PM indicates that residence time is not a factor in the lack of *Pyrodinium bahamense* var. *bahamense* in PF. The wide mouth of PF and deeper depth likely shortens residence time less than the 14.6 days, as water is flushed more effectively with stratification possibly creating efficient flushing loops. The short residence time of water in BT may prevent accumulation of dinoflagellates depending on life cycle length. Based on three SLL data points and two Sonde points in BT it appears that the bay is well mixed, without any certain area accumulating water with a residence time significantly longer than that of the whole bay. If more accurate bay water residence times are needed, a die tracer experiment like that outlined by Houghton, would be a useful next step.

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