Numerical modeling of tidal and wind-driven circulation in the Meso-American barrier reef lagoon, Western Caribbean

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Abstract - **The Meso-American Barrier Reef System (MBRS) is the second longest reef system in the world and the longest in the western hemisphere. Several promontories along the Belize barrier reef, including Gladden Spit, are known to attract large numbers of groupers and snappers, among other fishes, for spawning during set times of the year, mostly Jan-Jun. The fertilized eggs are buoyed to the surface and then transported by wave drift and wind-driven currents. Analysis of the circulation patterns within the lagoon is laying the groundwork for a better understanding of the transport of eggs, larvae, nutrients, pollutant, and sediment, which in turn will help coastal managers to conserve critical habitats. The numerical model implemented for the analysis of the circulation in the MBRS lagoon is the Surfacewater Modeling System (SMS v 8.0). Five simulation cases were executed, each 35 days long, to analyze the circulation within the lagoon under varying hydrometeorological conditions. The results from the five simulations show that the circulation in the MBRS lagoon is driven by trade winds, mostly trade winds, modified by tides, with little residual flow due to runoff. Under the influence of the trades, strong flows occur near Gladden Spit, initially westward into the lagoon and then southward.**

I. INTRODUCTION

Coastal lagoons are shallow water bodies, oriented parallel to the coast, and connected to the ocean through one or more inlets [1]. Restricted coastal lagoons have two or more inlets. Their tidal circulation is well-defined, and winds play an important role in the water exchange [1]. The circulation inside a lagoon can be inferred either through direct measurements or through numerical models. The high cost and effort involved in measurements prohibits the deployment of instruments at more than a few spatial locations. On the other hand, numerical models are best suited to analyze the circulation because of the amount of spatial and temporal information they can yield. Once a model is verified to realistically reproduce the observed water levels and currents, it can be used to simulate the circulation patterns under different conditions of hydrometeorological variability. The numerical model thus serves as a powerful tool where field data is sparse and information is needed on large spatial and temporal scales.

Finite element models are increasingly used for shallow water circulation analyses because of the ease with which the complex geometry can be approximated [2]. As examples, recent implementations of two-dimensional finite element models include a study of hydrodynamic controls on multiple tidal inlets in Ria Formosa, Portugal, [3] and a study of tidal circulation in the Gulf of Kutch, India [4].

The Meso-American barrier reef lagoon extends for 335 km from Bahía de Chetumal (Mexico) in the north to Bahía de Amatique (Guatemala) in the south (Fig. 1). It is bordered by Mexico and Belize in the north and west, Guatemala in the south, and the 220 km long Meso-American barrier reef in the east. The barrier reef is the second longest reef in the world and the longest in the western hemisphere [5]. The lagoon covers an area of 10581 km^2 and is situated between 87^o - 88^o W and 15^o 30' – 19^o N. The depths in the northern part of the lagoon average 2 to 3 m with a maximum of 6 m. The southern part reaches a maximum depth of 65 m in the Gulf of Honduras south of the Sapodilla Cays but has an average depth of 15 m. Seaward of the reef, depths plunge steeply from a few meters to 1000 m in less than 3 km. Bahía de Amatique lies immediately north of the Cayman Trough, which is the tectonically active boundary of the North American and the Caribbean plates [6]. The trough continues as the Motagua-

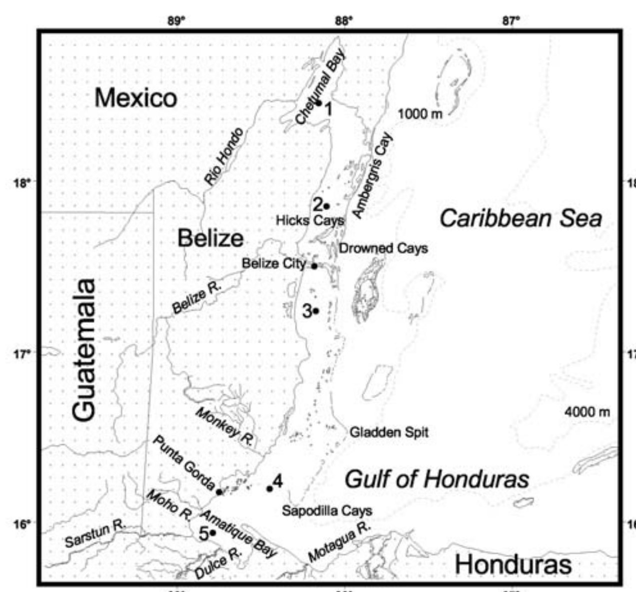

Fig. 1. The Belize barrier reef and lagoon. 1, 2, 3, 4, and 5 are the locations for which results are discussed.

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Polochic fault into Guatemala.

The MBRS region has a tropical savannah climate in the northern half and a tropical rainforest climate in the south [7]. The average summer air temperature is 27 °C and the average winter temperature is 24 °C. Rainfall follows a strong north-south gradient. In the north, the annual rainfall is 1200 mm [8], but rainfall in the southern region is between 3000 and 4000 mm yr^{-1}. Numerous rivers empty into the lagoon along its entire length, the major ones being Hondo and Belize in the north, and Monkey, Moho, Sarstún, and Dulce in the south. The concentration of rivers and the higher rainfall in the south leads to an increased outflow of freshwater in the southern part of the lagoon. The combined discharge of the rivers into the lagoon is more than 1000 m^3 s^{-1}, with more freshwater entering the southern part of the lagoon (606 m^3 s^{-1}) [9].

The dynamic forcing on the lagoon are due to tides and winds. The tide is mixed mainly semidiurnal with a mean range of 0.20 m [10]. Even though the MBRS lagoon is a microtidal system, tidal currents can play an important role in the transport within the lagoon. A southward flowing current with speeds of 0.10-0.20 m s^{-1} prevails along the seaward edge of the barrier reef [11]. Trade winds blow throughout the year from the east and northeast in southern Belize, with an average wind speed of 3 m s^{-1}. Cold air (northers) from continental North America blows from December to March, with periodical gusts of 5-8 m s^{-1}.

We decided to implement a two-dimensional finite element model to analyze the tidal circulation in the MBRS lagoon. Thus, the objectives were to study the net circulation under different hydrometeorological conditions, to determine the time series of water levels and velocities at different sections within the lagoon, and to obtain estimates of the volume fluxes into the lagoon through the reef channels.

II. MODEL DESCRIPTION AND IMPLEMENTATION

To model the circulation in the Meso-American barrier reef lagoon, we chose the Surfacewater Modeling System (SMS v8.0) (http://www.bossintl.com). SMS encompasses the RMA2 code of the Army Corps of Engineers. SMS is a 2D, depth-averaged, finite element, tidal, hydrodynamic model, with additional pre- and post-processing capabilities. RMA2 was initially developed by Resource Management Associates and later on modified by the US Army Core of Engineers' Waterways Experiment Station (http://chl.wes.army.mil/software/tabs/models.htp).

RMA2 computes water surface elevations and horizontal velocity components for subcritical free-surface flow. The model solves a set of finite element differential equations for turbulent flow with friction calculated using the Manning's parameterization, turbulence characterized by eddy viscosity coefficients, and includes wind stress and the Coriolis force. The x and y component momentum acceleration terms and the continuity equation are

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right)+\frac{gun^2}{\left(1.486h^{1/6}\right)^2}$$
$$+\left(u^2+v^2\right)^{1/2}-\tau v_a^2\cos\psi-2h\varpi\upsilon\sin\phi=0, \tag{1.1}$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right)+\frac{gvn^2}{\left(1.486h^{1/6}\right)^2}$$
$$+\left(u^2+v^2\right)^{1/2}-\tau v_a^2\cos\psi+2h\varpi\upsilon\sin\phi=0, \tag{1.2}$$

and

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0. \tag{1.3}$$

where h is depth, u and v are component velocities along the x and y Cartesian coordinates, respectively; t is time; ρ is water density; E is eddy viscosity; g is gravity (9.81 m s^{-2}); a is bottom elevation; n is Manning's roughness; τ is wind stress; V_a is wind speed; ψ is angle towards the direction of wind, counter-clockwise with 0^o on the positive x-axis; ω is the rate of earth's angular rotation; and Φ is latitude.

Equations (1), (2), and (3) are solved by the finite element method using the Galerkin method of weighted residuals [12]. The elements used in the mesh for the present study are mostly two dimensional triangles, with very few quadrilateral elements. The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson nonlinear iteration [12].

The eddy viscosity (E) is used to parameterize the turbulence characteristics. In RMA2, E can be specified prior to running the model or dynamically calculated from the equation $E = \rho u dx/P$ kg m^{-1} s^{-1}, where dx is the elemental length and P is the mesh Peclet number. P is similar to the mesh Reynolds number, but depends on the numerical method employed [13]. The value of P is between 15 and 40.

In shallow areas and around islands, the land is often exposed at low tide and submerged at high tide. The model is capable of handling these wet-dry areas efficiently, using the "marsh porosity" tool [14]. The residual water volume existing on a partially wet element is calculated by vertically integrating a wetted area curve associated with each node of the element. The model holds all partially wet elements for computation until all the associated nodes of the elements go dry [14].

A. Digitizing and mesh construction

We developed a mesh for the domain of the lagoon model based on digitization of the National Imagery and Mapping Agency bathymetric charts 28162, 28167, and 28190, recognizing that the available bathymetric information north of Belize City is of very poor quality. The land borders for the mesh are the entire coast of Belize, and part of the coasts of Mexico and Guatemala. The open water boundary on the east was initially set seaward of the barrier reef at the shelf break. However, as the depths immediately adjoining the reef were an order of magnitude greater, and the model became unstable, we used the barrier reef as the seaward model boundary.

There are 24 channels dissecting the barrier reef through which tides and meteorological processes exchange water. The reef is treated as a solid boundary. Most of the channels are of short length, with only four channels wider than 10 km. The total width of all 24 channels is 153 km, and the combined width of the 20 smaller channels is only 28 km. Islands inside the lagoon were also digitized as solid boundaries.

The bathymetry changes rapidly in the middle of the lagoon. To the south of Belize City, the lagoon is wide and relatively deep, with few obstructions. To the north, the depths are shallow with many islands. The group of islands (Drowned Cays and Hicks Cays) immediately to the north of Belize City acts as a significant hindrance to the through-flow between the northern and southern sections of the lagoon. Also, there are only two ocean channels in the northern half of the lagoon and most of the area is enclosed by the land boundaries of Chetumal Bay and Ambergris Cay, suggesting very limited water exchange.

The model mesh was constructed using the mesh module. The element front width was adjusted to be less than 300 which minimizes the number of equations involved in each iteration. The mesh consists of 9,321 elements and 19,432 nodes with a front width of 273 (the number of equations in the solution matrix that are assembled simultaneously). The average element area measures 1.14 km^2. The digitized contours were interpolated by the inverse distance weighted method using the nearest 16 points in each quadrant. Water depths in the model vary from 0 m to 51 m. The final model applies a viscosity of 300 kg m^{-1} s^{-1} and Manning's n values of 0.02 (for depths less than 2m) and 0.04 (for greater depths).

B. Boundary Conditions

The barrier reef lagoon is an extremely data poor area. We know of only three sets of water level time series on the boundaries and three sets of water level data inside the lagoon. We used the reef boundary data to force the model and the water level data from the interior lagoon locations to verify the simulation results. The boundary water level data were from Lighthouse Reef (27 Aug - Nov 2002), Gladden Spit (06 Dec 1998 - 02 Apr 1999), and Sapodilla Cays (23 Jan - 21 May 2000). Harmonic analysis was performed on the water level data and the amplitudes and epochs of the significant constituents at the 95% significance level were extracted. These harmonic constituents were used to create 35-day time series of water levels (Table 1).

TABLE 1: HARMONICS OF THE MEASURED TIDE AT THE THREE STATIONS USED AS BOUNDARY CONDITION

Constituent	**Measured tide**		
	Lighthouse	**Gladden**	**Sapodilla**
	ζ (cm) / g (°)	**ζ (cm) / g (°)**	**ζ (cm) / g (°)**
Semi-diurnal			
N_2	2.2 / 67	3.0 / 63	2.5 / 74
M_2	6.5 / 84	6.2 / 82	6.4 / 87
S_2	2.8 / 50	2.5 / 47	1.9 / 51
Diurnal			
Q_1	0.7 / 321	---	0.9 / 302
O_1	2.2 / 346	1.5 / 350	2.5 / 327
K_1	1.9 / 268	3.2 / 265	2.8 / 263

Numerical models typically require a few tidal cycles to stabilize. The required spin-up time was determined from trial and error to be approximately 120h. We determined this by comparing the difference between the 30-day output time series of water level and a series predicted from the harmonic constituents. The comparison revealed no significant difference between the two series.

C. Mass conservation

Finite element models are notorious for not conserving mass [15]. This is a major concern and we decided to verify that there is no unaccounted-for "leakage" of water through the inlets, which happens if the mesh design is poor [3]. We calculated the volume flux through the 24 channels for a 30 day-simulation run and computed the net flow. Our calculations resulted in a percentage difference of only 0.03%, corresponding to an inflow of 24 m^3 s^{-1} over 30 days. Thus, we are satisfied that there is no significant leakage in the model on the time scale of a month-long simulation.

D. Model calibration and verification

It is necessary to verify whether the model results are comparable to field values before any simulations are executed. For regions where data collection is scarce or almost non-existent, it is impossible to do complete, independent processes of calibration and verification, and the two are hence combined. We were constrained to adopt a combined check of calibrating and verifying the model due to lack of sufficient data sets for the present study. The data available was 27 days measured tidal elevation from Belize City Port which was collected between 06 Feb and 06 Mar 2002. The harmonic constituents from this data set were compared with the harmonic constituents of the model output (Table 2). The tidal amplitudes of the six major constituents show good agreement between observed and modeled data. The agreement is less good with respect to phase, where the modeled constituents lag observed constituents by approximately 15°. A separate spectral analysis indicates almost perfect coherence at diurnal and semidiurnal frequencies. Adjustments are made by refining the mesh in areas with sudden depth changes and by changing the eddy viscosity and Manning's n to achieve as close an agreement as possible between observed and modeled tidal constituents. We anticipate to improve on the calibration with the availability of further field observations in the future.

E. Fluxes through the channels

The channels connect the lagoon to the open ocean; in addition, they facilitate water exchange and transport particulates, eggs and larvae to/from the lagoon. For the lagoon to be in steady state, the inflow through the channels should equal the outflow. This is checked by averaging the fluxes through the channels over 720 h. This method also serves as a check on the model efficiency.

We calculated the flux through each channel averaged over 720 h. When tides are the only forcing, there is a net inflow of 24 $m^3 s^{-1}$. The time taken by the lagoon to go dry under this condition (lagoon volume/cumulative mean flux) is 153 years. We can thus conclude that the model simulation is reasonable. Addition of trades and rivers leads to net outflows of 43 and 44 $m^3 s^{-1}$ respectively. Inclusion of river flow leads to a slight increase in inflow in the channels south of Gladden Spit and a three-fold increase in outflow in the southernmost channel south of Sapodilla Cays, as compared to tidal forcing alone.

TABLE 2: COMPARISON OF MEASURED AND MODELED HARMONICS OF THE TIDE AT BELIZE CITY

Constituent	**Measured tide**	**Modeled tide**
Semi-diurnal	**ζ (cm) / g (°)**	**ζ (cm) / g (°)**
N_2	3.5 / 76	2.5 / 86
M_2	8.0 / 84	7.8 / 100
S_2	3.2 / 36	3.2 / 67
Diurnal		
Q_1	1.6 / 6	0.9 / 318
O_1	3.2 / 332	2.4 / 348
K_1	2.3 / 279	2.3 / 268

However, when the trades are included, the fluxes through the larger channels increase by several orders of magnitude. The southernmost channel compensates for the inflow that occurs through most of the other channels with a huge outward flow. The flux calculations show that under the influence of the trades, 21 channels experience inflow of oceanic water whereas under the influence of the tides alone, only 12 channels transport water into the lagoon. This has implications for larval transport because spawning takes place under windy conditions thereby creating the potential to move the larvae into the lagoon.

III. SIMULATION MODELING AND DISCUSSION

To analyze the circulation in the lagoon under varying hydrometeorological conditions, five simulations were run, each for a 35-day period. Hourly tidal velocities and water elevations were extracted at five locations within the lagoon for further analysis (Fig. 1). Net circulation was also analyzed to investigate the likely influence of winds and fresh water. The statistics (maximum/minimum water level, maximum/minimum east-west and north-south velocities, net speed, net direction, and kinetic energy) of the five simulations at five locations within the lagoon are given in Table 3. The simulation runs were:

TABLE 3: STATISTICS OF WATER LEVELS AND VELOCITIES AT FIVE LOCATIONS WITHIN THE LAGOON

Lat – Latitude; Lon – Longitude; η – max/min water level (cm); u – max/min east (+) – west (-) velocity (cm s^{-1}); v – max/min north (+) – south (-) velocity (cm s^{-1}); **V** – Magnitude of net speed (cm s^{-1}); D – Net direction (towards °T); S – RMS speed (cm s^{-1}).

	Location 1	Location 2	Location 3	Location 4	Location 5
Lat	18° 30'	17° 48'	17° 19'	16° 31'	15° 57'
Lon	88° 09'	88° 05'	88° 08'	88° 14'	88° 47'
Case #1: Tides at the boundary					
η	8/-1	10/-11	17/-18	19/-16	23/-20
u	0/-0	3/-2	2/-1	5/-5	3/-3
v	1/-1	3/-3	7/-6	10/-13	1/-1
V	0.0	0.1	0.1	0.2	0.0
D	247	164	237	156	156
S	0.2	0.6	1.6	2.5	0.7
Case #2: Tides and trades					
η	6/-3	10/-2	16/-18	19/-16	24/-19
u	1/1	3/-2	17/-22	1/-7	4/-2
v	2/0	2/-3	24/-25	9/-14	1/-2
V	1.4	1.2	6.3	3.3	1.3
D	47	163	175	249	118
S	0.2	0.8	8.1	2.8	0.9
Case #3: Tides, northers, and trades					
η	6/-19	10/-5	16/-23	19/-16	24/-19
u	3/-1	3/-3	17/-26	1/-9	5/-2
v	5/2	4/-7	24/-32	9/-15	1/-3
V	1.6	1.4	8.1	3.8	1.5
D	48	166	176	249	118
S	0.5	1.0	9.5	3.3	1.0

Case #4: Tides and river inflows					
η	8/-1	8/-4	19/-19	19/-16	23/-20
u	0/-0	3/-2	2/-1	5/-5	3/-3
v	1/-1	3/-3	7/-6	10/-13	1/-1
V	0.1	0.1	0.1	0.2	0.1
D	219	162	237	156	150
S	0.2	0.6	1.6	2.5	0.7
Case #5: Tides, trades, and river inflows					
η	6/-3	10/-2	16/-18	19/-16	24/-19
u	1/1	3/-2	17/-22	2/-7	4/-2
v	2/0	2/-3	24/-25	9/-14	1/-2
V	1.4	1.2	6.4	3.3	1.4
D	50	162	176	248	119
S	0.2	0.8	8.1	2.8	0.9

1. Tides: Tidal forcing at the boundaries with no additional wind or river input. The measured tides from Lighthouse Reef, Gladden Spit, and Sapodilla Cays were imposed on the channels.

2. Tides and trades: The MBRS lagoon is subjected to easterly trades for most part of the year. Winds blowing at an average of 3 m s^{-1} from 68° T were imposed on the model in addition to the tides.

3. Tides, northers and trades: The months Dec-Mar experience cold winds from the north that blow intensely for a few days and then calm down. The northers with a speed of 5 m s^{-1} and blowing from 15° T for five days were added to the existing trades in the third simulation.

4. Tides and river inflow: Six major rivers, (Rio Hondo, 50 m^3 s^{-1}, Belize River, 100 m^3 s^{-1}, Monkey River, 48 m^3 s^{-1}, Moho River, 98 m^3 s^{-1}, Sarstún, 146 m^3 s^{-1}, and Dulce, 313 m^3 s^{-1}), drain into the Belize lagoon. These river discharges were added to the tidal forcing in the fourth simulation.

5. Tides, trades, and river inflow: In the fifth simulation case, trade winds (as in Case 2) and river inflows (as in Case 4) were imposed on the tides.

1) Case 1: Tides

Time series of water levels and stick plots of the east-west and north-south velocities are plotted in Fig. 2. The net circulation has a northward flow in the northern half of the lagoon and a southward flow in the southern half, with anti-clockwise cells in Chetumal Bay and Amatique Bay. High residual velocities are on the order of 5 mm s^{-1}, and occur in the English channel (south of Belize City) and to the west of Gladden Spit. The average net velocities, however, are very small, on the order of 1 mm s^{-1}. The net currents are oriented either to the southwest (Locations 1 and 3) or southeast (Locations 2, 4, and 5) (Table 3). There is barely any variability in the water level at Location 1. This is expected because the tidal entrance is very far from Chetumal Bay which is fully enclosed by land. The RMS speeds are also very low, indicating low energetics of the system under tidal forcing.

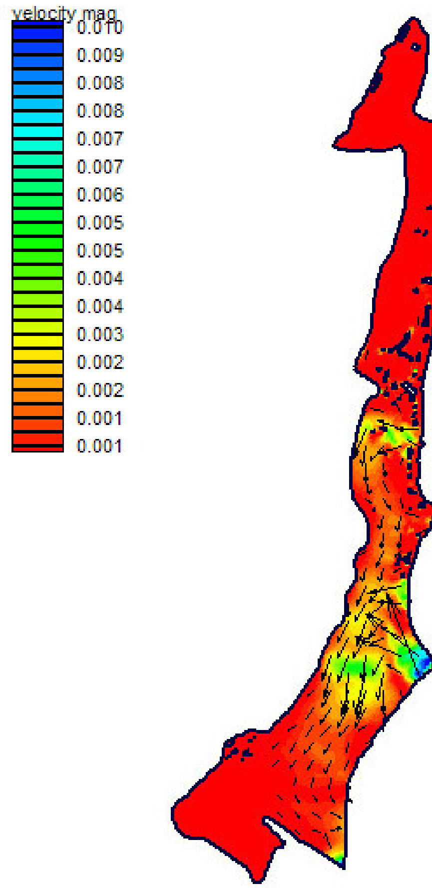

Fig. 2. Net circulation in the Belize lagoon under tidal forcing (Case 1)

2) Case 2: Tides and trades

The results of the second simulation are shown in Table 3 and Fig. 3 and Fig. 4. The net circulation in the lagoon is southward, indicating that the trade winds break up the north-south division in flow seen earlier in Case 1. The velocities are on the order of 10 cm s^{-1}. Several areas experience minimum flow velocities. The net circulation within Chetumal Bay shows a clockwise cell in the eastern portion and an anti-clockwise cell in the western portion of the bay. The net circulation in Amatique Bay is also split into an anticlockwise cell in the western half open to the lagoon and a clockwise cell in the eastern half. The velocities at Location 3 increase considerably under the action of the trades, by as much as 10 cm s^{-1} in the east-west direction and 20 cm s^{-1} in the north-south direction (Table 3). The net speed is also higher (6 cm s^{-1}). The net flow at Location 1 is entirely northeast, and the net flow directions at Locations 3 and 4 are reversed from Case 1. The trades also lead to a decrease in water level in Chetumal Bay and an increase to the southwest of

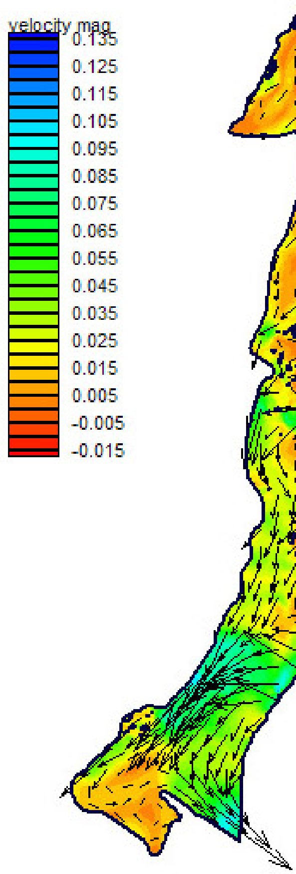

Fig. 3. Net circulation in the Belize lagoon under tidal forcing and trade winds blowing from 68 ^{o}T (Case 2)

Ambergris Cay and in Amatique Bay. The RMS speed is again high at Location 3, whereas the other locations do not show any significant difference from Case 1.

3) Case 3: Tides, northers and trades

The third simulation involved the addition of northers to the trades for the initial 5 days. The results of this simulation are shown in Table 3. The net circulation shows a slight increase in water level immediately north of Hicks Cay, but overall the pattern is similar to Case 2 considering a 35-day execution. The net circulation over one tidal cycle during the influence of the northers shows an increase in velocities throughout the lagoon, with maximum speeds in the English Channel and at Gladden Spit. The minimum water level drops to 19 cm at Location 1 (Table 3), but the other locations do not show any difference from Case 2. The net directions and the RMS speeds at the five locations are also almost the same as for Case 2. The time series of water level and velocity, however, undergo high frequency fluctuations under the influence of the northers.

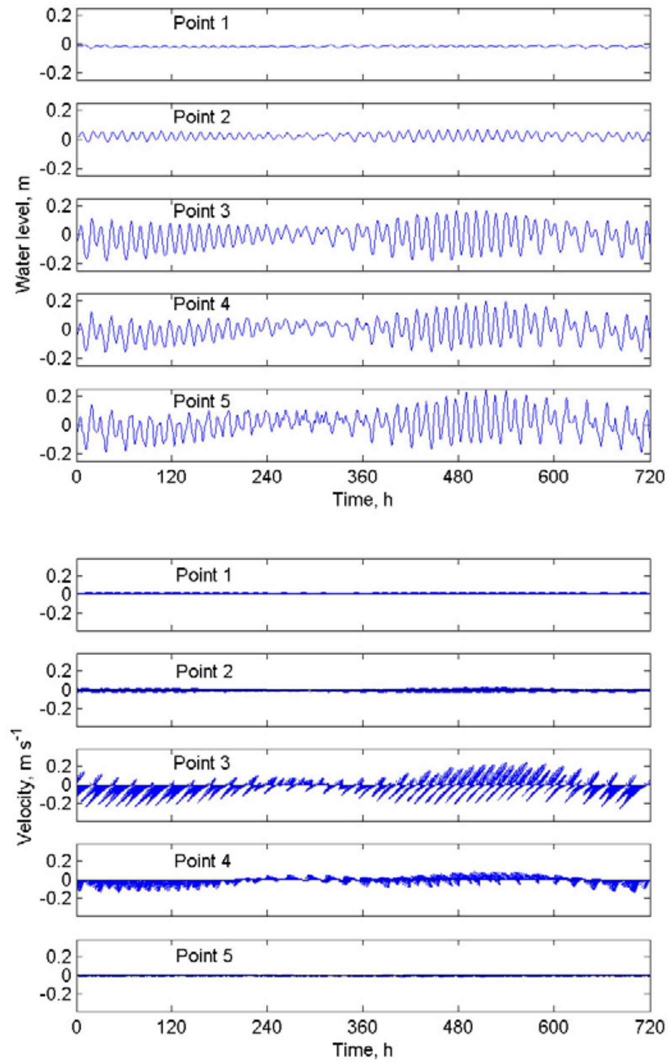

Fig. 4. Water levels and velocities at five locations in the lagoon under the influence of tides and trade winds blowing from 68 ^{o}T (Case 2).

4) Case 4: Tides and river inflow

The results of the fourth simulation, where discharge from 6 rivers are added, are shown in Table 3. The rivers discharge 755 m^3 s^{-1} of freshwater that can set up a two-layered flow in the vicinity of the river mouths. The 2D model cannot resolve the vertical structure, but it is still possible to analyze the circulation patterns. The net circulation within the lagoon is now southward with a break at the middle of the lagoon where the flow is towards north and east. The inflow at Rio Hondo pushes the earlier anti-clockwise cell in Chetumal Bay to the northern corner. The previous anti-cyclonic circulation pattern that existed in Amatique Bay breaks down, and has been replaced by a small anti-clockwise cell north of the Moho river. There are no circulation cells in the rest of the bay. The inflow from Rio Hondo leads to an increase in the water level at Location 1, on the order of 20 cm. The maximum and minimum velocities at Location 3 have decreased, and the net directions of flow are similar to Case 1. Thus, under a no wind-river flow condition, the lagoon response away from the river mouths resembles Case 1, whereas near the river mouths, the net circulation is modified by the river input.

5) Case 5: Tides, trades, and river inflows

The results of this simulation are shown in Table 3 and Fig. 5. The net circulation, and the velocities and water levels at the five locations are very similar to Case 2, indicating that winds exert more influence on the circulation within the lagoon than do river discharges.

IV. CONCLUSION

The results from the five simulations show that the circulation in the MBRS lagoon is influenced mostly by trade winds, and modified by tides. There is little residual flow due to runoff away from river mouths. The net flow is in opposite directions in the northern and southern halves of the lagoon in the absence of winds and river runoff. However, addition of winds and river inflow results in a mostly southward flow, with smaller circulation cells in the two bays. Under the influence of the trades, strong flows occur near Gladden Spit, initially westward into the lagoon and then southward.

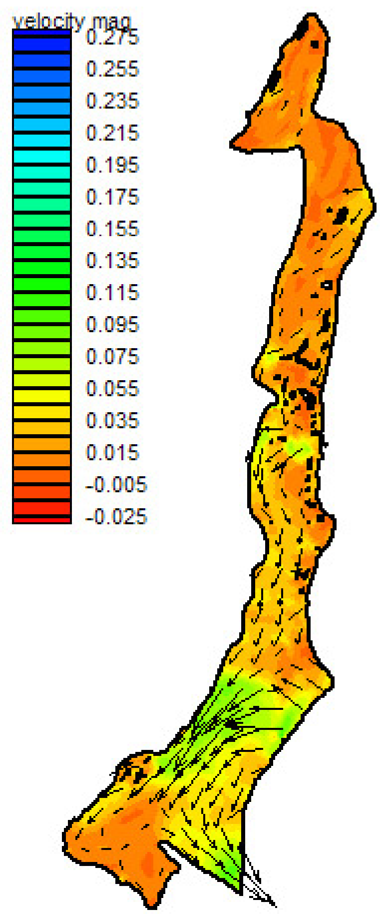

Fig. 5. Net circulation in the Belize lagoon under tidal forcing, trades and discharge from six rivers (Case 5)

REFERENCES

[1] B. Kjerfve and K. E. Magill, "Geographic and hydrodynamic characteristics of shallow coastal lagoons," *Marine Geology*, vol. 88, pp. 187-199, 1989.

[2] R. A. Walters, "Finite element solution methods for circulation in estuaries," in *Finite Elements in Water Resources, Proceedings of the Fifth International Conference, Burlington, VT, USA*, J. P. Laible, C. A. Brebbia, W. Gray, and G. Pinder, Springer Verlag, 1984.

[3] P. Salles, "Hydrodynamic controls on multiple tidal inlet persistence," *Ph. D. thesis*, MIT/WHOI, 00-30, 272 pp., 2000.

[4] A. S. Unnikrishnan and J. L. Luick, "A finite element simulation of tidal circulation in the Gulf of Kutch, India," *Estuarine Coastal and Shelf Science*, vol. 56(1), pp. 131-138, 2003.

[5] J. Gibson, M. McField, and S. Wells, "Coral reef management in Belize: an approach through Integrated Coastal Zone Management," *Ocean and Coastal Management*, vol. 39, pp. 229-244, 1998.

[6] E. Gischler, A. J. Lomando, J. H. Hudson, and C. W. Holmes, "Last interglacial reef growth beneath Belize barrier and isolated platform reefs," *Geology*, vol. 28(5), pp. 387-390, 1990.

[7] T. E. Miller, "Geologic and hydrologic controls on karst and cave development in Belize," *Journal of Cave and Karst Studies*, vol. 58(2), pp. 100-120, 1996.

[8] K. A. Rasmussen, I. G. Macintyre, and L. Prufert, "Modern stromatolite reefs stringing a brackish coastline, Chetumal Bay, Belize,", *Geology*, vol. 21, pp. 199-202, 1993.

[9] D. Thattai, B. Kjerfve, and W. D. Heyman, "Hydrometeorology and variability of water discharge and sediment load in the Inner Gulf of Honduras, Western Caribbean," *Journal of Hydrometeorology*, in press.

[10] B. Kjerfve, "Tides of the Caribbean Sea," *Journal of Geophysical Research*, vol. 86(C5), pp. 4243-4247, 1981.

[11] W. D. Heyman and B. Kjerfve, "Gulf of Honduras," in *Coastal Marine Ecosystems of Latin America*, U. Seeliger and B. Kjerfve (Eds.), Berlin: Springer-Verlag, pp. 17-32, 2001.

[12] R. T. Cheng, "Modeling of hydraulic systems by finite-element methods," in *Advances in Hydroscience*, V. T.

Chow (Ed.), vol. 11. NY: Academic Press, 1978, pp. 208-284.

[13] W. L. Wood, *Introduction to Numerical Methods for Water Resources*, NY: Oxford University Press Inc., 1993, 255p.

[14] L. C. Roig, "Mathematical theory and numerical methods for the modeling of wetland hydraulics," *Proceedings of the 1995 ASCE International Water Resources Engineering Conference, San Antonio, TX*, pp. 249-253, Aug 14-16, 1995.

[15] R. C. Berger, "Mass conservation in the RMA2V code," *Hydraulic Engineering: proceedings of the American Society of Civil Engineers, hosted by the San Diego Section, ASCE, San Diego, California*, pp. 873-878, July 30-August 3, 1990.

ACKNOWLEDGMENTS

We acknowledge support from the Mellon Foundation/The Nature Conservancy's Ecosystem Research Program and Dr. W. D. Heyman.