Stratification and Circulation in Lake Pontchartrain

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Abstract

A three-dimensional hydrodynamic model (Princeton Ocean Model, POM) was used to study the dynamic behavior of a saltwater plume originating from a navigation canal and advancing in the lake. The Inner Harbor Navigational Canal (IHNC) is part of the Mississippi River Gulf Outlet, which permits ships to navigate from the Gulf of Mexico to Lake Pontchartrain and the Mississippi River at New Orleans. Lake Pontchartrain is a relatively shallow, brackish estuarine lake with a mean depth of less than 4 m and a mean salinity of 7 ppt. At times, the IHNC brings highly saline water (> 20 ppt) into Lake Pontchartrain. Under certain conditions, this higher density water has been observed to form a thin layer of high salinity water over a large area near the bottom of the lake. Field data showed that the stratified zone was approximately 0.5 m deep and up to 250 km^2 in area. The salinity wedge in the IHNC had an elevation that was 1 – 3 m above the Lake bed, while outside of the canal entrance the depth of the density layer was of the order of 0.5 m compared to the mean Lake depth of 4 m. This difference in the density plume elevation causes a salt water flux into the lake. Stratification was apparent throughout the year but more persistent during the summer months.

A three-dimensional hydrodynamic model (POM) was developed for the area to study the effect of Lake circulation on the location and stability of the saltwater plume. Field and laboratory data were used for model calibration and verification. The forcing functions for the model include tide from nearby connections to the Gulf of Mexico, wind and river flows from tributaries to the north and west. The model includes 20 sigma levels with surface and bottom refinement in order to capture the momentum transfer from the wind shear and the density current near the bed. The horizontal grid resolution is 600 m.

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Introduction

Lake Pontchartrain is a brackish estuarine lake in Southeastern Louisiana with a mean depth of 3.7 m and an area of approximately 1630 km^2 (Figure 1). It has a diurnal tide with a mean range of 11 cm. Because it is very shallow, the Lake water column is generally well mixed. There are three tidal passes. The two natural tidal passes are the Rigolets and Chef Menteur. The third tidal pass is the man-made Inner Harbor Navigation Canal (IHNC). In the west, the Lake is connected to Lake Maurepas by way of Pass Manchac. The Lake receives runoff from several rural drainage basins, and an urban watershed to the south of the Lake, which includes the City of New Orleans and periodic diversions from the Mississippi River. The most important factor governing salinity distribution in the Lake is fresh water input (Sikora and Kjerfve, 1985). Salt fluxes in the estuary are mainly through the IHNC and the Rigolets. Saltwater intrusion from the IHNC causes periodic but strong stratification covering 250 km^2 of the Lake's floor near the IHNC (Poirrier 1978; Haralampides et al. 2000, Georgiou et al., 2000). Circulation currents in the Lake are wind driven except in the vicinity of the tidal passes. Hamilton et al. (1982) showed that the transport response to local wind is generally downwind in the shallow regions, and upwind in the deeper regions. Signell and List (1997) reported similar results, as did Haralampides (2000). Furthermore, Signell and List (1997), reported that at sub-tidal timescales the eastern end of the lake is dominated by remote forcing, the rim of the western part of the lake is dominated by local forcing, and the interior of the lake is weakly driven by a combination of local and remote forcing.

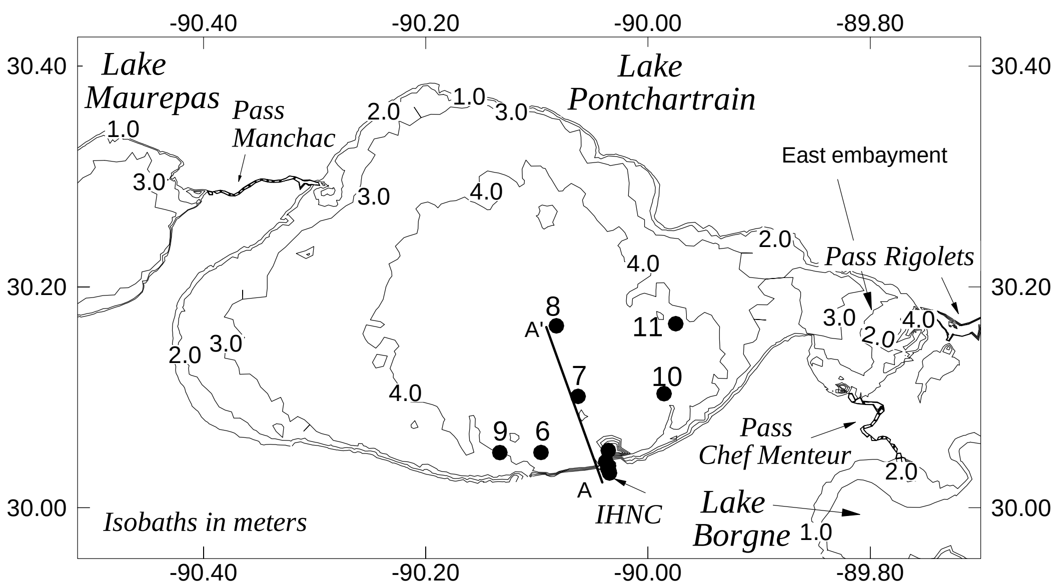

Figure 1. Geographic and bathymetric features of the Lake Pontchartrain estuary. Integer numbers indicate sampling locations.

Methods

Field Observations. Climatologic data collected by the Southern Regional Climatic Center (SRCC) at five stations in the Lake were obtained from the years 1997 to 2000. Aside from seasonal variations, winds patterns in the Lake vary locally in direction and magnitude as seen in Figure 2, with sustained directions of 1 – 2 days. Time dependent spectral analysis performed on hourly wind observations at the midlake station showed cyclical patterns, which were in accordance with spectral analysis of stage data at the same station. These patterns appear to follow a diurnal signal and a six-day cycle that could be related to the movement of storm systems. The results were verified with analysis of data from other Lake stations as well. Annual temperature variations in the Lake follow a typical cycle of heating and cooling with temperatures of 10^o C during the winter months and just above 30^o C during summer months (Figure 3). Local variations are in the order of ±3 – 5^oC. Similarly, annual salinity trends in the study area include variations shown in Figure 3. Heavy rain during the winter months of the deployment period (1998) reduced the salt concentration to near freshwater values. The increase in salinity as well as the unusual fluctuations in the summer months is associated with the reduced fresh water flow from the Lake and predominance of southeast winds. However, the signal amplitude in Figure 3 suggests that the interface of the wedge was fluctuating with the tide above and below the sensors. Additional sampling at stations 1 – 12 shown in Figure 1 was initiated during 1999 and 2000. The data showed that high salinity gradients with the combination of high temperature values during the summer months could lead to hypoxic conditions in the bottom waters. These waters can even become anoxic due to high sediment oxygen demand (SOD) in the surface sediments and when the high salinity gradients and temperature persist. Figure 4 shows a longitudinal transverse along section A-A' (Figure 1). The canal, on the left of the image, brings highly saline water to the lakeside mouth which first fills the scour hole, followed by the dredge hole, and then, still having substantial momentum and radial density gradient, propagates into the Lake during the flood cycle.

Modeling Approach. The Princeton Ocean Model was configured for the study in the Lake as described by Blumberg and Mellor (1987). The model was selected primarily due to its three-dimensional capability and the previous experience of the USGS in applying this model for Lake Pontchartrain. In addition, the model contains a free surface, a 2.5 level turbulence closure scheme for vertical mixing representation (Mellor and Yamada, 1982), nonlinear advective terms, coupled density and velocity fields and heating and cooling. Other model features include orthogonal curvilinear coordinates in the horizontal plane and sigma-coordinates in the vertical dimension, allowing for surface and bottom refinement. The latter is particularly important in the shallow regions of the basin, but most vital for the representation of density currents near the bottom layers. The initial model con-

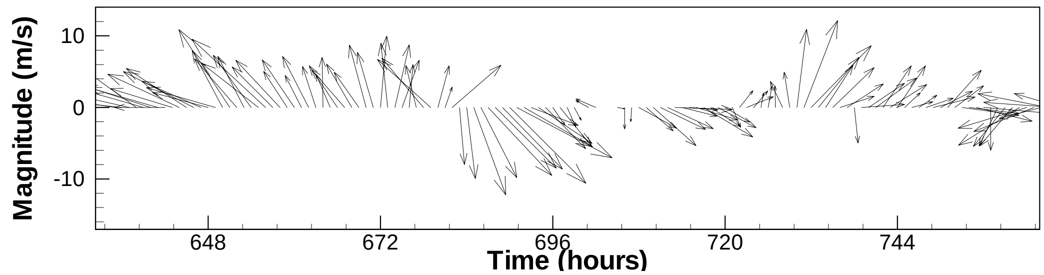

Figure 2. Small timescale wind variations at the midlake station in Lake Pontchartrain. Direction is sustained for more than 24 hours.

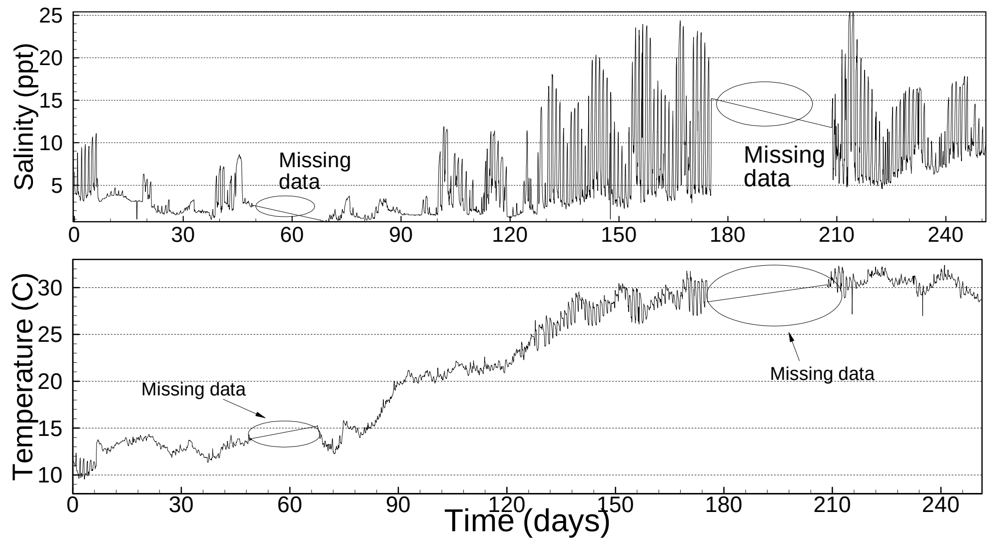

Figure 3. Seasonal Salinity and Temperature fluctuations at the IHNC during 1998 (Data collected by the New Orleans District, USACE).

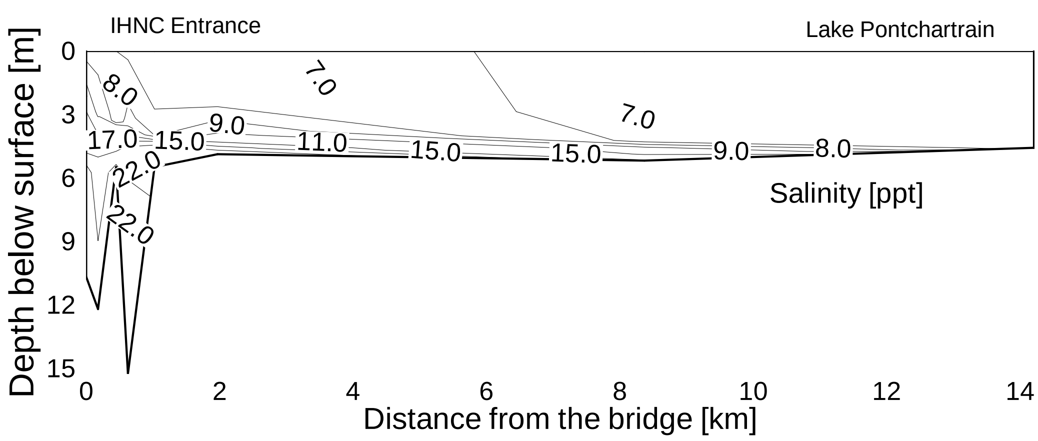

Figure 4. Elevation view of the saltwater density current at the IHNC (A-A').

figuration includes a domain of 115 x 70 equally sized horizontal grid cells (Figure 5) and 20 sigma layers with surface and bottom logarithmic refinement. The horizontal grid resolution is 600 m, and the vertical resolution varies from 5 – 25 cm. Local resolution of the domain is expected to increase in the future to address specific test scenarios. The model was driven with a diurnal tide (23 hour period, 15 cm amplitude) at the Rigolets, Chef Menteur and the IHNC. Also uniform (constant in space and time) wind stress was applied throughout the domain for each simulation. The model was driven with wind speeds of 2.5, 5, and 7.5 m/s. Runs with diurnal wind stress were also completed. The model was also run without wind in order to provide a basis of comparison. The thermodynamic boundary conditions included constant temperature and salinity from the rivers' flow, and linearly thermally stratified water at the tidal inlets with a constant feed of higher density gradients that simulated a salt wedge. The model also includes a constant Coriolis force. Surface forcing for temperature and salinity was not included during initial runs. The specific simulations reported in this paper have ambient salinities of 13 ppt, which represent values that occurred during the 1998 summer drought period.

Model Calibration. Initial calibration of the model was performed using data obtained from several agencies namely the SRCC, US Geological Survey (USGS), USACE and the University of New Orleans (UNO). Together, these agencies provide information on hourly stage levels, wind speed and direction, and air and water temperature near the surface. They also provide low frequency sampling data for vertical profiles of salinity and temperature near the impact zone of the saltwater plume. In addition, available water quality data collected by

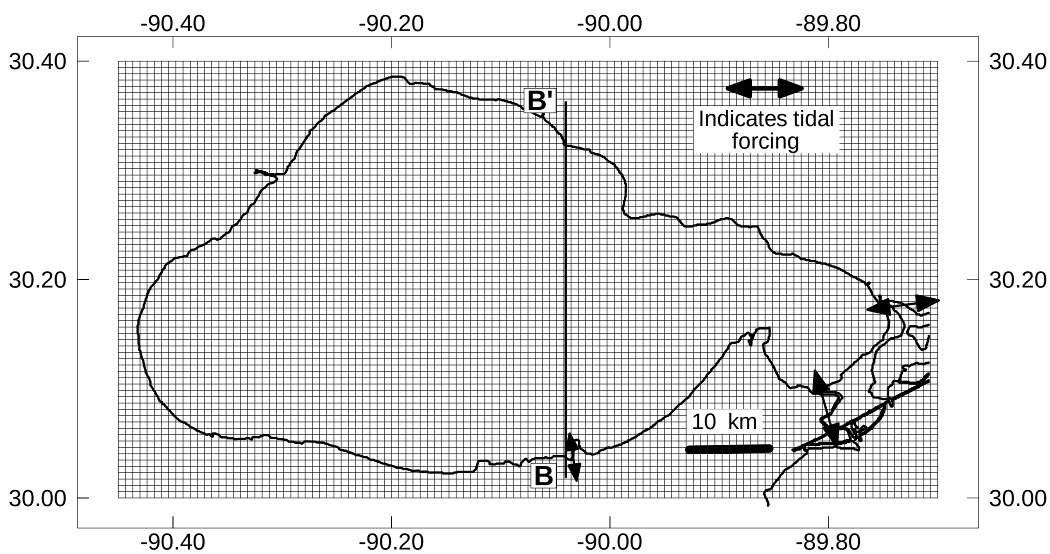

Figure 5. Computational domain for POM.

UNO from 1997 to 2000 include a number of significant hydrologic events, namely a spillway opening, an extensive drought, a record winter rainfall, several tropical storms and a hurricane. Some of these parameters are DO, salinity, Secchi disk transparency and temperature. Circulation patterns predicted by POM were initially compared with studies completed by Signell and List (1997), Haralampides (2000), Haralampides et al. (2001). The model produced similar predictions of surface water elevation and surface and bottom current magnitude under the same simulation conditions. However, model calibration with real time data from acoustic doppler current profilers (ADCP) and continuous monitoring data for salinity and temperature are still in progress.

Results and Discussion

Wind speeds over Lake Pontchartrain generally average above 3.0 m/s, thus dominating the circulation forcing and producing large gyres whose properties are dependent on wind direction in the central portion of the Lake. The model predicted a common depth averaged flow pattern over the domain consisting of two gyres rotating in the opposite direction. Flow was downwind at the shallow regions of the Lake (shoreline) and upwind in the deeper central regions (Figure 6). Similar patterns to those predicted in Lake Pontchartrain for each wind direction were also observed in Lake Maurepas. The formation of gyres is attributed to the variable depth distributions and sustained wind stress (Csanady, 1973). Hamilton et al. (1982), Signell and List (1997), Gael (1980), Haralampides (2000), and Haralampides et al. (2001) predicted similar patterns of gyres in their modeling studies of Lake Pontchartrain.

Table 1 summarizes the results from wind driven runs. An example of depth-averaged currents driven by a wind forcing of 5 m/s from different directions is 10 cm/s or higher in the eastern part of the Lake and near the passes, 5 - 7 cm/s along the shoreline, and less than 4 cm/s in the center of the Lake. An increase in the wind forcing to 7.5 m/s produced current magnitudes typically 33% higher than the 5 m/s scenario throughout the domain.

Although depth-averaged currents exhibited the double gyre pattern, velocity variations in the vertical were non-uniform. As expected, surface currents are in the direction of the wind while near bed currents are opposed to the wind in the deeper regions of the Lake. At the same sigma level, higher velocity magnitudes were observed near the bed in the deeper region of the Lake than in the shallow parts; this results in another gyre in the western shallow rim of the Lake with rotation similar to the depth-averaged gyre, only shifted to the west. This pattern was consistent for winds with northerly (Figure 6) and southerly components (Figure 7). Similarly, easterly and westerly wind forcing produced a gyre in the shallow north end of the Lake. In terms of stratification, the model produced results similar to the field data on impact area and plume expansion.

Table 1. Summarized results from wind driven POM runs. Table represents typical values for a 7 day run period.

Wind Direction	North		South		West		East	
Magnitude (m/s)	5	7.5	5	7.5	5	7.5	5	7.5
Depth-Averaged current magnitude (cm/s)								
Shoreline	5-6	8-9	6-6.5	7-8	6.5-7	8-9	7-8	≥9
Center	≤3.5	5	≤3.5	5	≤3.5	5	3-4	≤4
Near-Bed current magnitude (cm/s)								
Shoreline	1-2	5	1-2	3-3.5	1-2	3-4	4	2-3
Center	2	4	2	4.5	2-3	4.5	≤4	≥5

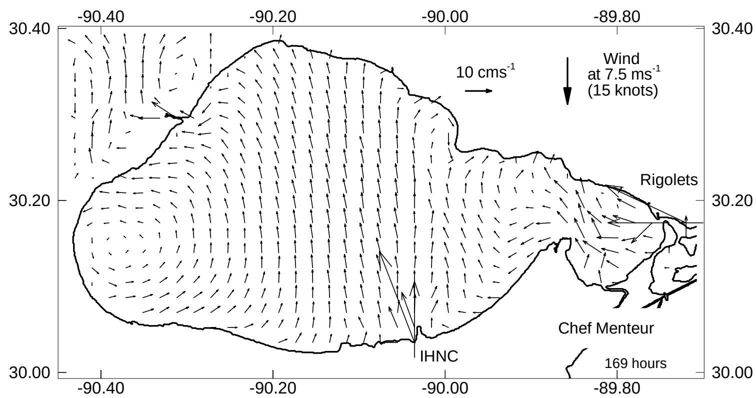

Figure 6. Currents near the bed (at t = 169 hours) driven by a northerly wind at 7.5 m/s (every third vector is shown in either direction).

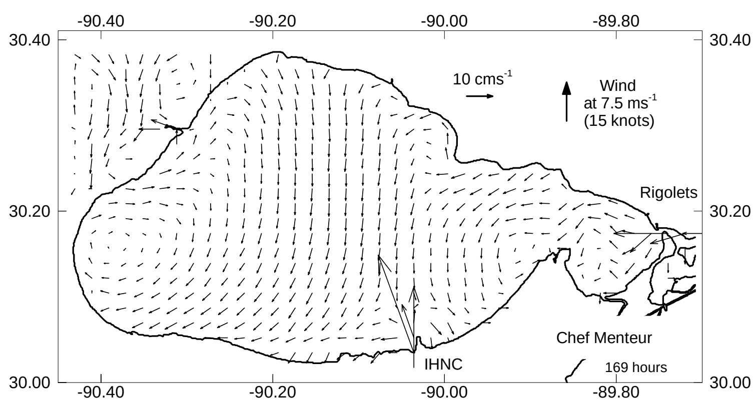

Figure 7. Currents near the bed (at t = 169 hours) driven by a southerly wind at 7.5 m/s (every third vector is shown in either direction).

The simulation without wind forcing indicated a radial expansion of the saltwater plume near the IHNC with fluctuations (area expansion and contraction) related to the tidal cycle, and a decreasing growth rate with each flood cycle until equilibrium was reached in approximately 7 days (Figure 9). Similar density effects were observed at the Rigolets, but the impacted area was limited to the east embayment (Figure 9). Water elevations during windless simulation varied throughout the Lake ranging from 13 - 14 cm near the passes, to 2 - 3 cm in the western part. Velocity magnitudes were typically higher near the passes with values greater than 10 cm/s, decreasing rapidly in the midlake section to approximately 1.5 cm/s (Figure 10).

Simulations with wind stress produced a shift in the position of the saltwater plume that depends on the direction of the wind and its magnitude. The modification of the transport of the saltwater wedge is generally in the direction of the near bed current, typically with an upwind component. Northerly and westerly winds favor the plume expansion to the north and west respectively. For strong northerly winds, periodic mixing was observed near the source during the ebb cycle, at times disconnecting the density current from its source. On the other hand, southerly winds helped suppress the northerly expansion of the plume but assisted in the lateral expansion to the east and west, along the south shore. At high and sustained southerly winds around 7.5 m/s, upwelling was observed near the south end of the Lake.

The model predictions on the thickness of the density current were typically in the order of 1.5 m and above near the IHNC, and 0.7 – 0.9 m near the advancing front of the plume (Figure 11). Field data reported that this thickness in fact rarely reached this value, often ranging from 1 – 2 m and 0.3 – 0.6 m respectively (Figure 4). Figure 11 shows the variation of the currents at section B-B' in Figure 5 for a north wind simulation during flood tide. Along this section and during flood cycles, approximately 15% of the top water column depth was downwind flow and 85% was upwind flow, while for the ebb cycles the flow split was 50%.

The results reported by the model in this study appear to be sensitive to the bottom roughness coefficient. Results from sensitivity analysis performed by varying the bottom roughness coefficient, indicate that the expansion of the saltwater plume is in fact directly impacted as the roughness height is increased. The stable external model time step is also highly sensitive to the roughness parameter. For example, for a roughness parameter of 20, the time step was 5 s while for a roughness parameter of 5 the time step was 1 s. The impact of decreasing bottom roughness was to increase the extent of the plume expansion and to decrease the plume depth. Some sensitivity analysis results are summarized in Figure 12. The values were derived at the same time interval for all simulations by averaging the plume thickness and plume expansion in the Lake, based on the 15 ppt and 17 ppt isohalines.

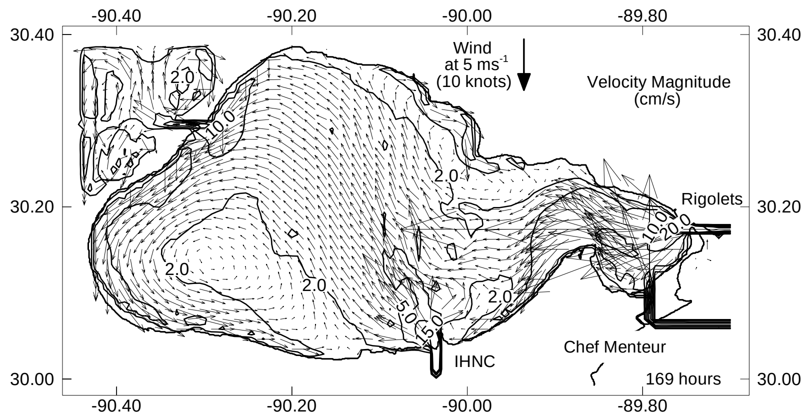

Figure 8. Depth-averaged currents (at t = 169 hours) driven by a 5 m/s northerly wind and tide (every other vector is shown in either direction).

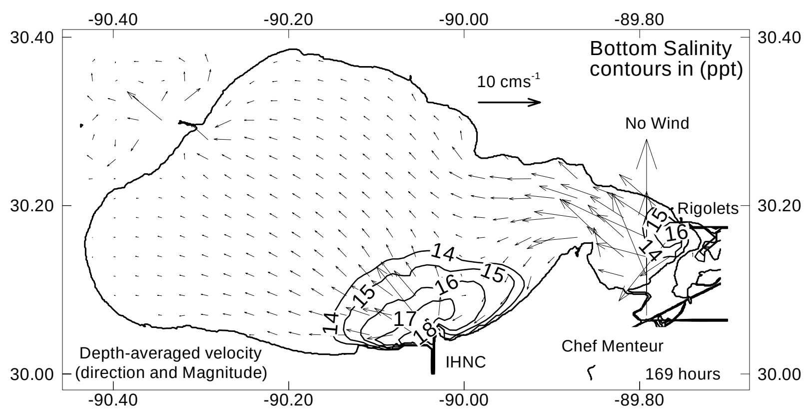

Figure 9. Depth-averaged currents and near bed salinity distribution (at t = 169 hours) for a POM simulation with no wind forcing (every fourth vector is shown in either direction).

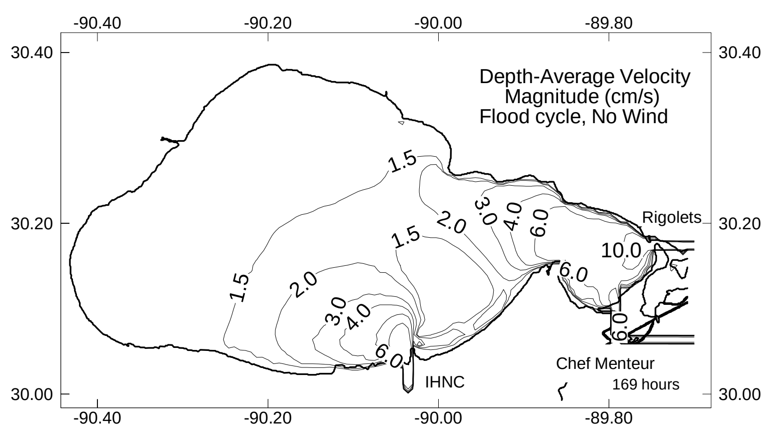

Figure 10. Depth-averaged current magnitudes (at t = 169 hours) driven by tide at the IHNC, Rigolets and Chef Menteur Passes.

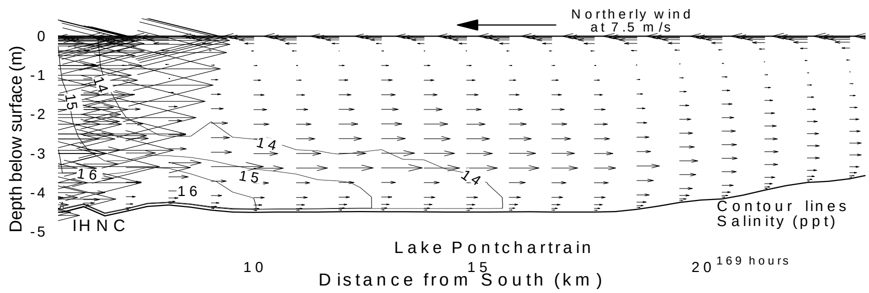

Figure 11. Elevation view of the velocity structure and density current (at t = 169 hours) along section B - B' (midsection), viewed from the east.

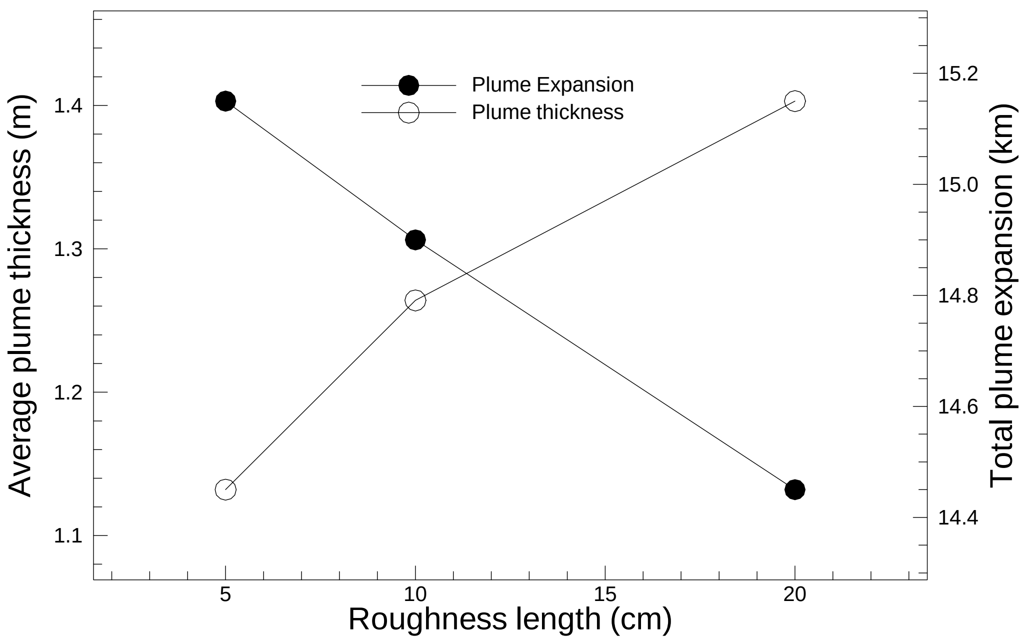

Figure 12. Bottom roughness length sensitivity analysis results at t = 71 hours.

Conclusions

The POM simulations confirmed previous studies that showed formation of a typical two-gyre circulation pattern due wind shear. In addition, the gyre on the western rim of the Lake appeared to be oscillating in accordance with the tidal cycle. This was observed for wind shear induced by winds with northerly and southerly components.

Water circulation in Lake Pontchartrain due to tidal exchanges and wind is significant for the expansion and deformation of the saltwater plume. Model results show a significant interaction of density currents and bottom currents. Generally, a north wind caused an added expansion of the plume in the northerly direction while a southerly wind suppressed the northerly advance of the plume. An explanation for this effect is that bottom currents, which tend to be counter to the wind, exert a shear on the plume thus causing it to shift upwind. Similar shifts were noted for all wind directions. On the contrary, easterly and southeasterly winds generate sufficient long-shore currents to keep the density current suppressed throughout the 7 day run period.

Acknowledgements

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