Hillsborough Bay Inflow Modification Study: An Application of the Tampa Bay Coastal Ocean Model

by

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Abstract

With a large salinity gradient existing between the rivers and the ocean, the saline environment of an estuary is crucial to its ecosystem functionality. For Tampa Bay, the Howard F. Curren Advanced Wastewater Treatment Plant (HFCAWTP) presently yields an outflow of nearly freshwater to the Hillsborough Bay portion of Tampa Bay. In order to estimate the potential impact that the removal of this outflow may have on the salinity and flow fields of Hillsborough Bay, as part of the Tampa Augmentation Project, both numerical circulation model and Knudsen theorem applications are made. The numerical model study compares the instantaneous and nontidal, mean estuarine circulation and salinity distributions for the Hillsborough Bay on the basis of the HFCAWTP outflow being either included with, or excluded from, the freshwater inflows. It is found that the potential reduction of the treated reclaimed water inflow to the bay from the HFCAWTP will not significantly affect the circulation or the salinity distributions of Hillsborough Bay or of the larger Tampa Bay. The estimation through a Knudsen theorem application shows an 0.13 psu increase of salinity after remove the HFCAWTP outflow when averaged within Hillsborough Bay. Thus, both approaches demonstrate that the effects of HFCAWTP outflow removal are very small when compared with variations that occur naturally.

Keywords Tampa Bay, Coastal Ocean Circulation Model, environmental perturbations, Knudsen theorem

1 Introduction

Tampa Bay, like many estuaries near metropolitan areas, has a variety of competing uses. Ecologically, it provides nursery and habitat for estuarine, coastal and deeper-water fishes and other marine organisms, while with a surrounding population of some four million people, it also serves as a recreational resource, a depository for treated municipal wastes, and with the only deep-water port on Florida's west coast, it services the marine transportation industry. Thus, of importance for bay management is the determination of how the bay may respond to altered utilizations.

With large salinity differences between the rivers (0 psu) and the ocean (~35 psu), the salinity distribution, a controlling factor for many marine organisms (e.g., Gunter, 1961), is critical component of the estuarine ecosystem. The spatial and temporal distribution of an estuary's salinity field is mainly controlled by river discharge and tides (e.g. Prandle, 1985; Simpson et al., 1990; Geyer, 1993; Xia et al., 2011) and by winds (e.g. Weisberg, 1976; Chen and Sanford, 2009; Aristizábal and Chant, 2015; Giddings and MacCready, 2017; Kang et al., 2017; Zhu et al., 2020). It can also be affected by man-made structures (e.g. Das, 2010; White et al., 2018) and by runoff regulation (Qiu and Zhu, 2013). Variations in the abundance of estuarine organisms may occur through physical attributes of habitat (such as the salinity and flow fields) that vary with freshwater inflows (e.g., Kimmerer, 2002; Gillanders & Kingsford 2002).

Here we apply a very high resolution, unstructured grid (a triangular grid in this case), numerical circulation model to assess the results of a fresh water inflow modification proposed for the Hillsborough Bay portion of Tampa Bay by the City of Tampa, FL Tampa Bay Augmentation Project (TAP). TAP intends to supply additional potable water by using highly treated reclaimed water from the City's Howard F. Curren Advanced Wastewater Treatment Plant (HFCAWTP) that is presently being released into Tampa Bay.

The location of the present HFCAWTP outflow relative to Hillsborough Bay and the entirety of Tampa Bay, the adjacent Gulf of Mexico and the various natural river inflows are shown in Figure 1. The numerical model to be applied is the Tampa Bay Coastal Ocean Model (TBCOM) that includes the entire Tampa Bay vicinity and its adjacent Gulf of Mexico with horizontal resolution as fine as 20 m to include Tampa Bay, Sarasota Bay, the intra-coastal waterway and all of the inlets connecting these water bodies with each other and with the Gulf of Mexico, as shown in Figure 2. To assess the potential effects of the HFCAWTP outflow removal, we compare the instantaneous and non-tidal, mean estuarine circulation and salinity distributions for the Hillsborough Bay sub-region of Tampa Bay with either the HFCAWTP outflow being included, or excluded from, the freshwater inflows.

The remainder of the paper is as follows. Section 2 discusses the development of TBCOM and why it is an appropriate tool for this study. Section 3 describes the experimental design of the study. The results of numerical experiments are discussed in section 4. A more simplified estimation analysis using the Knudsen theorem to back up the numerical analyses is provided in section 5. Section 6 offers a summary and conclusions.

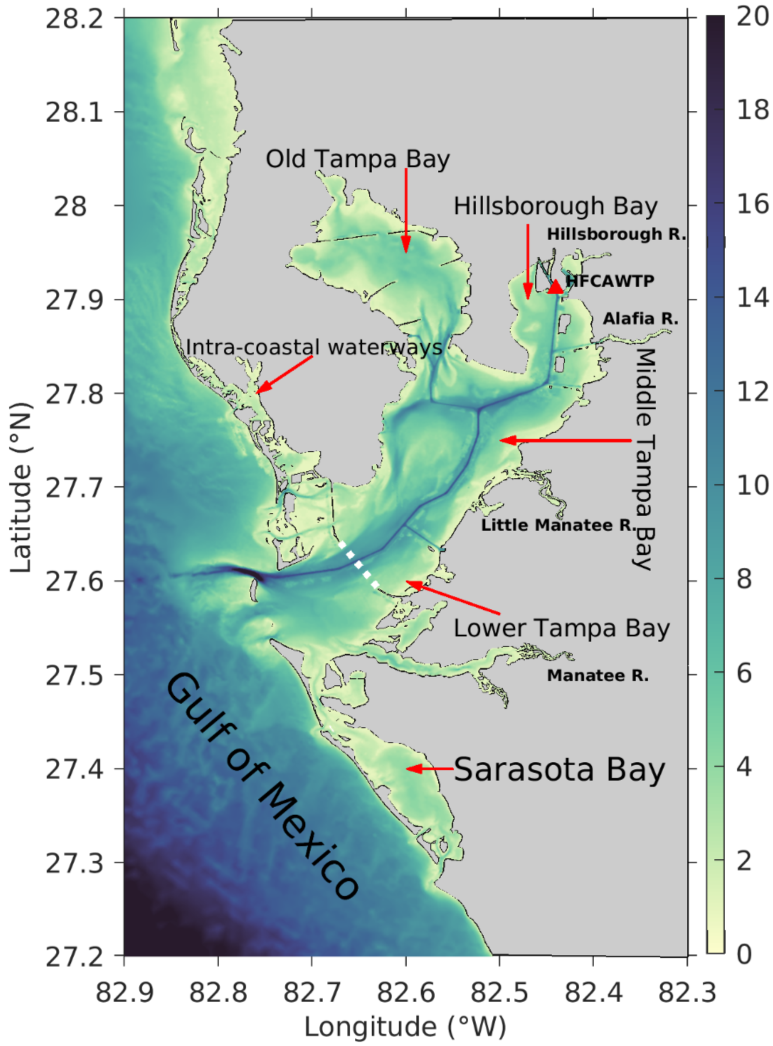

Figure 1. The major structural features and subregions of Tampa Bay, with color-coded bathymetry (units in m). The HFCAWTP location is in the upper right.

2 Tampa Bay Coastal Ocean Model

TBCOM downscales from the deep-ocean, across the continental shelf and into the estuary by nesting the unstructured grid, Finite Volume Community Model (FVCOM, e.g., Chen et al., 2003), which has been successfully applied in estuarine and coastal systems (e.g., Yuan et al., 2015, Niu et al.,2018, Xia et al.,2020, Sahoo et al.,2021, Kang and Xia, 2022), into the West Florida Coastal Ocean Model (WFCOM, e.g., Zheng and Weisberg, 2012, as modified by

Weisberg et al., 2014). WFCOM covers continental shelf region of the eastern Gulf of Mexico, from just west of the Mississippi River Delta to just south of the Florida Keys, by nesting FVCOM in the Gulf of Mexico Hybrid Coordinate Model (GOM-HYCOM, e.g., Chassignet et al., 2009). By deriving its deep-ocean boundary values of variables (including tides) from the GOM HYCOM and its continental shelf forcing from WFCOM, TBCOM further increases the grid resolution to resolve the finer details of the Tampa Bay vicinity, yielding a three-dimensional, density dependent estuarine model that is both fully connected to the adjacent ocean and includes the geometrical complexity of the shoreline and bathymetry as well as the ability to flood and dry.

Given that estuaries are mixing regions for freshwater and seawater, salinity is a primary variable for determining how flow modifications may impact estuarine ecology. Conceptual mixing arguments demonstrate the need for very high-resolution models with flooding and drying capabilities for considering salinity variations, especially in the shallowest nearshore regions. With fresh water readily mixed over shallow depths, dilution is proportional to depth; hence, if either depth variations are not resolved by model, or the exclusion of flooding-drying necessitates a minimum depth for model stability (e.g., Zheng et al., 2003, Chen et al., 2008), then it is not possible to estimate shallow water salinity variations owing to freshwater inflow modifications.

The starting point for TBCOM was the work of Weisberg and Zheng (2006) followed by those of Zhu et al. (2015a, b, c). The first of these applied FVCOM to Tampa Bay and demonstrated the utility of using an unstructured grid model for simulating the circulation. By further increasing horizontal resolution, the next three applications studied the effects of deepening and widening the shipping channels, diagnosed the point by point salt balances throughout the bay and the flushing times for the bay as a whole and for its sub-regions, respectively. Chen et al. (2019), carried these studies a step farther by diagnosing the point by point momentum balances throughout the bay. The grid configuration used in all but the first of these aforementioned works is given in Figure 2.

With the initial applications to Tampa Bay all being diagnostic hindcasts, the next step was to combine the Tampa Bay grid with WFCOM to produce a daily, automated nowcast and forecast model available on the internet for public and other uses. As presently configured, TBCOM has 219,337 triangular elements with 115,369 nodes in the horizontal and 11 uniformly distributed σ-layers in the vertical (where σ-layers are terrain following layers that expand or contract proportionally with varying water depth). The horizontal resolution (Figure 2) gradually increases from about 8.5 km along the open boundary to about 200 m near the coast, and as fine as 20 m within Tampa Bay. With such a high resolution, TBCOM uniquely resolves the main shipping channel and all of the inlets and waterways connecting the Tampa Bay, Sarasota Bay and the Intra-Coastal Waterway with each other and with the adjacent Gulf of Mexico. Land elevation and bathymetry data sets are from NOAA and USGS (Hess, 2001). Along the open boundary, hourly values of sea level, velocity, temperature and salinity are provided along the open boundary by WFCOM, interpolated to the open boundary nodes and then smoothly merged with those values from TBCOM over a transition zone consisting of the 10 outermost nodes. Given that WFCOM already includes tides, no additional tidal forcing is required for TBCOM.

For each daily nowcast/forecast run, the initial conditions are taken from the previous day's hindcast result. At the surface, TBCOM is forced by momentum (winds) and heat fluxes provided by the NOAA NCEP NAM with spatial and temporal resolutions of 12 km and 6 hours, respectively. Recognizing that the net surface heat flux may be biased (e.g., Virmani &

Weisberg, 2005) and to correct for possible systematic temperature drifts, we relax the modeled sea surface temperature (SST) to the satellite remote sensing derived Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) product (Donlon et al., 2012). Finally, daily river discharges are downloaded from the USGS website, and the river inflow sites are also shown in Figure 2. With this TBCOM nowcast/forecast system construct completed in August 2017, Hurricane Irma provided a reality check of the extreme case the following month. Chen et al. (2018) describes the TBCOM performance for this initial, unplanned proof of concept demonstration. The veracity of TBCOM has also been evaluated in under normal conditions (Chen 2021) using in situ observations.

Publicly available TBCOM outputs have been posted continually since September 2017 at http://ocgweb.marine.usf.edu/~tbm/index.html. These include a one day hindcast and 3.5 days of forecasts for surface currents and sea levels over the entire domain, plus sea level time series at selected sites. Subsequently added (in collaboration with colleagues at the Florida Fish & Wildlife Commission, Florida Wildlife Research Institute) was a red tide tracking tool to forecast where observed *Karenia brevis* red tide cell concentrations would be transported to over the next 3.5 days (Liu et al. 2018).

Along with these hurricane storm surge and red tide applications, TBCOM also played an important role in tracking the pollutant plume that emanated from an emergency release of water from the defunct Piney Point orthophosphate stack in April 2021 (e.g., Liu et al. 2021; Beck et al. 2022). TBCOM also helped to guide dead fish cleanup operations by Pinellas County during the major red tide event that ensued subsequent to the Piney Point release. Other recent applications include the works of Xie et al. (2019, 2021) describing the precision of GPS observations on a spar buoy anchored at the mouth of Tampa Bay.

3 Experimental Design

To investigate the influence of the potential reduction of the treated reclaimed water inflow from the HFCAWTP, two sets of numerical model simulations (dry season: March 1, 2018 to May 31, 2018; wet season: July 1, 2018 to September 30, 2018) were run. Each set included two simulations, one with the HFCAWTP outfall discharge flow, the other without the discharge. The initial conditions were TBCOM hindcast results (February 28 and June 30, 2018). Given the limited area extent of Hillsborough Bay and its mostly shallow depths, baroclinic adjustments to fresh water inflows there occur rapidly. Thus, we conservatively discarded the first month of simulations (March 1 to March 31, 2018, and July 1 to July 31, 2018) by which time the salinity field was fully adjusted to the new forcing conditions of the HFCAWTP outfall being either on or off and used the subsequent two months (April 1, 2018 to May 31, 2018, and August 1, 2018 to September 30, 2018) for analyses.

Of the 22 river inflow sites to the TBCOM domain (Figure 2a), Hillsborough Bay hosts four of these: the Hillsborough and Alafia rivers, the Tampa Bypass Canal, and Bullfrog Creek (Figure 2b), with averaged discharge rates during the model simulation period of about 8.7 (although for most of this time the discharge is 0.0), 7.88, 2.1, and 0.8 m^3/s, respectively in the dry season, and about 27.3, 27.3, 5.7, and 2.9 m^3/s, respectively in the wet season. The realistic time series of river fluxes were used in the experiments.

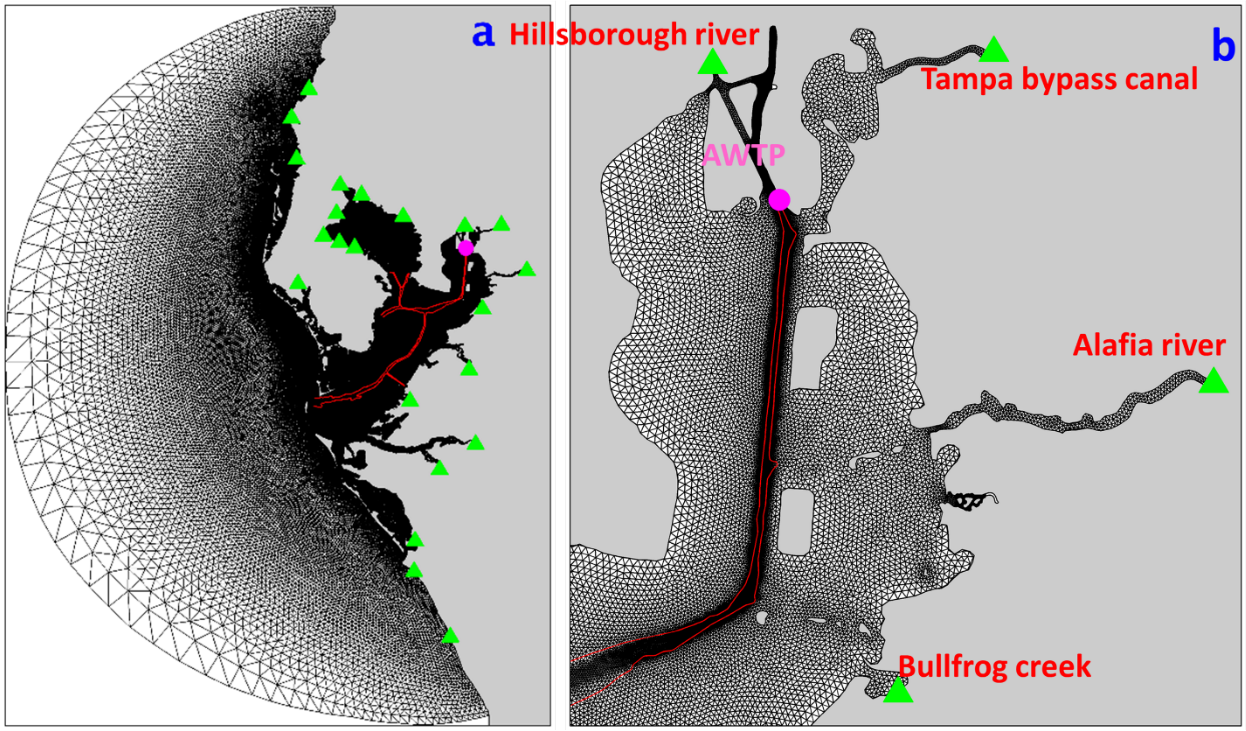

Figure 2. The locations (green triangles) of river discharge in the TBCOM model domain (a) and a zoomed view of the Hillsborough Bay subregion (b). The pink dots represent the location of the HFCAWTP outfall. The red lines indicate the shipping channel.

In comparison with the natural river inflows to Hillsborough Bay, the discharge record for the HFCAWTP outfall is shown in Figure 3. These discharge rates range from 1 to 3 m^3/s over most of the record, so we chose 3 m^3/s (106 cfs) as the HFCAWTP discharge to use in the simulation. The salinity of this HFCAWTP outfall was set as 1 psu based on the observations provided. Whereas the choice of 3 m^3/s is larger than the mean (that visually looks closer to 2 m^3/s), there are times of larger discharge, so this choice seems reasonable.

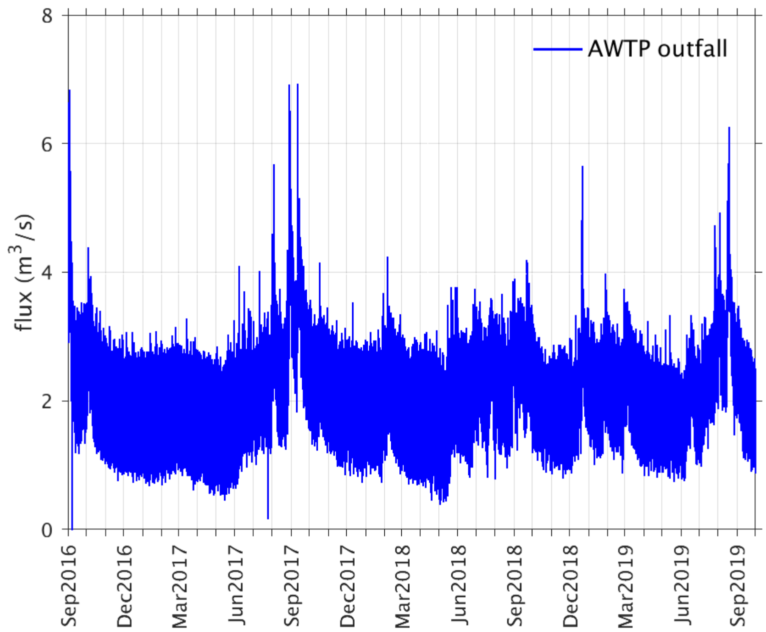

Figure 3. The discharge record for the Howard F. Curren Advanced Wastewater Treatment Plant outfall into Hillsborough Bay.

4 Results

The nontidal, near-surface circulations during the wet season (Figures 4a and 4b) show a generally directed outflow, whereas by virtue of the vertically integrated salinity compensation to the pressure gradient (baroclinic pressure gradient), the near-bottom circulations (Figure 4d and 4e) show a generally directed inflow. The mean flow distribution complexities, both at the surface and bottom, reflect the geometrical complexities of the Hillsborough Bay and its main shipping channel. Consistent with, and as explained in the earlier work of Weisberg and Zheng (2006), there is a general convergence of flow into the main shipping channel at the surface, where the surface dynamic height tends to have a local minimum, and a divergence away from the main shipping channel near the bottom. Thus, at least over the deeper portion of the bay, the mean circulation exhibits a classical two-layered estuarine circulation pattern, as expected. The differences of the nontidal circulations between the two experiments are shown in Figures 4c and 4f. No substantive differences are seen. Quantitatively, the differences between the average current speeds with and without the outfall within a 200 m radius of HFCAWTP amount to 3.6 cm/s at the surface and 0.6 cm/s at the bottom (Table 1). These reduce further to less than 1 cm/s over a 3000 m radius, which is near the detection limit of a velocity measuring device such as an acoustic Doppler current profiler (ADCP).

The influences of HFCAWTP on the average circulations for the dry season are shown in Figure 5. Whereas the differences for the nontidal circulations between the experiments with and without the HFCAWTP outfall during the dry season are slightly larger when compared with the wet season, these differences are still quite small (Table 1).

The non-tidal salinity distributions during wet season within the near surface (Figures 4a and b) and near bottom sigma layers (Figures 4d and e) follows the circulation. Salinity generally decreases from the Hillsborough Bay mouth to its head, both at the near surface and near bottom, but with the up-estuary advection of salt being most evident near the bottom along the main shipping channel. The differences of the nontidal salinity between the two experiments are shown in Figures 4c and 4f. As with the nontidal circulation, no substantive differences are observed. The salinity in Hillsborough Bay increases when the HFCAWTP outfall is removed, but this increase, over most of the bay, is quite small. Quantitatively, the differences between the average salinity over the whole bay with and without the outfall amount to 0.21 psu at the surface and 0.16 psu at the bottom (Table 2). The increase is a bit larger to 0.36 psu at the surface and 0.18 psu at the bottom over a 1000 m radius. Immediately adjacent to the HFCAWTP outfall (200 m radius), the salinity increases by about 0.75 psu at the surface and 0.18 psu at bottom.

Table 1. Time and space average change of current speed within different distance away from the HFCAWTP.

Radius from HFAWTP	Difference of speed (wet season)		Difference of speed (dry season)	
	Surface (cm/s)	Bottom (cm/s)	Surface (cm/s)	Bottom (cm/s)
200m	3.6	0.6	5.6	1.6
500m	2.0	0.3	3.8	1.0
1000m	1.4	0.2	2.7	0.8
3000m	0.5	0.1	1.1	0.3
Hillsborough bay	0.2	0.0	0.7	0.2

For the dry season, the influence of HFCAWTP on the average salinity is increased due to the decrease of the natural river influxes (Figure 5). Whereas the differences for the average salinity between the experiments with and without the HFCAWTP outfall during the dry season are slightly larger when compared with those during the wet season, these differences are still quite small (Table 2).

Table 2. Time and space average change of salinity within different distance away from the HFCAWTP.

Radius from HFAWTP	Difference of salinity (wet season)		Difference of salinity (dry season)	
	Surface (psu)	Bottom (psu)	Surface (psu)	Bottom (psu)
200m	0.75	0.18	2.38	0.48
500m	0.46	0.18	1.52	0.48
1000m	0.36	0.18	1.11	0.44
3000m	0.27	0.17	0.73	0.43
Hillsborough bay	0.21	0.16	0.46	0.33

Recognizing that instantaneous and record length-averaged (61-day average) distributions of nontidal current and salinity may differ, the analyses also include an examination of the instantaneous currents and salinity. The distributions of the near surface instantaneous currents and salinity throughout Hillsborough Bay sampled over about one semidiurnal tidal cycle either with or without the HFCAWTP outfall, and their differences are shown in Figures 6 and 7, respectively, for the wet season simulation. The instantaneous current is much stronger than the record length-averaged current because the record length-averaging filters out the tidal current variations that generally are much stronger than the non-tidal currents (by gravitational convection). In both simulations (with or without the HFCAWTP outfall), the isohalines move up and down estuary with the tidal current. Thus, at any given location, the salinity usually varies by a few psu. While not shown, salinity also varies on the time scales of weather frontal passages (days to weeks) as well as seasonally. All of these natural variations (by tides, winds and rivers) have salinity effects that are much larger than the small effects found for the cessation of the HFCAWTP outflows.

One additional point that requires mention is that TBCOM, as presently run, does not include evaporation and precipitation. Consequently, TBCOM tends to underestimate salinity (i.e., evaporation – precipitation tends to increase the salinity of Tampa Bay). This effect results in a systematic error for salinity, but one that is on a spatial scale much larger than the HFCAWTP outflow scale. In other words, the omission of evaporation-precipitation in the present TBCOM simulation does not influence our findings on the salinity variations due to a cessation of the HFCAWTP outflow in any way.

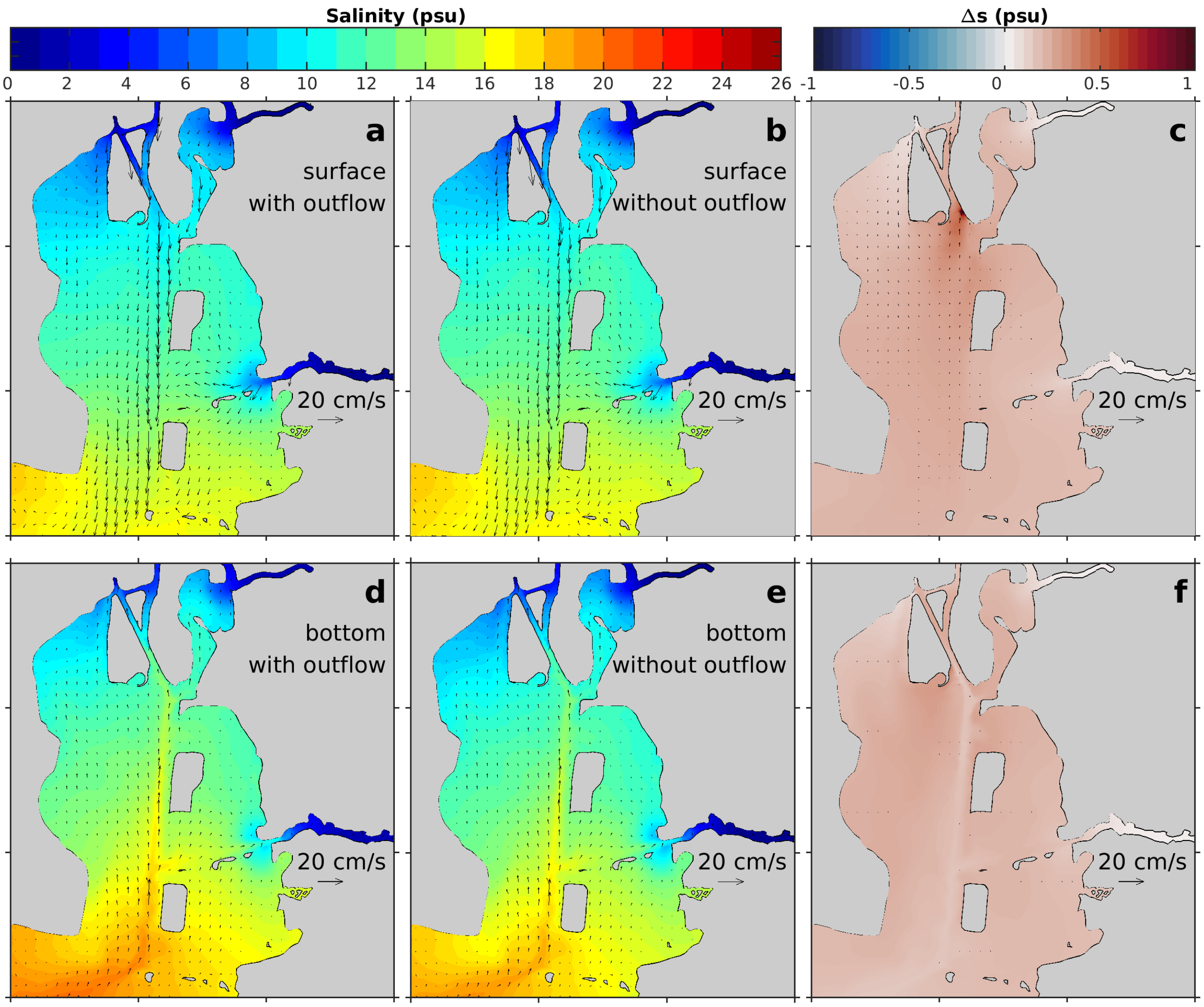

Figure 4. Model results of nontidal (61-day average) currents (arrows) and salinity (color coded) during the wet season. Distributions of the nontidal currents and salinity throughout Hillsborough Bay at the near surface (a, b) and the near bottom (d, e) layers for the experiment either with the HFCAWTP outfall (left column), or without the HFCAWTP outfall (middle column). The differences of the average currents and salinity between the two experiments (with and without the HFCAWTP outflow) in the near surface (c) and the near bottom (f) layers.

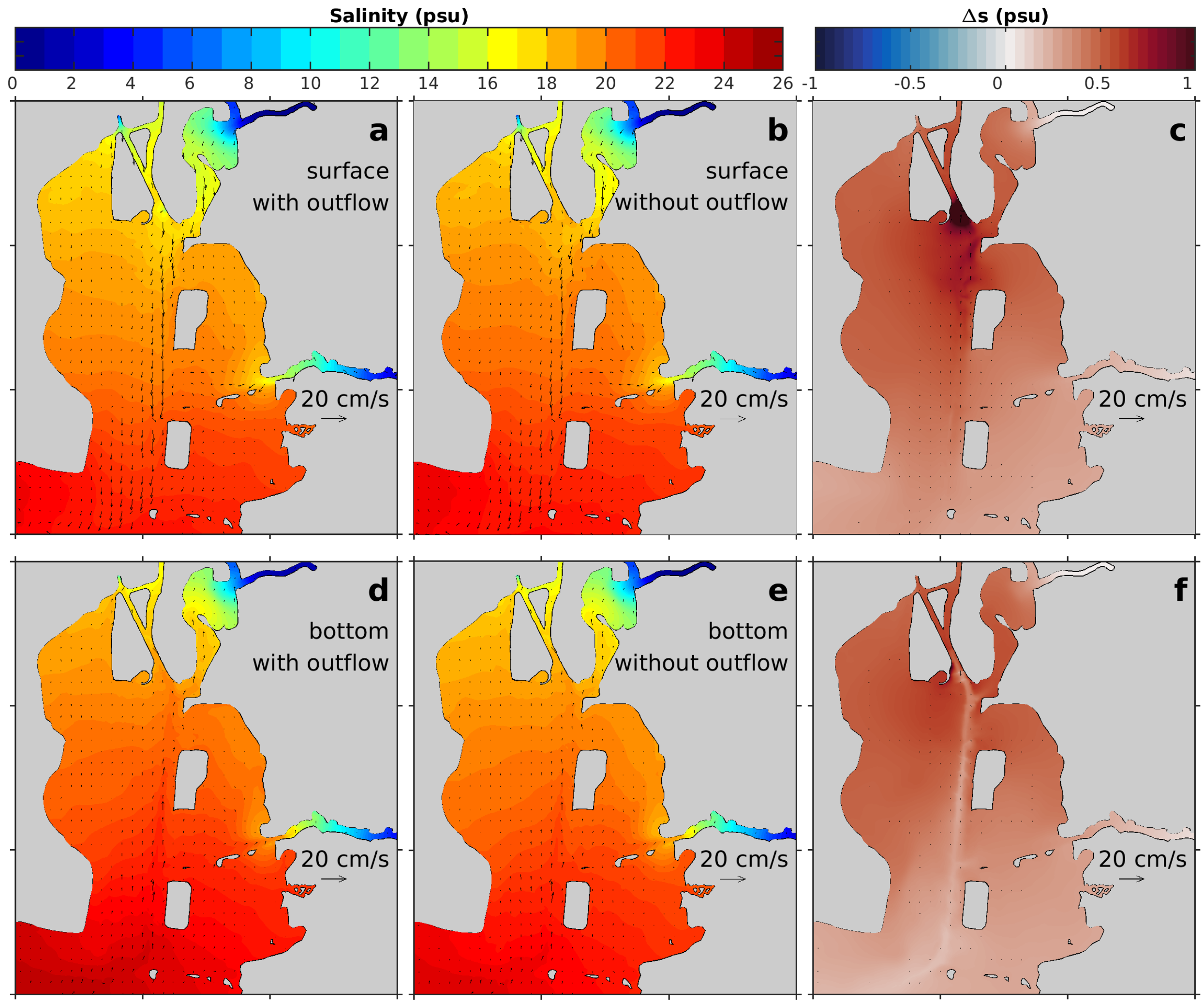

Figure 5. Same as Figure 4 but for the dry season.

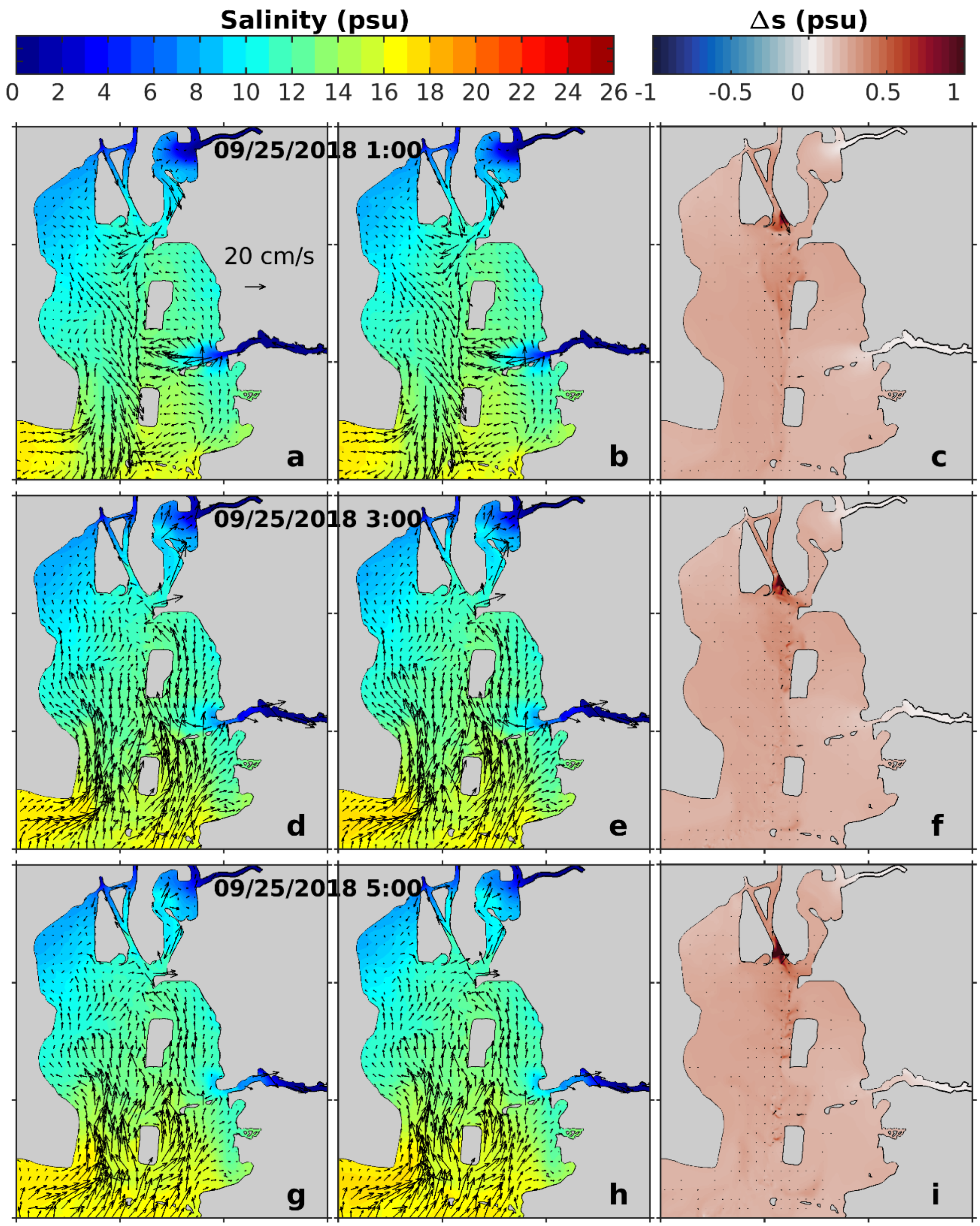

Figure 6. Instantaneous, near surface layer currents (arrows) and salinity distributions (color coded) during the wet season within Hillsborough Bay sampled at 2 hour intervals simulated by TBCOM, either with the HFCAWTP outfall (left column), or without the HFCAWTP outfall (middle column). The right column shows the differences between the middle and left columns.

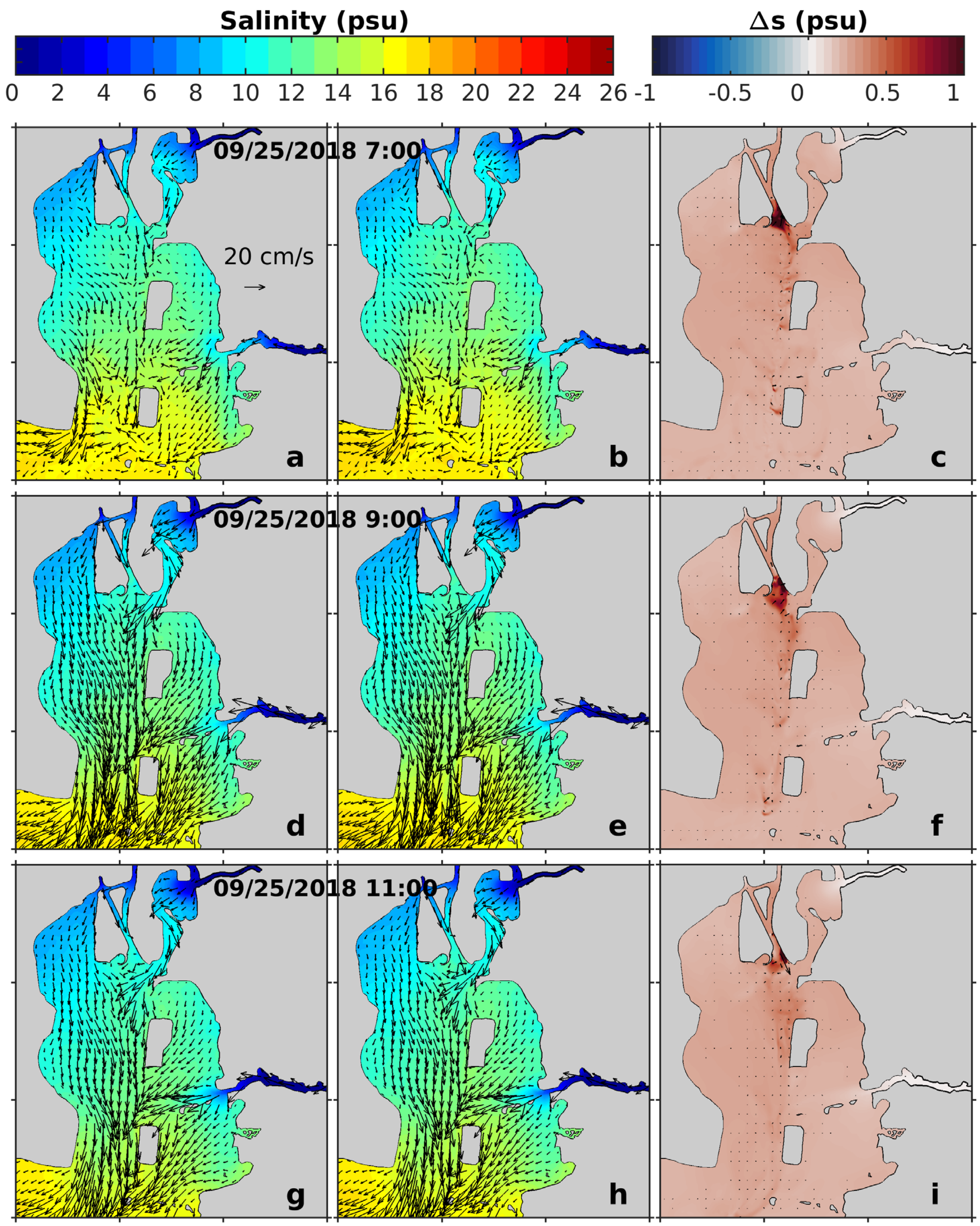

Figure 7. Continuation of Figure 6.

5 Estimation of the effect of salinity through Knudsen theorem

The distribution of salinity in an estuary is influenced by advection (the circulation) and mixing, assuming negligible precipitation and evaporation changes occurring over a short duration. To simulate these processes the model must be fully three-dimensional, density dependent and with a mixing parameterization that is also flow dependent (the larger the flow and the flow gradients, the larger the mixing). TBCOM has these attributes.

Despite these complexities, we may crudely estimate the effects of freshwater inflow modification by using a simplified, mean estuary circulation (the upper layer being directed seaward and the lower layer landward) construct yielding what is referred to as the Knudsen theorem (e.g., Knudsen, 1900, MacCready and Geyer, 2010, Burchard et al., 2018) that may be derived by considering Figure 8. On average, there exists a water volume outflow near the surface and an inflow at depth (Q_{out} and Q_{in}, respectively) at the mouth of the estuary, plus an inflow of river water (Q_R) at the head of the estuary. In a steady balance condition, the salt flux through the mouth of the estuary is control by the river flux and the exchange flow.

Given this theorem, we may ask what the change in the mean salinity of the estuary may be if amount of the inflowing river water is changed. We can do this by balancing both the mass of water and the mass of salt with a well-mixed, box model as depicted in the Figure 8.

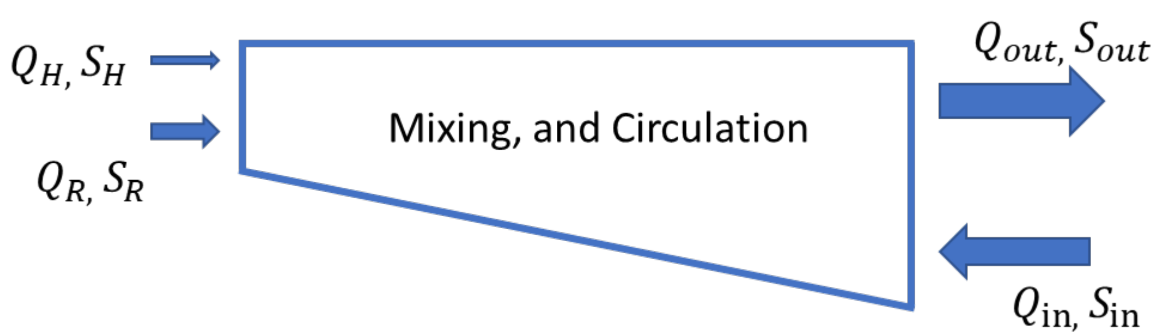

Figure 8. Schematic of simplified box model.

Here, Q_R is the volume flux of the river, Q_H is the volume flux of the HFCAWTP, Q_{out} is the volume flux of upper branch of estuarine circulation out of the estuary, Q_{in} is the volume flux of lower branch of estuarine circulation in the estuary. Thus, to balance the mass of water:

$$Q_{out} = Q_{in} + Q_R + Q_H \qquad (1)$$

If each of these water fluxes contain a certain salinity, then the volume flux of water times the salinity gives the salt flux. In the steady state these must also balance. Let (S_H, S_R, S_{in}) be the salinities of the water flowing into the bay and let S_{out} be the salinity of the water flowing out of the bay; hence,

$$Q_{out}S_{out} = Q_H S_H + Q_R S_R + Q_{in} S_{in} \qquad (2)$$

For Hillsborough Bay: Q_R = (27.3+27.3+5.7+2.9) m^3/s= 63.2 m^3/s and S_R = 0 psu, and for HFCAWTP: Q_H = 3 m^3/s and S_H = 1 psu.

We assume an average Hillsborough Bay depth of 3 m with equal inflow and outflow depths of 1.5 m each and the average speed of the estuarine circulation of 0.03 m/s. Further, taking the width of Hillsborough Bay at its mouth to be 6300 m (from Google Earth), we can estimate:

$$Q_{in} \approx 1.5\text{m}*6300\text{m}*0.03\text{m/s}=283.5\ \text{m}^3/\text{s}$$

$$Q_{out} \approx Q_{in} + Q_R + Q_H = 349.7\ \text{m}^3/\text{s}$$

Assume the salinity of this landward flux S_{in} to be 20psu, we can then estimate S_{out} from (2):

$$S_{out} = (Q_H S_H + Q_R S_R + Q_{in} S_{in})/Q_{out}$$

Thus, with the HFCAWTP included: S_{out} = 16.22 psu, whereas with the HFCAWTP excluded: S_{out} = 16.35 psu. The difference between these two estimates amount to: ΔS = 16.35-16.22 = 0.13 psu, which is similar to what was estimated from the much more complete TBCOM simulation.

The reason for this small change is that neither the volume flux, nor the salinity of the inflowing water will change much with the HFCAWTP outflow, which is small when compared with the natural river inflows or with the mean estuary circulation. Moreover, given the flushing time for Tampa Bay of several months (Zhu et al, 2015b), the transitions from wet to dry seasons of shorter duration also will not alter the influx through the Hillsborough Bay mouth enough to significantly modify this finding.

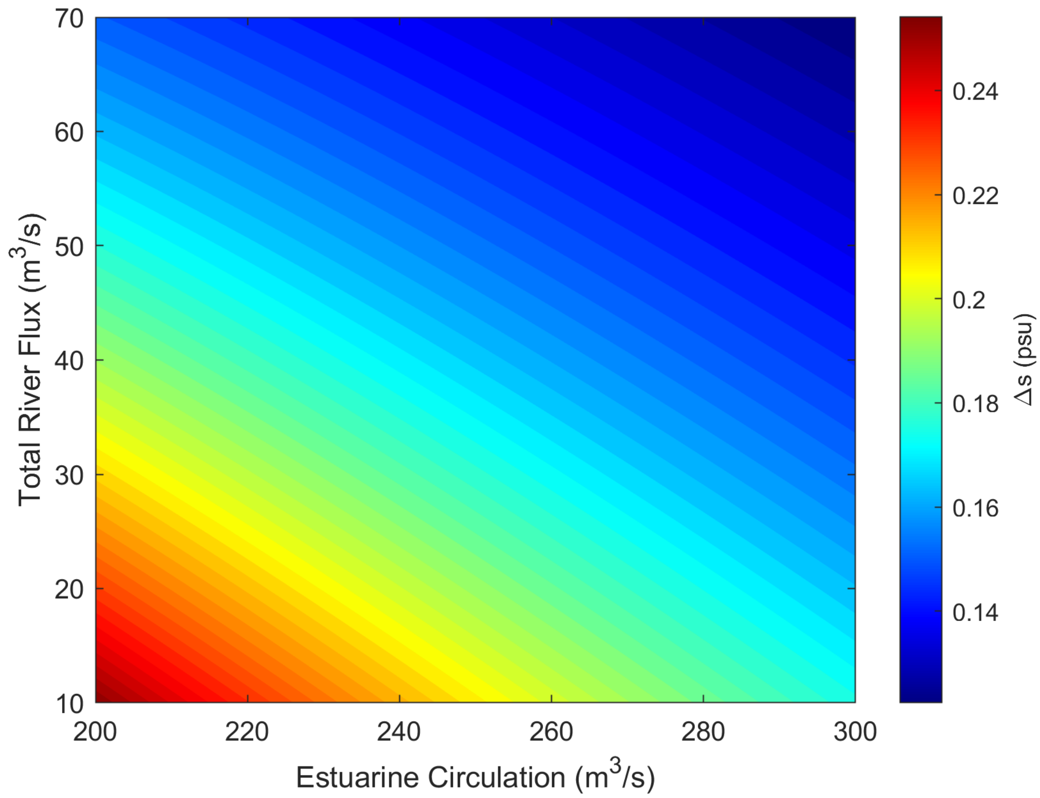

Figure 9. Change of average salinity (ΔS) Hillsborough Bay under different river flux and estuarine circulation circumstances due to the removal of HFCAWTP outflow calculated by Knudsen theorem.

The river flux can be affected by evaporation, precipitation and human activities. The estuarine circulation can be affected by wind and tide. In order to have a better estimation of the influence of HFCAWTP inflow modification on Hillsborough Bay's salinity, the changes of average salinity in Hillsborough Bay under different river flux and estuarine circulation conditions assuming 3 m^3/s HFCAWTP inflow calculated by Knudsen theorem are shown in Figure 9. We can see that the changes are increased due to the lower river discharge and estuarine circulation. In the extremely low river flux (10 m^3/s) and estuarine circulation (200 m^3/s) case, the change of average salinity in Hillsborough Bay is about 0.26.

6 Summary and Conclusions

We applied the Tampa Bay Coastal Ocean Model (TBCOM) to assess the potential effects of terminating the discharge of treated reclaimed water into the Hillsborough Bay portion of Tampa Bay at the location of the Howard F. Curren Advanced Wastewater Treatment Plant (HFCAWTP) outflow. TBCOM is a numerical circulation model that downscales from the deep ocean, across the continental shelf and into Tampa Bay with veracity sufficiently demonstrated to justify its utility for addressing salinity and circulation changes owing to the HFCAWTP discharge being switched on or off.

The numerical experiment approach was to consider the HFCAWTP discharge being either on or off during either wet or dry seasons. The differences for the nontidal circulations and salinity between the experiments with and without the HFCAWTP outfall during the dry season are slightly larger when compared with the wet season. This is due the smaller river flux input to the bay during the dry season. Smaller river flux in dry season makes HFCAWTP flux relatively important at this period of time compared with wet season. The differences of salinity and currents are small compared with the tidal variation when investigating the distribution of the near surface instantaneous currents and salinity over about one semidiurnal tidal cycle either with or without the HFCAWTP outfall.

As a check on the numerical experiments, we also considered a simpler, analytical approach using the relationships between estuarine fresh water inflows and salinity. Through the Knudsen theorem, the estimated salinity different between two cases is small. This is mainly because the HFCAWTP outflow is small when compared with the natural river inflows or the mean estuary circulation. This simple box model derived from Knudsen theorem confirms the order of the magnitude of the salinity change estimated with the numerical model. For more precise result and temporal and spatial variation, we still need to rely on the numerical model.

In conclusion, the potential reduction of the treated reclaimed water inflow from HFCAWTP will not significantly affect the circulation or the salinity distributions of Hillsborough Bay or the larger Tampa Bay. These effects are very localized and minimal when compared with variations that occur naturally. This finding in Hillsborough Bay by both numerical and the box model derived from the Knudsen theorem may be applied to water bodies with similar environmental conditions. A caveat is that the Knudsen theorem approach provides bulk estimation, versus a site-specific estimation. If the latter is required, then a high-resolution numerical circulation model is the appropriate estimation tool.

Given the application presented herein, plus other recent applications discussed in section 1, TBCOM offers opportunities for a variety of interdisciplinary environmental applications throughout Tampa Bay, Sarasota Bay, the Intra-Coastal Waterway and all of the connections between these and the adjacent GOM.

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