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Towards the Development of a Coastal Prediction System for the Tampa Bay Estuary

by

Heather Holm Havens

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Marine Science
College of Marine Science
University of South Florida

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Dedication

I wish to thank everyone in the Ocean Monitoring and Prediction Lab for their support. To my lab mates Monica Wilson and Sherryl Gilbert for always having their doors open. To Vembu Subramanian for his technical support and comic relief. To Steve Meyers for his assistance with modeling issues and editing. To my committee members, Paula Coble, Cindy Heil and John Paul for their scholarly advice. A special thanks to my advisor, Mark Luther, for his compassion and guidance throughout my time at USF. For all of my friends and family for their support to get me to this point, especially my parents. To my husband for his continuous encouragement and for being a partner in my journey.

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Towards the Development of a Coastal Prediction System for the Tampa Bay Estuary

Heather Havens

ABSTRACT

The objective of this research is to evaluate a coastal prediction system under various real world scenarios to test the efficacy of the system as a management tool in Tampa Bay. The prediction system, comprised of a three-dimensional numerical circulation model and a Lagrangian based particle tracking model, simulates oceanographic scenarios in the bay for past (hindcast), present (nowcast) and future (forecast) time frames. Instantaneous velocity output from the numerical circulation model drives the movement of particles, each representing a fraction of the total material, within the model grid cells.

This work introduces a probability calculation that allows for rapid analysis of bay-wide particle transport. At every internal time step a ratio between the number of particles in each individual model grid cell to the total number of particles in the entire model domain is calculated. These ratios, herein called transport quotients, are used to construct probability maps showing locations in Tampa Bay most likely to be impacted by the contaminant.

The coastal prediction system is first evaluated using dimensionless particles during an anhydrous ammonia spill. In subsequent studies biological and chemical characteristics are incorporated into the transport quotient calculations when constructing probability maps. A salinity tolerance is placed on particles representing *Karenia brevis* during hindcast simulations of a harmful algal bloom in the bay. Photobleaching rates are incorporated into probability maps constructed from hindcast simulations of seasonal colored dissolved organic matter (CDOM) transport.

The coastal prediction system is made more robust with the inclusion of biological parameters overlaid on top of the circulation dynamics. The system successfully describes the basic physical mechanisms underlying the transport of contaminants in the bay under various real world scenarios. The calculation of transport quotients during the simulations in order to develop probability maps is a novel concept when simulating particle transport but one which can be used in real-time to support the management decisions of environmental agencies in the bay area.

Dissertation Introduction

Tampa Bay is the largest open water estuary in Florida (Hu et al., 2004) and is home to the 10th largest port system in the United States (Lewis et al., 1999). Many anthropogenic stresses to the water quality in Tampa Bay are the result of growing urban and agricultural watersheds (Bricker et al., 2007) surrounding the bay. Anthropogenic stresses include dredging to accommodate commercial shipping vessels (Bricker et al., 2007; Vincent, 2001), non-point source pollution resulting in excess nitrogen loading (Cross, 2007; Greening and Janicki, 2006; Morrison et al., 2006) and hazardous material spills (Lewis et al., 1999; Owens and Michel, 1995). As a result, Tampa Bay has been the focus of major water quality restoration efforts in recent years (Greening and Janicki, 2006). Natural stresses to the water quality in the bay are present in the form of annual harmful algal blooms of *Karenia brevis* initiated offshore in the Gulf of Mexico and brought into Tampa Bay by complex circulation features (Steidinger et al., 1998; Walsh et al., 2001).

Several monitoring programs regularly sample in Tampa Bay for water quality parameters such as excess nutrients (Florida Department of Environmental Protection (FDEP)) and harmful algae (Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWRI)). These sampling programs constitute separate

studies carried out by different agencies and are primarily event response in nature. A need exists to better understand the transport and fate of these water quality parameters in Tampa Bay through the development of a real-time water quality monitoring program.

For a coastal monitoring program to exist in real-time a prediction system that is capable of ingesting real-time meteorological (wind speed and direction) and circulation (water level, salinity and fresh water flux) data needs to be developed. The data acquisition, processing and quality control should be automated. Numerical modeling of this data should be periodically ground-truthed with sampling data to determine the accuracy of the model at predicting the distribution of bay-wide water quality parameters. Results should be easily accessible to the water management community via the internet.

This dissertation details research towards the development of a coastal prediction system and its capability as a predictive management tool for Tampa Bay. Predictions made by the system encompass the simulation of oceanographic parameters in the past (hindcast), present (nowcast) and future (forecast) time frames (Vincent, 2001). The prediction system is comprised of a numerical circulation model coupled with a Lagrangian particle tracking model. A Lagrangian tracking scheme prevents artificial diffusion and allows for realistic particle movement versus an Eulerian approach which is overly diffusive (Burwell, 2001).

The circulation model simulates the physical dynamics within the estuary using real-time oceanographic forcing conditions. The particle tracking model simulates the transport of

material within the bay using dimensionless particles or with the incorporation of non-conservative behaviors. Probability maps are generated from the particle tracking simulations to show probability distributions of material in Tampa Bay based on location. Four studies are carried out to examine the efficacy of the coastal prediction system as a management tool.

First, the coastal prediction system is utilized in real-time during a hazardous material spill with the purpose of alerting authorities to potential high impact areas in Tampa Bay. Forecast particle distributions are used by FWRI scientists to guide sampling for increased algal concentrations that could result from the flux of nutrients into the bay. The effectiveness of the prediction system as an event response tool is examined and the data are ground-truthed with samples collected by the FDEP and the FWRI.

Second, the spatial distribution of a harmful algal bloom is simulated and compared with samples collected by the FWRI in 2005 during the peak of a previous *Karenia brevis* bloom in Tampa Bay to determine the capacity of the model to capture general features of the observations. Particles are given a post-processing salinity tolerance based on the measured salinity range of *K. brevis* in the field. The capability of the model to reproduce the dispersion of an event in hindcast mode is critical in the determining the accuracy of the prediction system.

Third, the distribution of colored dissolved organic matter (CDOM) from the four largest freshwater riverine sources in Tampa Bay is examined during both wet and dry season

conditions. Daily decay rates are imposed on the particles to simulate seasonal CDOM photobleaching rates measured in the field. The ability to incorporate non-conservative behaviors into the prediction system distribution maps is a powerful tool to more precisely describe freshwater content in Tampa Bay.

Finally, the prediction system is evaluated during a FDEP study to forecast the advection of nitrogen from an urbanized region of Tampa Bay. This study examines the extent to which circulation in this region affects water quality and subsequently seagrass growth. The combination of a forecast simulation with field work is an example of adaptive sampling and is used as a method for verifying the prediction system results.

Together these studies constitute initial parameterizations of a coastal prediction system developed for Tampa Bay. The prediction system assisted managers in real-time during a hazardous material spill and successfully predicts the location of a resulting algal bloom. Hindcast simulations, generated from the prediction system, of a harmful algal bloom correlate well with samples collected at the time of the event. The distributions of freshwater and nutrient fluxes are mapped and examined in relation to seagrass coverage. Each of these studies are conducted with the purpose of better understanding the transport and fate of water quality parameters in the Tampa Bay estuary while also supporting management decisions for environmental issues affecting the bay. To this end, an online component of the coastal prediction system, that incorporates results from the studies that follow, is in development to better manage response and mitigation efforts in Tampa Bay.

Chapter 1: Particle Tracking Simulation of an Anhydrous Ammonia Spill

Introduction

The hydrodynamics of the Tampa Bay estuary are influenced primarily by astronomical tides, winds and river runoff (Vincent, 2001). Classical estuarine circulation (Pritchard, 1967) for a partially to well-mixed estuary such as Tampa Bay, has a two-layered flow with fresh water flowing towards the mouth of the estuary at the surface and saline water flowing landward at depth. Bay-wide estuarine circulation varies depending on environmental conditions and is the driving force behind the advection of material within the bay (Weisberg and Zheng, 2006).

Reliable and accurate observations and predictions of bay-wide circulation assist with commercial shipping, hazardous material response and environmental management. The potential for accidental or intentional contamination within Tampa Bay is significant due to the types of hazardous materials (e.g. petroleum products, sulfuric acid and anhydrous ammonia) regularly transported through the Port of Tampa by commercial vessels. In the event of a hazardous material spill within Tampa Bay operational prediction models can be used to accurately predict, or forecast, the transport of the pollutant (Vincent, 2001).

Circulation models have been developed to simulate the dispersion of pollutants (Dimou and Adams, 1993; Gomez-Gesteira et al., 1999; Scott, 1997) where transport and fate are best described by the movement of individual particles rather than their concentration. Particle transport models generally consist of two components: a hydrodynamic component to define the kinetics of the flow and a particle tracking component to define the transport of the pollutant (Benkhaldoun et al., 2007). A coastal prediction system has been developed for Tampa Bay that interfaces a realistic numerical circulation model with meteorological forecasts to predict the hydrodynamics within the bay. Overlaid on top of the circulation model is a Lagrangian particle tracking model which simulates the transport of contaminants by assigning a particle to a water mass and following the particle as it is advected by the instantaneous model velocity field (Burwell, 2001; Meyers and Luther, 2008). Similar prediction systems have been developed to simulate the transport of contaminants in locations where two-dimensional barotropic circulation is sufficient (Gomez-Gesteira et al., 1999; Periáñez, 2004); fully three-dimensional simulations are necessary to resolve the gravitational circulation controlling the advection of materials in Tampa Bay (Weisberg and Zheng, 2006).

The Tampa Bay coastal prediction system is evaluated during a hazardous material spill. The particle tracking model predicts the dispersion of material based on forecast circulation dynamics and records the distribution of particles at each internal time step. From these particle distributions probability maps are constructed showing areas in the bay with the highest potential for contamination. Periáñez (2004) simulated the dispersion of contaminants in the Strait of Gibraltar using a similar model configuration

(hydrodynamics plus particle tracking). No evaluation of their model was performed during a spill event.

The objective of this paper is to describe the Tampa Bay coastal predication system and to determine whether the forecasting component of the system can assist responders during an anhydrous ammonia spill in Tampa Bay. The numerical model and observational parameters are discussed in the following section. Comparisons between the particle transport simulation and in situ ammonium measurements are discussed. The utility of the particle transport simulation in alerting responders to areas of Tampa Bay with the highest probability of being affected by the spill is evaluated based on sampling conducted using model output. Conclusions are drawn as to the physical transport mechanisms affecting the spill and the effectiveness of the model forecast at predicting this transport.

Methods

The coastal prediction system

A numerical circulation model, based on the Princeton Ocean Model (Blumberg and Mellor, 1987), is forced with real-time oceanographic observations of the physical forcing functions for Tampa Bay to produce three-dimensional fields of circulation, temperature, salinity and water level in past (hindcast) and future (forecast) time frames. The hindcast model uses quality controlled data for boundary conditions and the forecast

model is initialized from the most recent hindcast output fields and holds constant the final model boundary conditions (except for wind speed and direction which are held at predicted values obtained from the National Weather Service).

The circulation model used in this study is that developed by Meyers et al. (2007) which divides the bay into a 70 by 100 grid of cells in the horizontal and 11 sigma levels in the vertical. The model is forced at the bay mouth with water level obtained from the Tampa Bay Physical Oceanographic Real-Time System (TB-PORTS) and salinity obtained from the Environmental Protection Commission (EPC). Winds, evaporation and precipitation are forced uniformly over the entire model surface. The model simulation is also forced at discrete points using daily observations of fresh water flux (rivers and canals) obtained from the US Geological Survey (USGS) National Water Information System and monthly averaged wastewater discharge obtained from treatment plants. A detailed description of the model hydrodynamics and evaluation can be found in Meyers et al. (2007). The instantaneous model velocity fields generated by the circulation model are used to drive the particle tracking model.

An algorithm developed by Burwell (2001) is used to advect dimensionless particles according to the simulated three-dimensional circulation model velocity field. Particles, each representing a fraction of the total hazardous material, are generated by the tracking model evenly throughout the water column within the grid cell closest to the site of the spill. A random walk technique (Dimou and Adams, 1993; Korotenko et al., 2004; Periáñez, 2004; Proctor et al., 1994) is used to simulate the dispersion of material by

linearly interpolating the position of each particle between time steps based on the velocities of neighboring grid cells and summed with a random vector function computed independently at every time step for each particle (Meyers and Luther, 2008). Lagrangian particle tracking code records the time and location of particles within the model grid cells at each time step; for this study the locations of particles are written to files every 30 min during a 7 day-long simulation.

At each time step the ratio between the number of particles in any individual model grid cell to the total number of particles in the model domain is calculated. This value is called the transport quotient, and is a measure of the likely distribution of hazardous material within Tampa Bay (see Appendix A). Cells with the highest transport quotients contain particles for the greatest amount of time during the simulation. Conversely, cells with low transport quotients during the simulation rarely contain particles. From these transport quotients a probability map can be constructed predicting the areas in Tampa Bay most likely to be affected by the transport of hazardous material.

Anhydrous ammonia spill

Bulk quantities of liquid anhydrous ammonia, a compound used in fertilizer production, are transported under high pressure into the Port of Tampa by ship and from there by pipeline to fertilizer production facilities in surrounding counties. The transport of material in this manner poses a potential health and pollution hazard should there be an accidental or intentional release of ammonia into surface waters. Anhydrous ammonia

rapidly dissolves upon contact with water into ammonium hydroxide; the amount dissolved into solution is dependent on pH, temperature and salinity of the water. Ammonium hydroxide remains at the water surface much like an oil slick (Raj et al., 1974)

The night of 12 November 2007 a rupture in an anhydrous ammonia pipeline occurred releasing an estimated 5-30 tons of ammonium hydroxide into the Alafia River over a period of two days. The Alafia River feeds directly into Hillsborough Bay (HB) in the northeast portion of Tampa Bay and subsequently into Middle Tampa Bay (MTB) (Figure 1). Two days after the spill strong northwesterly winds (order 20 knots) were recorded over a 24 h period within HB (Figure 2) influencing the transport of the hazardous material within Tampa Bay.

The model simulation was initialized on calendar day 18 November 2007 following a request for assistance by event responders. The modeling effort is split into hindcast and forecast phases. The Lagrangian tracking model first uses hindcast model output over model days 13-17 November 2007 to estimate spill position on the day the of model initialization (Figure 3). The source function (i.e. particle release point) for the model is the easternmost grid cell in the Alafia River (Figure 4). The tracking model then continues in forecast mode beginning on 18 November and continues for a 48-h period (Figure 3.) to predict the transport of ammonia in Tampa Bay.

The concentration of ammonium particles in the model is conserved throughout the hindcast/forecast simulation. The non-conservative properties of ammonium in seawater are ignored and ammonium is considered to be in solution with water however, it should be noted that ammonium concentrations are affected by chemical and biological activity and physical processes (Conomos et al., 1979). For example, ammonium hydroxide is readily consumed by phytoplankton and also interacts with sediment through adsorption and desorption (Chao et al., 2007). Some toxigenic species of *Pseudo-nitzschia spp.* have been shown to increase in number to form a bloom (>100,000 cells L^{-1}) in coastal waters rich in ammonium (Bates et al., 1998). Diatoms of the genus *Pseudo-nitzschia spp.* have been observed in Tampa Bay since the 1960s and are persistent in the bay at background concentrations (<1000 cells mL^{-1}) (Badylak et al., 2007). Therefore the anthropogenic introduction of ammonium into the bay is expected to impact phytoplankton growth.

In order to determine the impact the spill had on the ecosystem of the bay, water samples were collected on two occasions in order to determine (1) the starting concentration levels of ammonium in the Alafia River and (2) if there was a resulting change to phytoplankton biomass in Tampa Bay.

In the days immediately following the spill, water samples were collected at the surface along the Alafia River by scientists at the Florida Department of Environmental Protection (FDEP) to measure ammonium concentrations in the river. Samples were collected from stations starting the day after the anhydrous ammonia spill and continuing for 2 days (Figure 4). Station 1 was located about 1 km west of the spill site. The

remaining 9 stations continued westward down the Alafia River toward Tampa Bay. Station 9 was located in HB at the mouth of the river and station 10 was between two dredge spoil islands in HB.

Scientists at the Florida Fish and Wildlife Research Institute (FWRI) investigated phytoplankton concentration and community composition as a result of the increased ammonium levels in the bay. One water sample was collected from 12 different stations along the eastern coast of Tampa Bay (Figure 5) on 19 November 2007 at a depth of 0.5 meters and each of the 12 samples were analyzed for algal composition. The FWRI defines a low algal count as $>1x10^4$ cells L^{-1}, a medium count as $>1x10^5$ cells L^{-1} and a high count as $>1x10^6$ cells L^{-1} (for diatom species). The 12 sample sites were chosen by the FWRI due to the high probability of increased levels of ammonium in those areas based on the transport quotients generated by the coastal prediction system.

Results

Model results for 13-20 November 2007 show a plume of ammonium (represented by Lagrangian particles) moving down the Alafia River and into Tampa Bay (Figure 3). On the first day tidal currents carry the particles westward to the mouth of the Alafia River and then back towards the east. This oscillating tidal advection repeats for another day before the particles enter HB. The ammonium remains localized near the Alafia River for another day until it is carried southward. The ammonium is heavily concentrated offshore of Apollo Beach 2 days later. At the end of the simulation the particles are

distributed from Apollo Beach to the mouth of the Little Manatee River. The ammonium particles remained within 2 km of the eastern coast of Tampa Bay for the duration of the simulation.

Three representative cross sections of the bay are chosen to examine current flow: across central HB (aligned with the mouth of the Alafia River and bisecting the two dredge islands), across southern HB and across central MTB (aligned with the mouth of the Little Manatee River) (Figure 6). At each of these locations the average vertical structure of the currents over the 7-day simulation is calculated following the methods of Meyers et al. (2007). An outward (negative) flow is present at all depths along the eastern boundaries of each of the three cross sections with speed generally increasing toward the surface, ranging from about 2 cm s^{-1} near the bottom to 10 cm s^{-1} near the surface. In central HB the current is flowing inward (positive) within and above the shipping channel, except for a small area at the surface, with a maximum speed greater than 8 cm s^{-1}. Flow is also positive to the west of the channel at all depths. In southern HB the flow is uniformly negative within the upper two meters of the water column. Maximum outflow is about 15 cm s^{-1} on the surface of the eastern coast and decreases with depth. Two areas of subsurface inflow are present: one is slightly offset to the east of the channel the other is located along the western edge of the channel. Their maximum speeds are only about 2 cm s^{-1}. In central MTB the vertical structure of the estuarine circulation breaks down and a horizontal gradient is found with outward flow within and to the east of the shipping channel. Again, the maximum speed is about 10 cm s^{-1}. Weak inflow (<2 cm s^{-1}) within the channel is confined to a few small areas along the eastern

slope and in the middle of the water column above the channel. A larger, but still weak, area of inflowing current is located to the west of the channel and extends from the bottom to about one meter below the surface.

The mean horizontal velocity in the Alafia River during the simulation is calculated as a function of depth and horizontal position (Figure 7). At the mouth of the river, flow is outward at all depths. The maximum outflow is at the surface and about 10 cm s^{-1}. A layer of inward flowing water with a maximum speed around 4 cm s^{-1} is found to the east of the mouth and follows the bathymetry of the river upstream creating a two-layered circulation pattern within the river. The net transport is upstream along the river bottom and downstream in the surface layers of the river.

A probability map is generated from model day 19 November 2007 of the forecast simulation (Figure 5). The model grid cells with the highest transport quotient values (concentration of particles) on that particular model day are the easternmost cells in the Alafia River and the cells offshore of Apollo Beach. The transport quotients decrease significantly to the south of the Little Manatee River and within MTB.

The FDEP water samples collected the day after the anhydrous ammonia spill, between station 2 and station 9 on the Alafia River, contained elevated concentrations of ammonium (>2 mg L^{-1}) (Figure 4). Samples were collected from station 2 on the first day only. On the second day samples from the upstream stations and the westernmost station (half of the samples collected) contained <1 mg L^{-1} of ammonium. Station 9,

located directly at the mouth of the river, was the only station where ammonium concentrations were higher on the second day of sampling than on the first day. The water samples collected 3 days after the spill contained concentrations of ammonium that averaged <0.5 mg L^{-1}. Samples from station 10, located within HB between two dredge spoil islands, never contained greater than trace amounts of ammonium (~0.02 mg L^{-1}) during the 3-day period. Similar concentrations of ammonium (0.01 mg L^{-1}) were recorded during another *Pseudo-nitzschia spp.* bloom (Bates et al., 1998). Concentrations of ammonium measured at each of the other stations were at least an order of magnitude higher than those recorded from station 10.

All algal samples were collected by the FWRI along the eastern coast of the bay on 19 November 2007, based on the forecast model estimates of ammonium distribution for that day (Figure 5). The *Pseudo-nitzschia spp.* cell counts collected by the FWRI for the first 3 stations were in the medium range. Samples from station 4, located to the north of Apollo Beach, contained cell counts of *Pseudo-nitzschia spp.* that constituted a large bloom. Cell counts from stations 1-3 to the north of Apollo Beach, station 5 to the south of Apollo Beach and station 6 at the mouth of the Little Manatee River were in the medium range for a *Pseudo-nitzschia spp.* bloom. Samples from the remaining stations constituted counts at low to background levels.

Discussion

The particle trajectory hindcast/forecast simulation demonstrates the physical dynamics in Tampa Bay following the anhydrous ammonia spill. Particles in the Alafia River are initially subject to tidal action and are retained within the river due to mixing within the upstream flowing bottom layers of the river (Figure 7). Particles that reach the river mouth, where flow is outward at all depths, are rapidly transported southward along the eastern coast of Tampa Bay due in part to the presence of a strong current, seen in each of the 3 velocity profiles (Figure 6) as well as strong northwesterly winds that act to pile water along the eastern boundary of the bay (Figure 2).

In order to determine what impact the 2-day wind peak on 15 November 2007 has on the transport of ammonium, a separate simulation is run holding winds constant at 5 m s^{-1} from the northeast. These conditions are those roughly found in the bay on 13 November. Results from this simulation (not shown) suggest that the wind peak plays a significant role in the transport of material within Tampa Bay. The particles emerge from the Alafia River on the second day of the simulation and disperse more widely throughout central HB and MTB. Few particles are found adjacent to the eastern coast. This demonstrates the need to use a realistic wind field when conducting the model prediction, even for a time period as short as 24 h.

Analyses of the collected water samples show that the simulation accurately models the transport of ammonium from the Alafia River. During the FDEP sampling period (13-15

November) model particles are not transported near the two spoil islands in HB. This is consistent with the trace levels of ammonium found at station 10 (Figure 4).

The model particle distribution was used by the FWRI to determine the algal sampling region. Scientists from FWRI measured a medium to large sized *Pseudo-nitzschia spp.* bloom on 19 November 2007 in the area where the model simulation indicates a high concentration of ammonium. The highest concentrations of *Pseudo-nitzschia spp.* were collected at station 4 just north of Apollo Beach where the transport quotient values are also high (Figure 5). Particle concentration in the model decreases to the south and west of Apollo Beach, consistent with decreasing *Pseudo-nitzschia spp.* concentrations collected from the surrounding stations to the south. No sampling was done away from the eastern coast of MTB, so the narrowness of the model particle distribution cannot be verified. The *Pseudo-nitzschia spp.* concentrations continue to decrease, as with the simulated ammonium concentrations, in southern MTB. The bloom is hypothesized to have formed due to increased ammonium that was transported out of the Alafia River and into the bay. The nature of an event response study is such that control measurements are rarely taken in advance. Consequently, there were no samples collected prior to the anhydrous ammonia spill to rule out the previous presence of a *Pseudo-nitzschia spp.* bloom.

Together the circulation model and the Lagrangian particle tracking model form the coastal prediction system for Tampa Bay which is capable of simulating the physical transport of pollutants in the bay. The simulations do not take into account the effects of

weathering or biological processes on the pollutants. As a result the particle concentration estimates are likely overestimated by an unknown factor. Future versions of the prediction system should incorporate realistic biological and chemical processes.

The coastal prediction system is used to support management decisions for several environmental issues affecting the bay (see Appendix B), specifically to simulate the trajectory of hazardous material spills for the FDEP and the FWRI. The models are capable of rapidly producing forecast simulations that, in the event of a spill, can alert authorities to areas in Tampa Bay with a high probability of being affected by the hazardous material. The prediction system at present is only accessible to scientists in the Ocean Monitoring and Prediction Lab (OMPL) at the University of South Florida. The forecast simulations are compiled into an animation that is provided to end users at their request. In the future, decision makers will be allowed access to an online component of the coastal prediction system. Event responders and other end users will be able to describe a spill scenario by entering criteria into an online form. The prediction system will ingest the criteria then, using real-time data compiled from TB-PORTS, display a 48 h simulation predicting how winds and currents will move the material around Tampa Bay. The ability to quickly set up custom scenarios will help manage response and mitigation efforts in real-time during an actual spill.

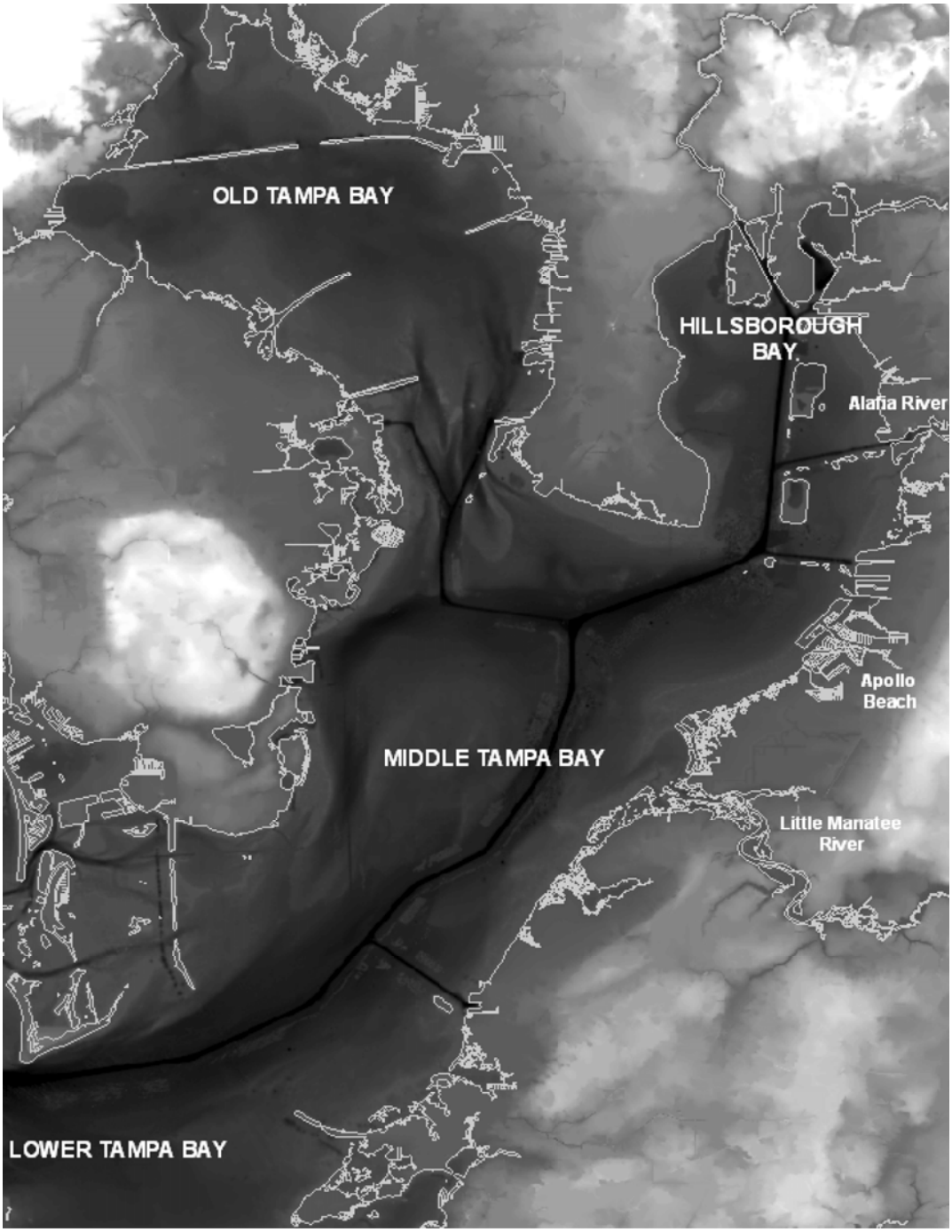

Figure 1 Bathymetric map of the Tampa Bay estuary. Tampa Bay can be divided into four quadrants: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB) and Lower Tampa Bay (LTB). A shipping channel runs from LTB through the central axis of the bay into MTB before splitting into two channels, one going to OTB the other to HB. The Alafia River drains the Hillsborough County watershed and empties into the eastern side of HB. An anhydrous ammonia spill occurred within the Alafia River and was transported into HB.

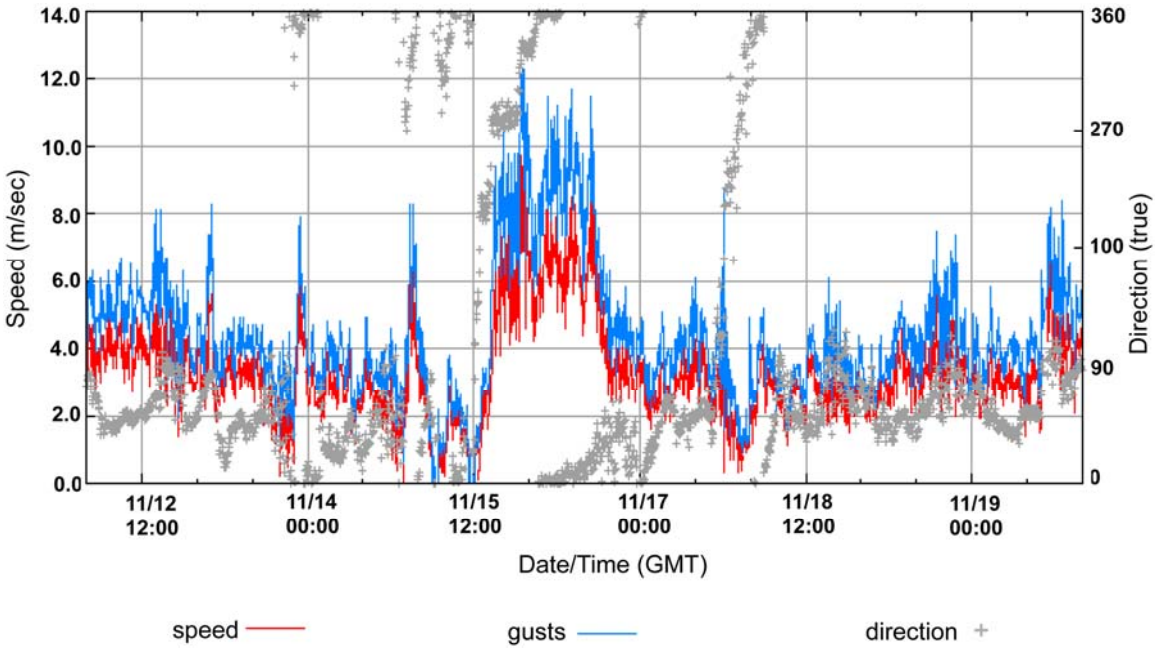

Figure 2 A National Oceanic and Atmospheric Administration (NOAA) plot showing winds in Hillsborough Bay from 12-20 November 2007. The plot shows wind speed (m/s) and direction (true) of winds during the week-long simulation. Wind speed (red) and wind gusts (blue) are overlaid on top of each other. The direction of winds is represented by hatch marks.

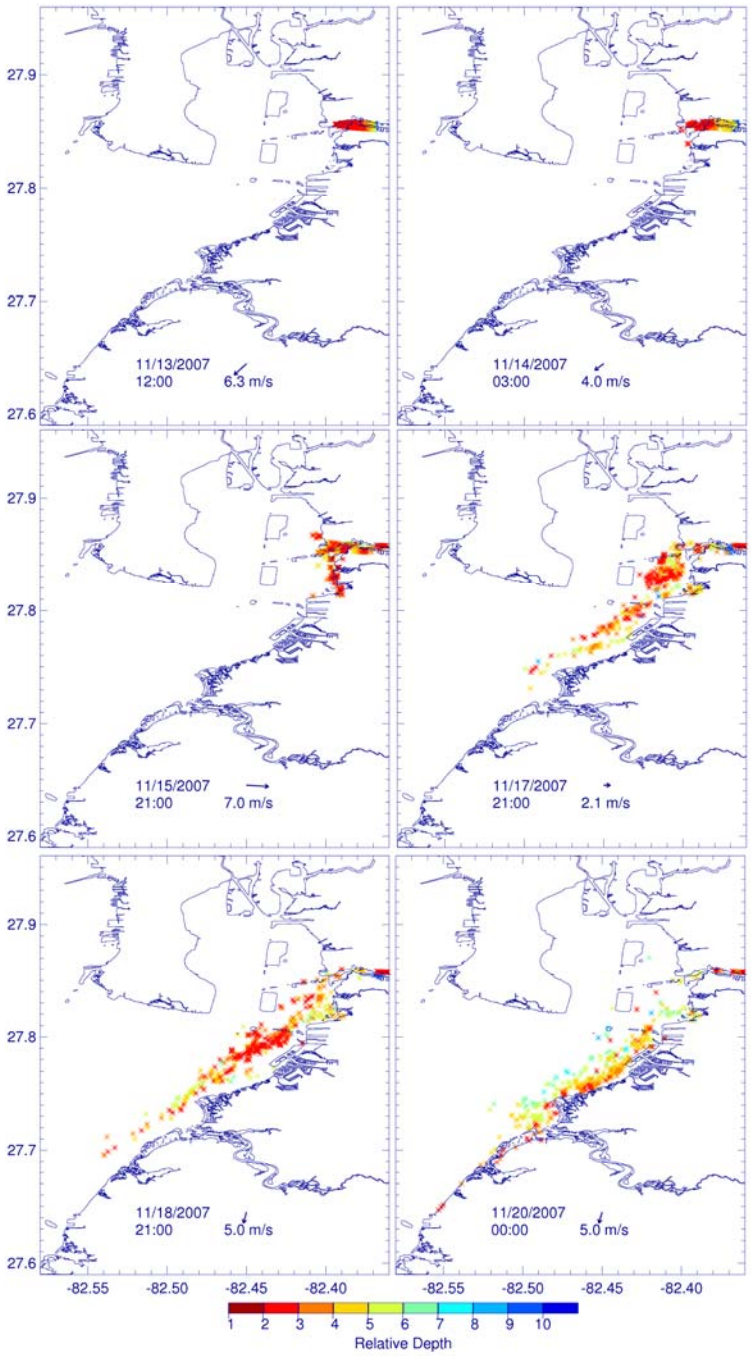

Figure 3 Frames from a numerical model simulation initialized on 18 November 2007 following an anhydrous ammonia spill in the Alafia River. The frames show the transport of model particles, representing ammonium, from the Alafia River in eastern Hillsborough Bay into Middle Tampa Bay. The simulation is run in hindcast mode from 13-17 November and in forecast mode from 18-20 November. The time stamp is in UTC. Wind speed (m/s) and direction (indicated by arrows) are shown for each frame. The scale represents the depth of the particles in the water column with values to the left of the scale being at the surface progressing to values to the right of the scale being at the bottom.

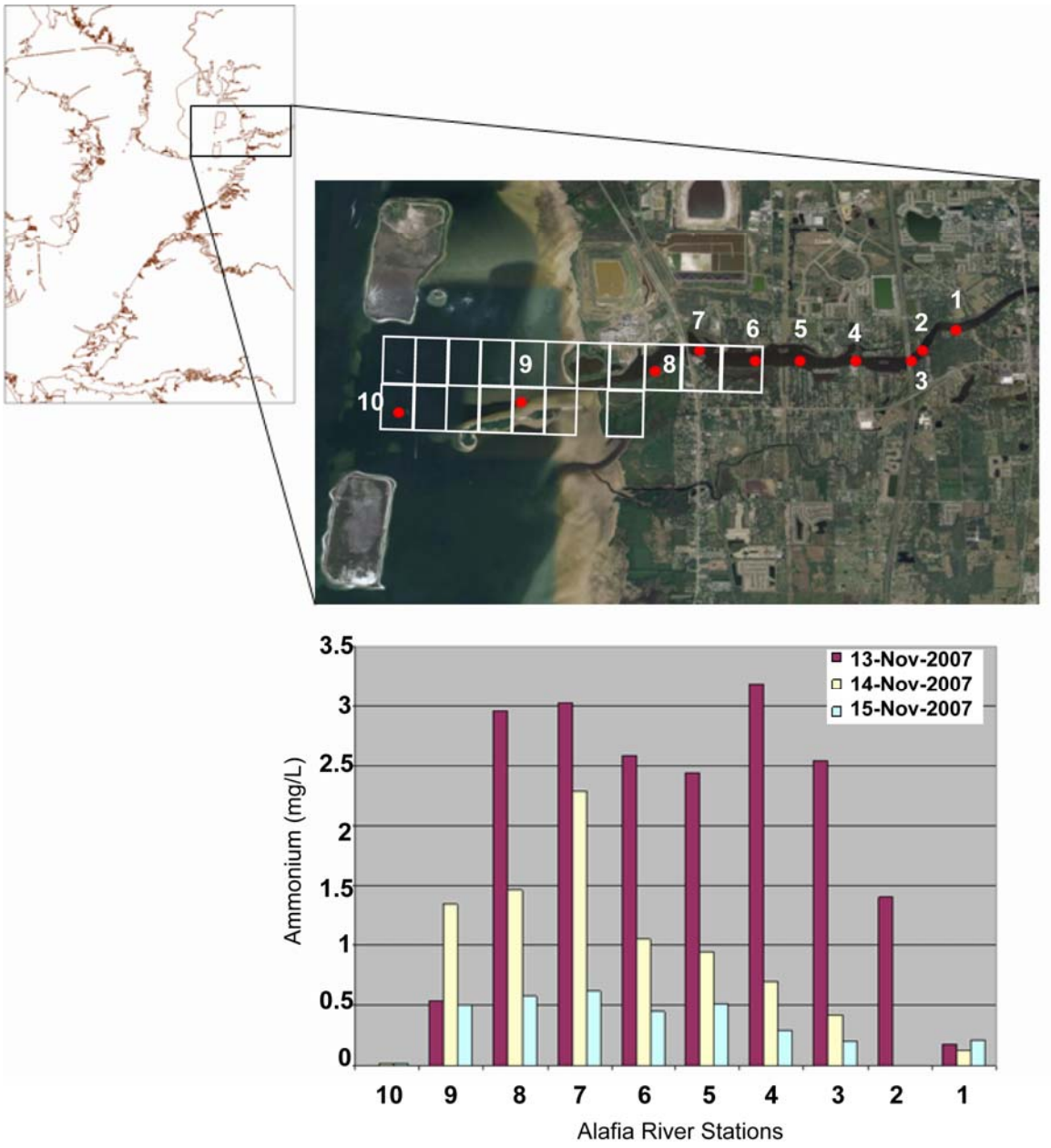

Figure 4 Water samples collected by the Florida Department of Environmental Protection (FDEP) immediately following an anhydrous ammonia spill in the Alafia River. The samples were collected by the FDEP from the 10 stations shown on the satellite image over a period of three days: 13-15 November 2007. The grid overlaying the satellite image shows the model grid cells that encompass the FDEP sample sites.

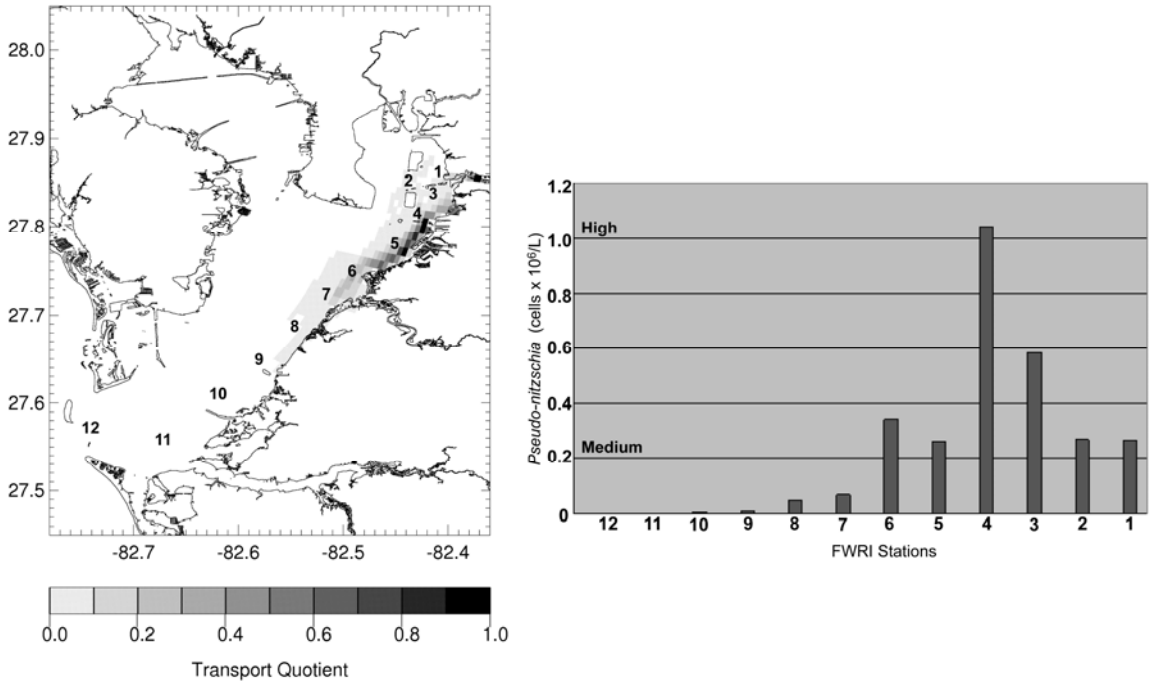

Figure 5 Water samples collected by the Florida Fish and Wildlife Research Institute (FWRI) after an anhydrous ammonia spill. The samples were collected from 12 stations, shown on the figure, along the eastern coastline of Tampa Bay on 19 November 2007. The bar graph shows the concentrations of *Pseudo-nitzschia spp.* counts (cells x 10^6 L^{-1}) at each station. Labels on the graph indicate the FWRI classifications for medium (>$2x10^5$ cells L^{-1}) and high (>$1x10^6$ cells L^{-1}) cell counts (for diatom species). Transport quotients (Q), shown underlying the FWRI sample locations, are calculated for each model grid cell on 19 November 2007 and range on a scale from zero (low probability of finding a particle in a grid cell) to one (high probability of finding a particle in a grid cell). The highest concentrations of *Pseudo-nitzschia spp.* were collected from station 4 where the Q values are also high. Particle concentrations decrease south of station 5, consistent with decreasing *Pseudo-nitzschia spp.* concentrations.

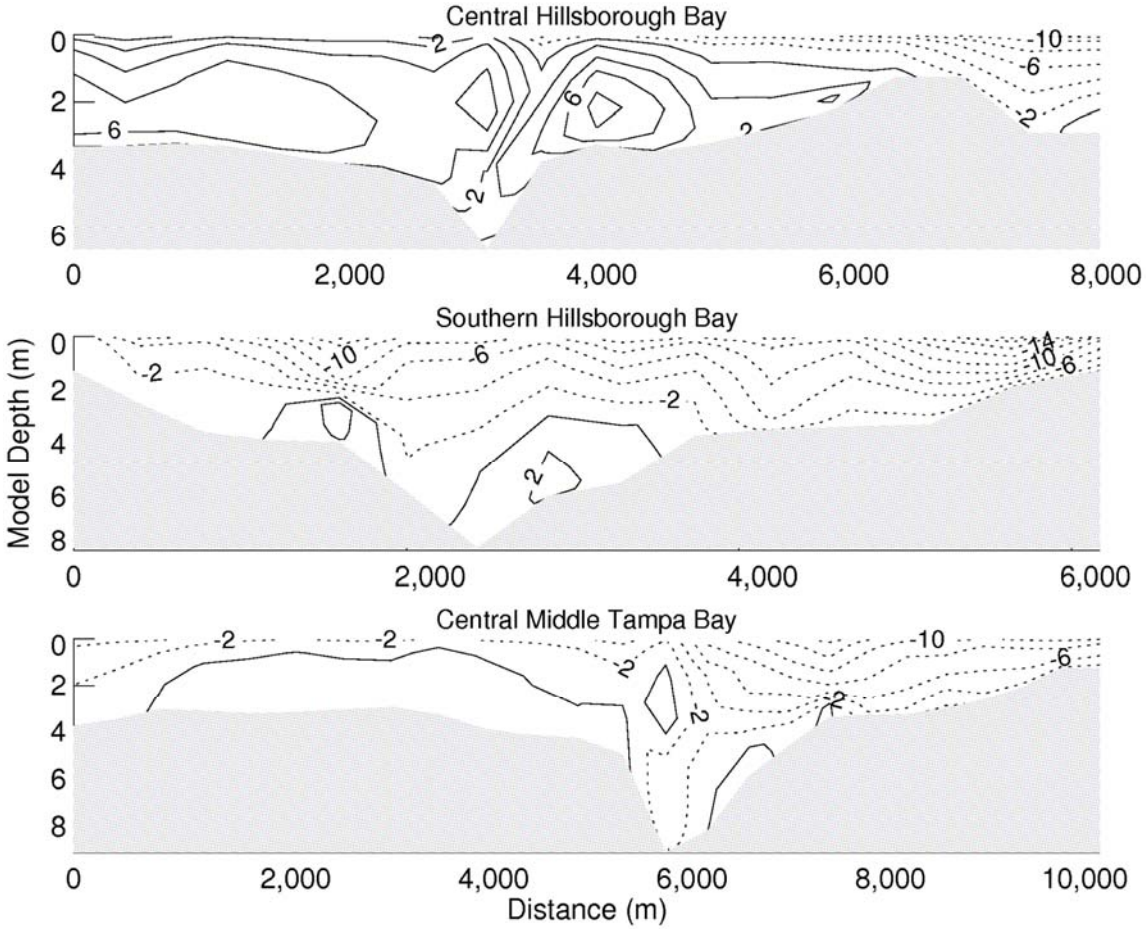

Figure 6 Vertical profiles of model output net velocities for three locations within Tampa Bay: across central Hillsborough Bay (aligned with the mouth of the Alafia River and bisecting two dredge islands in Hillsborough Bay), across southern Hillsborough Bay and central Middle Tampa Bay (aligned with the mouth of the Little Manatee River). The shaded region shows the bathymetry at the given locations, with the deep incision in each being the dredged shipping channel. Currents flowing inward (into the bay) are represented by positive velocities while outward currents (out of the bay) are represented by negative velocities. Velocities are in cm s^{-1}.

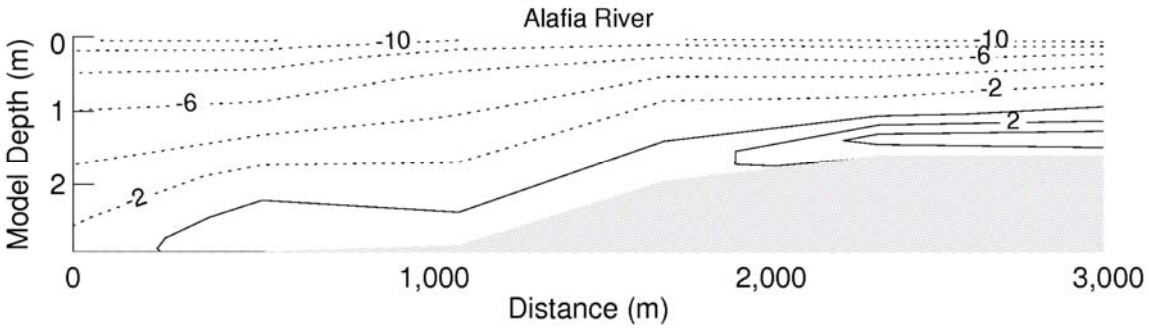

Figure 7 Vertical profile of model output net velocities for the Alafia River. The shaded region shows the bathymetry in the river. Currents flowing upstream are represented by positive velocities while outward downstream currents are represented by negative velocities. Velocities are in cm s^{-1}.

Chapter 2: Lagrangian Particle Tracking of a Toxic Dinoflagellate Bloom

Introduction

Toxic blooms, resulting from large numbers of the unarmored dinoflagellate *Karenia brevis*, are an almost annual occurrence along the West Florida Shelf (WFS) (Steidinger et al., 1998; Walsh et al., 2001) with observations of colored water and fish kills dating back to 1844 (Tester and Steidinger, 1997). Blooms of brevetoxin producing *K. brevis* are responsible for neurotoxic shellfish poisoning, fish kills and respiratory irritation (Magaña et al., 2003). The economy of Florida is impacted from these recurring blooms in the form of shellfish bed closures, medical costs, loss of tourism and disposal of dead fish (Kirkpatrick et al., 2004). A forecast system to predict the transport of these blooms could help alleviate some of these economic impacts.

In order to understand and predict the transport of harmful algae in Tampa Bay, some knowledge of the dynamics of bloom initiation and development is necessary. Background concentrations of *Karenia* populations are ubiquitous in Gulf of Mexico waters (Geesey and Tester, 1993) and certain physical factors are necessary to initiate the development, maintenance and transport of *K. brevis* blooms (Steidinger and Haddad, 1981) once concentrations exceed background levels. Optimum growth conditions for *K.*

brevis in the field occur in water with temperatures between 20-28º C and salinities of 31-37 (Steidinger and Ingle, 1972); this species does not typically bloom in salinities <24 (Maier Brown et al., 2006). During daylight hours *K. brevis* cells concentrate in the upper water column, due to a positive phototactic response (Heil, 1986), where transport and dispersion are subject to local winds and currents (Tester and Steidinger, 1997). *K. brevis* blooms originate 18-64 km offshore of the Florida coast (Steidinger, 1975) and are concentrated and transported inshore by complex interactions between coastal currents, wind-driven circulation and shelf features (Steidinger et al., 1998). Sampling from a 1971 bloom in Tampa Bay indicated that *K. brevis* cells enter the bay from the Gulf of Mexico via a dredged shipping channel (Steidinger and Ingle, 1972).

Tampa Bay is a drowned river bed estuary, about 50 km in length and covering more than 10^3 km^2 (Zervas, 1993). A dredged shipping channel runs along the axis of the bay extending from Lower Tampa Bay (LTB) into Middle Tampa Bay (MTB) before splitting, one fork going west into Old Tampa Bay (OTB) and one fork going east into Hillsborough Bay (HB) (Figure 8). The buoyancy driven circulation within Tampa Bay is typical of an estuarine system, with mean flow of saline Gulf of Mexico water into the bay along the bottom and mean flow of fresh water out of the bay at the surface (Meyers et al., 2007; Weisberg and Zheng, 2006). Water exchange with the Gulf of Mexico occurs at the mouth of the bay, with mean inflow through Egmont Channel and mean outflow through both Egmont and Southwest Channels (Meyers et al., 2007). *K. brevis* cells are thought to accumulate at fronts along the WFS during upwelling favorable conditions (Stumpf et al., 2008) and enter Tampa Bay on the inflowing current through

Egmont Channel (Steidinger and Ingle, 1972). Monitoring programs have recently become operational in the Gulf of Mexico and Tampa Bay to predict the onset and transport dynamics of *K. brevis* blooms.

A Harmful Algal Bloom (HAB) monitoring program in the Gulf of Mexico and Tampa Bay is overseen by scientists at the Florida Fish and Wildlife Research Institute (FWRI). As part of the program, water samples are collected by volunteers and sent to scientists at FWRI for microscopic analysis to determine *K. brevis* cell counts (Heil and Steidinger, 2009). Cell counts are grouped into categories based on potential ecological effect: counts $<10^3$ cells L^{-1} are considered background level, shellfish beds are closed when counts exceed 5×10^3 cells L^{-1}, fish kills can occur at concentrations of 5×10^4 cells L^{-1} or greater and water discoloration becomes apparent with concentrations $>10^6$ cells L^{-1} (Walsh et al., 2002). Sampling becomes more vigorous (i.e. increased frequency and number of samples collected) following reports of a bloom or bloom impacts.

The process of determining cell concentrations from samples is laborious and costly; a more interactive monitoring system, that combines field data with dynamic modeling, would provide a more useful management tool. One such system, the NOAA Gulf of Mexico HAB Operational Forecast System, reports, in the form of weekly bulletins, the predicted spatial extent, movement and intensification of HABs in the Gulf of Mexico (Fisher et al., 2006). The heuristic forecast model utilizes a combination of satellite imagery and wind predictions to simulate the extent and impact of *K. brevis* blooms in the Gulf of Mexico (Stumpf et al., 2009). Model forecasts from this system are verified

with FWRI cell counts, however the only boundary condition used in their model to determine the transport of these cells is predicted wind speed and direction.

Prediction systems that are capable of fully three-dimensional numerical simulations (i.e. (Decker et al., 2007)) using observations of multiple boundary conditions (e.g. daily winds, freshwater inflow, water level and salinity) are needed to guide HAB monitoring which, in Tampa Bay, at present relies predominantly on the collection of water samples in response *K. brevis* impacts (e.g. fish kills, discolored seawater or reports of respiratory irritation) with little advanced warning (Heil and Steidinger, 2009; Schofield et al., 1999). A prediction system capable of accurately forecasting bloom transport, based on underlying circulation dynamics, would assist health officials and environmental managers with the mitigation of health concerns and economic loses.

Numerical circulation models simulate the physical dynamics that transport toxic HABs into and within coastal waters. Franks and Signell (1997) use a circulation model developed from Blumberg and Mellor (1987) coupled with a biological model to simulate the initiation of toxic *Alexandrium tamarense* blooms in the Gulf of Maine. Lagrangian particle tracking models are also accurate tools for determining the initiation (Chen et al., 2007a) and transport (Cerejo and Dias, 2007; Yanagi et al., 1995) of harmful algae. Lanerolle et al. (2006) use a two-dimensional numerical model and Lagrangian particle tracking to simulate the transport of *K. brevis* in response to along-shore wind stresses in the Gulf of Mexico. Three-dimensional simulations are necessary to resolve the

gravitational circulation controlling the advection of materials in Tampa Bay (Weisberg and Zheng, 2006).

Here, a coastal prediction system, comprised of a three-dimensional numerical circulation model coupled to a Lagrangian particle tracking model, is evaluated to determine the capacity of the model to capture the general features of a 2005 *K. brevis* bloom in Tampa Bay. The circulation model is driven with hindcast forcing parameters (surface wind stress and freshwater flux) to reproduce the underlying circulation dynamics present in the bay during the 2005 *K. brevis* bloom. Vertical profiles of the instantaneous velocity fields generated by the circulation model show transport mechanisms for various sections of the bay. These velocity fields drive a Lagrangian particle tracking model (Meyers and Luther, 2008) which simulates the transport of *K. brevis* cells within Tampa Bay by following particles, each representing a fraction of the biological material, as they are advected throughout the model domain. Probability maps, constructed from the particle transport simulations, show locations in Tampa Bay that are most likely to be impacted by the bloom. The resulting probability maps are compared with cell concentrations in *K. brevis* samples collected during the peak of the 2005 bloom.

A salinity tolerance is placed on the particles when constructing the probability maps to simulate somewhat realistic biological behavior as particles encounter different water masses. This study does not incorporate an all-inclusive biological model and, as such, several biological parameters, including vertical movement by *K. brevis* with light, are not considered.

The objective of this paper is to evaluate the hindcasting capability of a coastal prediction system to simulate the basic spatial patterns of an observed *K. brevis* bloom in the Tampa Bay estuary. The parameterizations of the numerical circulation model and the particle tracking model are discussed in the following section. Comparisons between the particle transport simulations and observations of *in situ K. brevis* concentrations are discussed. An evaluation of bay-wide probability maps which illustrate the likelihood of *K. brevis* occurrence in Tampa Bay is performed to determine the utility of the simulations as event response tools. Finally, conclusions are drawn as to the physical mechanisms involved in the transport of the 2005 *K. brevis* bloom within Tampa Bay.

Methods

Numerical circulation model

The circulation model is a primitive equation numerical model adapted from the Princeton Ocean Model (Blumberg and Mellor, 1987) for Tampa Bay (Galperin et al., 1991; Vincent, 2001). The circulation model domain is divided into a grid of 70 by 100 cells in the horizontal and 11 sigma levels in the vertical. The model is initiated with hindcast boundary conditions that have been quality controlled. The model is forced at the bay mouth with water level obtained from the Tampa Bay Physical Oceanographic Real-Time System (TB-PORTS) and the University of South Florida Coastal Ocean Monitoring and Prediction System (COMPS) and salinity obtained from the

Environmental Protection Commission (EPC). The model simulation is also forced at discrete points using daily observations of fresh water flux (rivers and canals) obtained from the US Geological Survey (USGS) National Water Information System and monthly averaged wastewater discharge obtained from treatment plants. The model simulates the hydrodynamics and velocity fields in Tampa Bay; a detailed description of the model hydrodynamics and evaluation can be found in Meyers et al. (2007).

The vertical structure of the instantaneous horizontal velocity fields is averaged over a three month period (June-August 2005) to examine mean current flow across sections of the bay. Four representative cross sections are chosen: across the mouth of Tampa Bay, across Middle Tampa Bay (aligned with the Little Manatee River), across the mouth of Hillsborough Bay and across the mouth of Old Tampa Bay. For the north-south (v) component of the horizontal velocity, positive values represent northward current flow (into the bay); negative values represent current flow directed southward (out of the bay). For the east-west (u) component of the horizontal velocity, positive values represent an eastward component to the current flow; negative values represent a westward component to the current flow. The velocity fields generated by the circulation model are used to drive the particle tracking model of Burwell (2001).

Particle tracking

A Lagrangian based particle tracking method, versus an Eulerian method, has the advantage of realistic sub-grid scale motion and best approximates movement of particles

in the bay. Dispersion in the particle tracking model is accomplished with a random walk technique (Burwell, 2001) using a 4th order Runge-Kutta scheme with model velocity linearly interpolated to position particles at each model time step. The particle tracking code records the time and location of particles within the model grid cells at each time step; for this study the locations of particles are written to files every 60 minutes during each month-long simulation. For details of this scheme see Havens et al. (2009) and Meyers and Luther (2008).

Hindcast circulation model output is used to simulate particle transport during the peak months of the 2005 *K. brevis* bloom in Tampa Bay: June-August. The tracking model is initialized at the beginning of each month during a flood tide. Particles are distributed evenly throughout the water column into the model grid cells across Egmont Channel based on prior inference that *K. brevis* blooms enter Tampa Bay through this channel. Particles mix unless they are flushed out of the mouth at which point they are not allowed to re-enter the model domain.

As particles are transported between various model grid cells, they are assigned a salinity based on the salinity of the grid cell they occupy at each time step. A post-processing salinity restriction is placed on the particles when they are found in grid cells with salinities that are below the *K. brevis* tolerance of 24 (Maier Brown et al., 2006; Steidinger and Ingle, 1972).

At every internal time step in the simulations, a ratio between the number of particles in each individual grid cell and the total number of particles in the model domain is calculated. This ratio, called the transport quotient, is calculated according to the methods of Havens et al. (2009) but with the additional incorporation of the salinity restriction (see Appendix A). Grid cells with the highest transport quotients contain particles for the longest amount of time during that model simulation. Surface probability maps are constructed from the monthly averaged transport quotients. Particles with a salinity restriction are not included in the transport quotient calculations. Probability maps therefore show areas in Tampa Bay that fall within the salinity tolerances of *K. brevis* and have the greatest probability of being affected by the bloom based on circulation dynamics.

Sampling

Water samples were collected during the 2005 *K. brevis* bloom by FWRI scientists as part of a routine state HAB monitoring program and in response to reported bloom sightings and fish kills. Samples were collected at the surface, mid-depth and bottom of the water column from stations outside and within Tampa Bay from May to August of 2005. Concentrations of *K. brevis* cells from the collected water samples will be referred to as background ($<10^3$ cells L^{-1}), low (10^3-10^4 cells L^{-1}), medium (10^4-10^5 cells L^{-1}) or high ($>10^6$ cells L^{-1}). Low concentrations of *K. brevis* cells result in commercial shellfish bed closures, medium concentrations are responsible for fish kills and large concentrations cause visible water discoloration.

Results

The three month averaged horizontal current flow at the mouth of Tampa Bay (Figure 9) through the Egmont Channel is negative (outward) at all depths with a maximum of 70-75 cm s^{-1} near the surface and around 35 cm s^{-1} near the bottom; flow through the Southwest Channel is positive (inward) along the western boundary, increasing from 10 cm s^{-1} near the bottom to 40 cm s^{-1} near the surface, and negative throughout the rest of the channel with a maximum speed of 30-35 cm s^{-1}.

Across MTB the average current is northward within and above the shipping channel increasing from around 2 cm s^{-1} at the bottom of the channel to 14 cm s^{-1} at the surface and extends west of the channel (Figure 9). Flow east of the channel is to the south with a maximum speed of more than 14 cm s^{-1} at the surface. There is a westward component to the flow in MTB to the west of the channel increasing from 2 cm s^{-1} along the bottom to 8 cm s^{-1} at the surface (Figure 10). There is a weak eastward component to flow within and above the channel; currents generally are flowing to the north within the channel. A strong eastward component to the flow is present to the east of the channel with speed generally increasing toward the surface, ranging from 6 cm s^{-1} near the bottom to >12 cm s^{-1} at the surface.

Current flow across the mouth of HB on average is predominately southward and increases in speed towards the middle of the water column. East of the channel flow is

strongly to the south along the eastern shore. Peak inflow (10 cm s^{-1}) is well to the west of the channel near the Interbay Peninsula. Two areas of weak inflow (<2 cm s^{-1}) are present in the bottom and upper 2 m of the shipping channel and to the east of the channel near the bottom. Particles enter HB within these two areas of weak inflow and along the Interbay Peninsula.

Averaged current flow diverges across the mouth of OTB; currents flowing northward into OTB from MTB are confined to the western boundary of OTB while currents flowing out of OTB to the south are confined to the eastern boundary of OTB (Figure 9). There is a strong westward component to the northward flow (maximum 14 cm s^{-1}) from MTB deflecting currents along the western boundary of OTB and while currents flowing out of OTB are deflected eastward by somewhat weaker flow (maximum 10 cm s^{-1}) (Figure 10).

An animation of the surface particle positions for June 2005 shows particles contained in LTB during the first week of the simulation (results not shown). On model day 15 of the simulation the majority of the particles are concentrated within the shipping channel to northeast of the Sunshine Skyway Bridge. Some particles are transported into the middle of HB and just south of the Gandy Bridge in OTB by model day 20. The last model day of the June simulation (Figure 11a) shows: 1) the majority of particles located within MTB, 2) some particles being transported throughout HB and 3) a small number of particles traveling north of the Gandy Bridge, none going north of the Howard Franklin

Bridge. Baywide salinity at the particle locations is generally high (>29) at the end of the month.

During the first few days of the July 2005 simulation particles at the surface are rapidly transported along the shipping channel to the north of the Sunshine Skyway Bridge. Halfway through the simulation the particles are dispersed throughout MTB. By model day 20 a large number of particles are carried into OTB, most located south of the Gandy Bridge and some mixed between the Gandy Bridge and the Howard Franklin Bridge; very few particles are transported into HB. This pattern persists through the end of the simulation (Figure 11b), with no particles transported north of the Courtney Campbell Causeway in OTB and very few particles ever making it into HB. Baywide salinity encountered by the particles at the end of July is becoming fresher, as compared to June, with a large portion of MTB just above the *K. brevis* salinity tolerance of 24.

Rapid transport of surface particles along the shipping channel from Egmont Key also occurs during the initial days of the August 2005 simulation. On model day 10 particles are concentrated in MTB along the shipping channel have begun to disperse to either side of the Interbay Peninsula. The majority of particles remain tightly contained within the shipping channel in MTB on model day 15; a small number of particles are transported into the middle of OTB and into the middle of HB. The majority of particles remain concentrated near the Interbay Peninsula by model day 25; some particles are transported north of the Howard Franklin Bridge in OTB. By the end of the simulation (Figure 11c) few particles were transported into either upper OTB or upper HB. Those particles in

OTB were concentrated along the coasts between the Gandy Bridge and the Howard Franklin Bridge. Model baywide salinity at the end of August remains near tolerance levels in MTB and OTB with increasing salinities toward LTB.

Transport quotients, averaged over the month of June (Figure 12a), are highest along the southwestern coastline near Conception Key. A lower proportion of particles are found north of the Sunshine Skyway Bridge within the shipping channel. Transport quotient values decrease significantly in the rest of the bay for the month of June. Averaged transport quotients for July (Figure 12b) remain high along the southwestern coastline. High proportions of particles can also be seen under the Sunshine Skyway Bridge and contained along the shipping channel in MTB. The highest August transport quotients (Figure 12c) are tightly contained within the shipping channel. The particle concentrations decrease slightly to the north near the Interbay Peninsula and near the entrances to OTB and HB. Model grid cells in OTB and HB contained particles for proportionately much less time than grid cells in the shipping channel during the three simulations.

High concentrations ($>10^6$ cells L^{-1}) of *K. brevis* cells were first detected in January 2005 during routine sampling approximately 15 miles offshore of Tampa Bay in the Gulf of Mexico. High concentrations of cells were observed in early May at several locations around Palma Sola and low concentrations (10^3-10^4 cells L^{-1}) were observed at Anna Maria (Figure 13a). High concentrations persisted into the middle of May at Palma Sola while medium concentrations (10^4-10^5 cells L^{-1}) were detected the third week in May at

Anna Maria. One measurement within Tampa Bay, at Indian Key, contained background concentrations ($<10^3$ cells L^{-1}) of *K. brevis*.

High cell concentrations persisted offshore of Palma Sola through June (Figure 13b) as did medium concentrations at Anna Maria Island. At the end of June high concentrations were detected at Conception Key and in the MTB shipping channel; low concentrations were measured near St. Petersburg and background concentrations were measured near the mouth of the Little Manatee River.

Only background concentrations of *K. brevis* were detected offshore of Palma Sola throughout the month of July (Figure 13c); medium concentrations at Anna Maria and high concentrations in the MTB shipping channel persisted throughout the month. Samples collected at the beginning of July showed that while previously high concentrations at Conception Key decreased to medium concentrations, high concentrations were measured just to the north at Indian Key. Low concentrations were detected near St. Petersburg. The high concentrations at Indian Key decreased to medium concentrations in mid-July and persisted through the end of the month. One sample collected from the Little Manatee River in the middle of the month showed background concentrations of *K. brevis*. Background concentrations were also found in OTB near the Gandy Bridge at the end of the month; this was the only sample collected from OTB.

Background concentrations persisted at Palma Sola throughout August (Figure 13d). The medium concentrations at Conception Key were also present throughout August, while only background levels were detected at Indian Key. High concentrations were measured in samples collected at the beginning of August at Anna Maria, while concentrations in the shipping channel of MTB decreased to the medium range. At the end of August the concentrations of *K. brevis* in the shipping channel of MTB and near St. Petersburg had decreased to background levels.

It should be noted that only one sample was collected from OTB during the 2005 bloom since there were no reports of fish kills in the area during the bloom and additionally low salinities typically preclude the survival of *K. brevis* in this region for any substantial length of time. Sampling in OTB was conducted the following year during another *K. brevis* bloom in Tampa Bay. Those data were collected during August and September 2006 (see Appendix C).

Discussion

An extensive *K. brevis* bloom was present in Tampa Bay during the summer of 2005. The bloom entered through the mouth of Tampa Bay and, based on the model results above, was transported into the bay along the dredged shipping channel; these results are similar to those of Steidinger and Ingle (1972) from the 1971 bloom.

The short-term averaged flow (June-August 2005) is outward across both the Egmont Channel and the Southwest Channel with the exception of a narrow band of inward flow along the western boundary of the Southwest Channel. This differs from the longer-term averaged flow which is uniformly inward across the Egmont Channel and uniformly outward across the Southwest Channel (Meyers et al., 2007). These results suggest, at least during this short simulation, that high *K. brevis* cell concentrations first observed in early May 2005 at Palma Sola traveled northward and entered Tampa Bay through the Southwest Channel sometime around early June. This cannot be determined conclusively at this time however, because with the open boundary at the mouth, the circulation model does not accurately address exchange between Tampa Bay and the Gulf of Mexico (Weisberg and Zheng, 2006). More evaluations are needed to determine how *K. brevis* cells enter Tampa Bay.

Strong axial surface currents transport simulated particles from the mouth of the bay along the shipping channel, out of LTB, under the Sunshine Skyway Bridge and into MTB. Broad flow to the northwest extends west of the shipping channel at all depths in MTB resulting in the westward dispersion of particles shown in the probability maps. This is agreement with the findings of Meyers et al. (2007), that surface flow converges (not shown) to the shipping channel both to the south and north of the Sunshine Skyway Bridge and that a westward component of the flow exists to the south of the Interbay Peninsula. The westward component of the flow in western MTB explains the distribution of particle concentrations in the probability maps. The probability maps for July (Figure 12b) and August (Figure 12c) show increased concentrations of particles

west of the shipping channel in MTB. Particles are carried northward into MTB within and along the shipping channel and deflected to the west where they join with southwestward flow (not shown) along the western shore (Meyers et al., 2007). An equally strong counter-flowing current is present along the eastern coast of Tampa Bay; this current was also observed by Havens et al. (2009). The southeasterly current explains the low concentrations of *K. brevis* cells found to the east of the shipping channel in both the probability maps and in the observations of *in situ K. brevis* concentrations. Particles entrained in the negative current are rapidly transported towards the bay mouth and out of the model domain.

The highest transport quotients, and therefore the areas with the highest probability of being affected by the bloom, are found along the shipping channel in MTB. Similarly, the highest *K. brevis* concentrations sampled within the bay were along the shipping channel in MTB. These *in situ* results are in agreement with results from the simulations. Both show *K. brevis* cells being concentrated along the shipping channel, mostly within MTB.

Anecdotal reports suggest that there were no signs of *K. brevis* impacts (i.e. fish kills, reports of respiratory distress, etc.) in either OTB or HB during the 2005 bloom. Only one water sample was collected by FWRI scientists from either OTB or HB during the three month period when the *K. brevis* bloom was at its peak in Tampa Bay suggesting that fish kills were not reported from either of these areas during this period. OTB is not routinely monitored for *K. brevis* due to the low salinities typically found in that region

(see Appendix C). In fact, across the mouth of HB the area of inflowing currents where particles could enter is very small and restricted to flow along the Interbay Peninsula. Particles are restricted from entering OTB by divergent currents at the mouth that act to deflect particles entering from MTB towards the western boundary where they are entrained in southwestward flow (Meyers et al., 2007). The small number of particles that were transported into OTB and HB were able to "survive" in the model and did not encounter salinity restrictions. These results suggest that circulation features and not a salinity barrier prevented a bloom from forming in the northern parts of the bay. Further investigation is needed to determine why the bloom was not transported into either area.

It should be noted that a quantitative comparison between the model simulations and the *in situ* observations could not be performed due to the scarcity of observations. Sampling is currently limited due to lack of funding and adequately trained personnel (Heil and Steidinger, 2009).

The products generated by the numerical circulation and particle tracking models accurately reproduce the spatial distribution of the *in situ* samples collected during the 2005 *K. brevis* bloom. This study is the first of many data calibrations to the models with the goal of evaluating the coastal prediction system under real world scenarios. With more robust field evaluations and incorporation of real-time oceanographic data from the Tampa Bay Physical Oceanographic Real-time System (TB-PORTS), the coastal prediction system can serve as a useful forecasting tool to accurately and rapidly predict future bloom events. This interactive HAB forecasting system, comprised of monitoring

and modeling, will provide greater insight into the transport of recurring *K. breivs* blooms in Tampa Bay and can help mitigate the economic impacts resulting from these HABs.

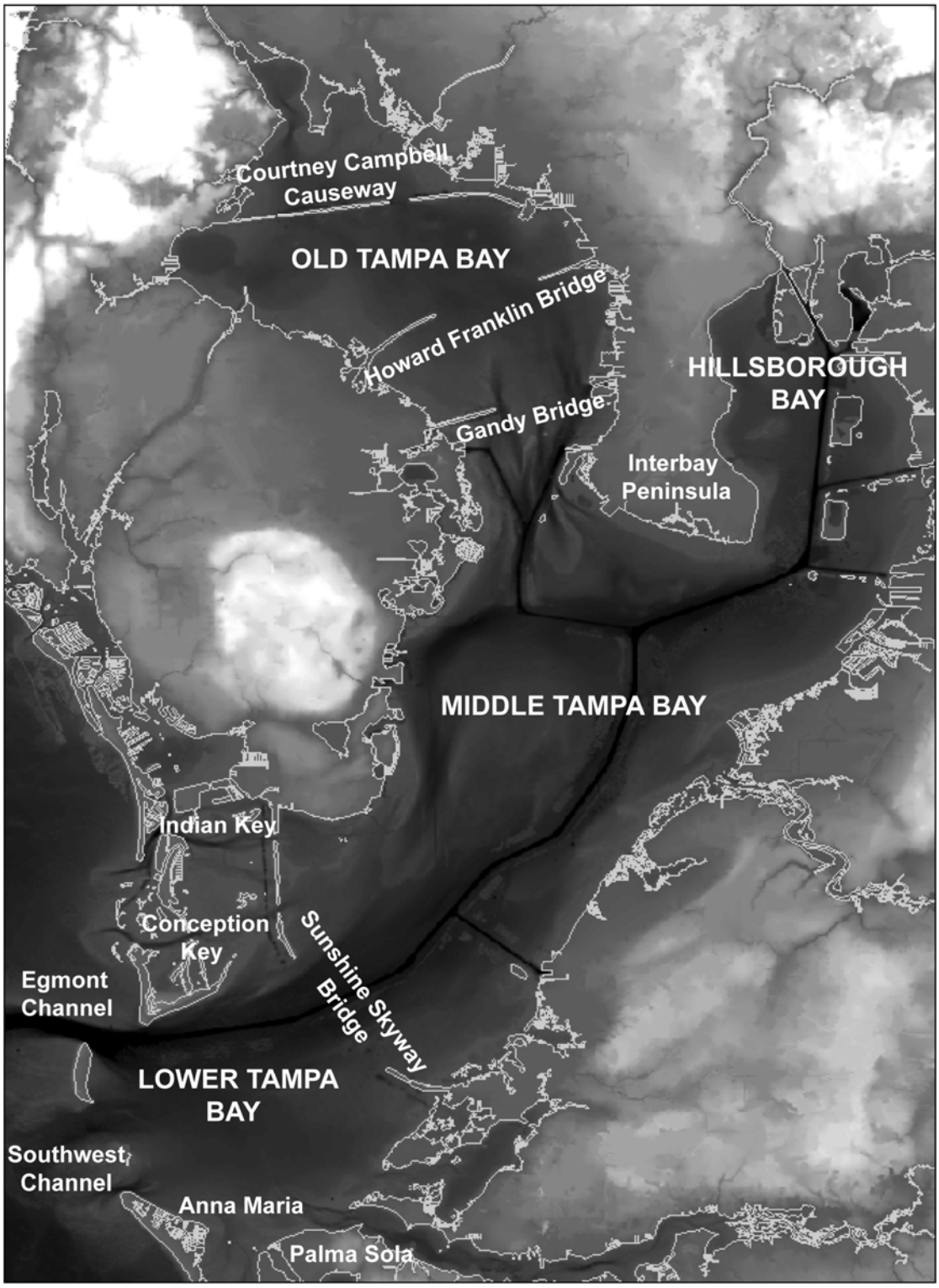

Figure 8 Bathymetric map of the Tampa Bay estuary with the darkest cuts representing the dredged shipping channels. Tampa Bay can be divided into four quadrants: Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay and Lower Tampa Bay. Bridges and causeways are labeled.

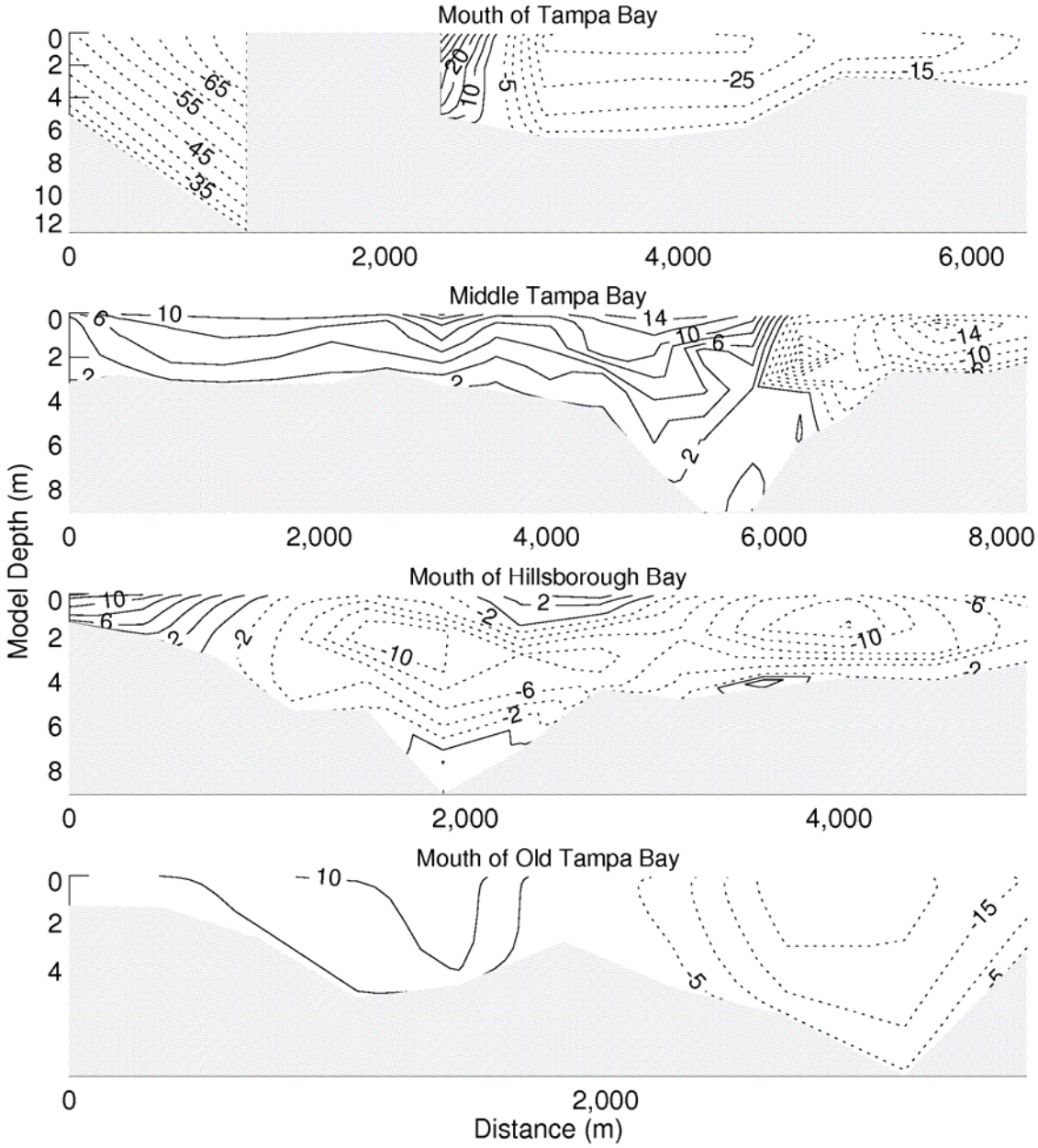

Figure 9 Vertical profiles of the north-south (v) component of the horizontal current flow averaged across four locations within Tampa Bay: across the mouth of Tampa Bay, across Middle Tampa Bay (aligned with the Little Manatee River), across the mouth of Hillsborough Bay and across the mouth of Old Tampa Bay. The shaded region shows the bathymetry at the given locations. Currents flowing northward (into the bay) are represented by positive velocities while southward currents (out of the bay) are represented by negative velocities. Velocities are in cm s^{-1}.

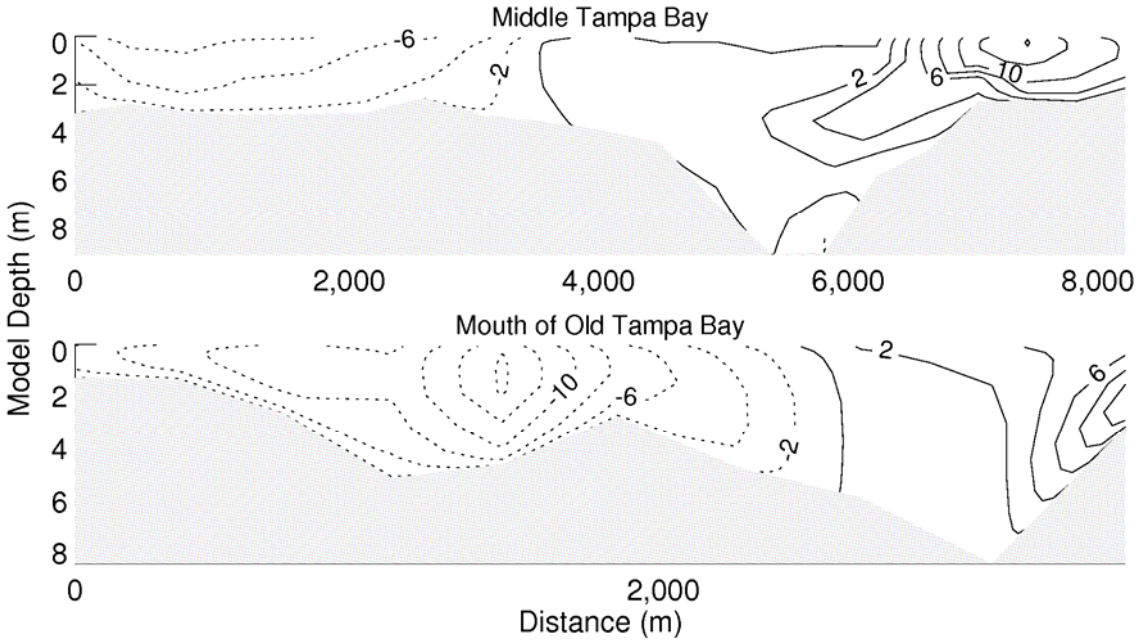

Figure 10 Vertical profiles of the east-west (u) horizontal current flow averaged across two locations within Tampa Bay: across Middle Tampa Bay (aligned with the Little Manatee River) and across the mouth of Old Tampa Bay. The shaded region shows the bathymetry at the given locations. Positive velocities represent an eastward component to the current flow; negative velocities represent a westward component to the current flow. Velocities are in cm s^{-1}.

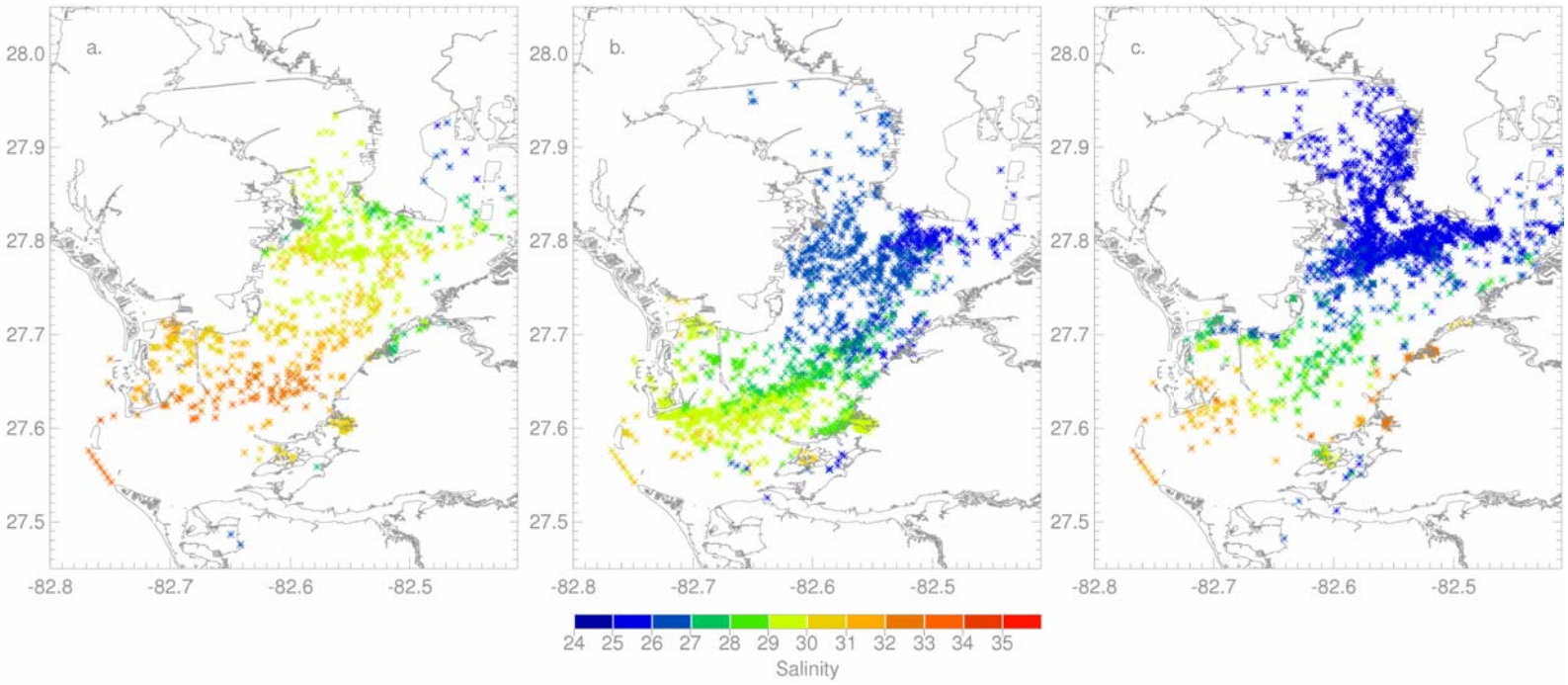

Figure 11 Numerical model simulations initialized at the beginning of (a) June, (b) July and (c) August 2005. The three frames show the transport of model particles, representing *Karenia brevis* cells, on the last model day of each simulation. The time stamp is in UTC. The scale represents the salinity of the water parcel that the particles encounter.

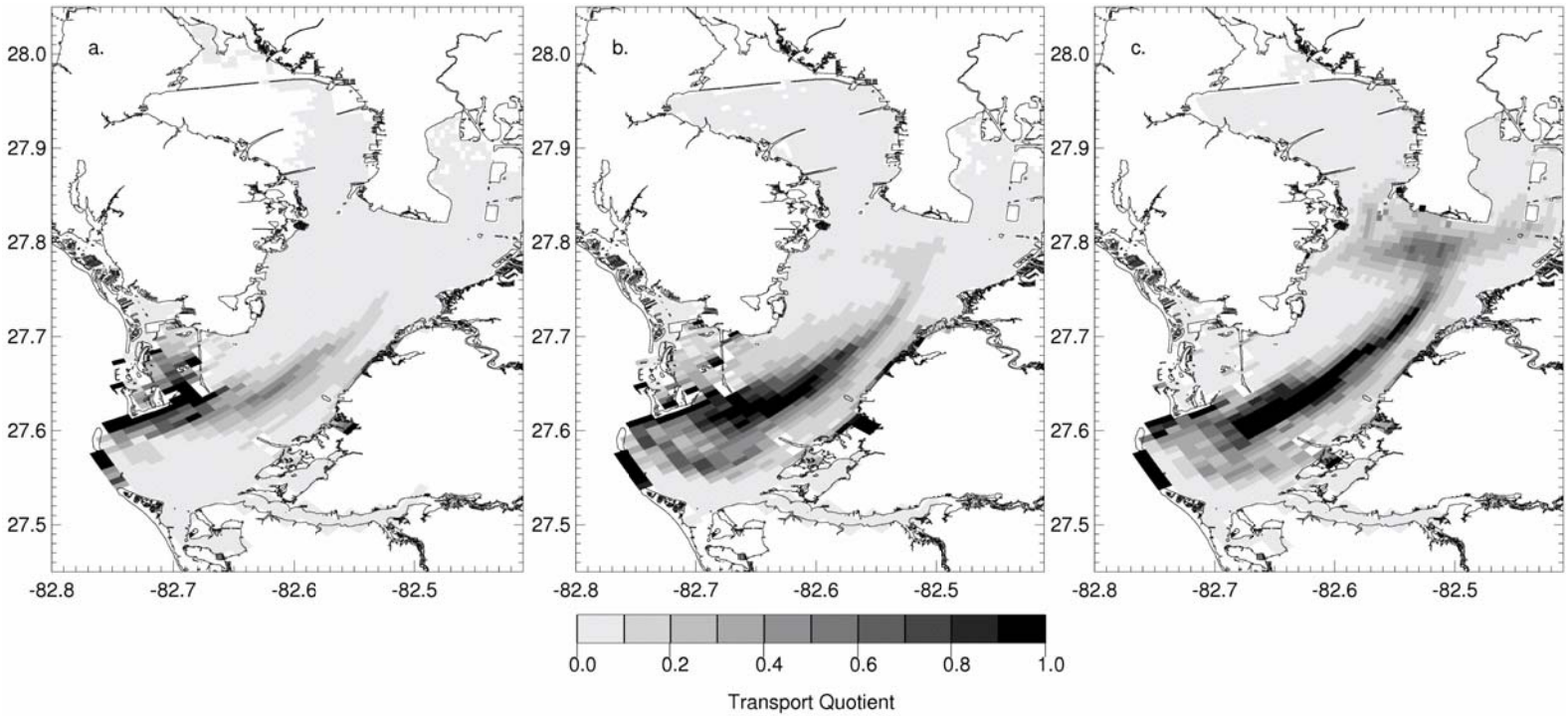

Figure 12 Transport quotients are a ratio between the number of particles, representing *Karenia brevis* cells, in each individual grid cell and the total number of particles in the model domain. Transport quotients range on a scale from zero (low probability of finding *K. brevis* in a model grid cell) to one (high probability of finding *K. brevis* in a model grid cell). The three frames show average transport quotient values for (a) June, (b) July and (c) August 2005.

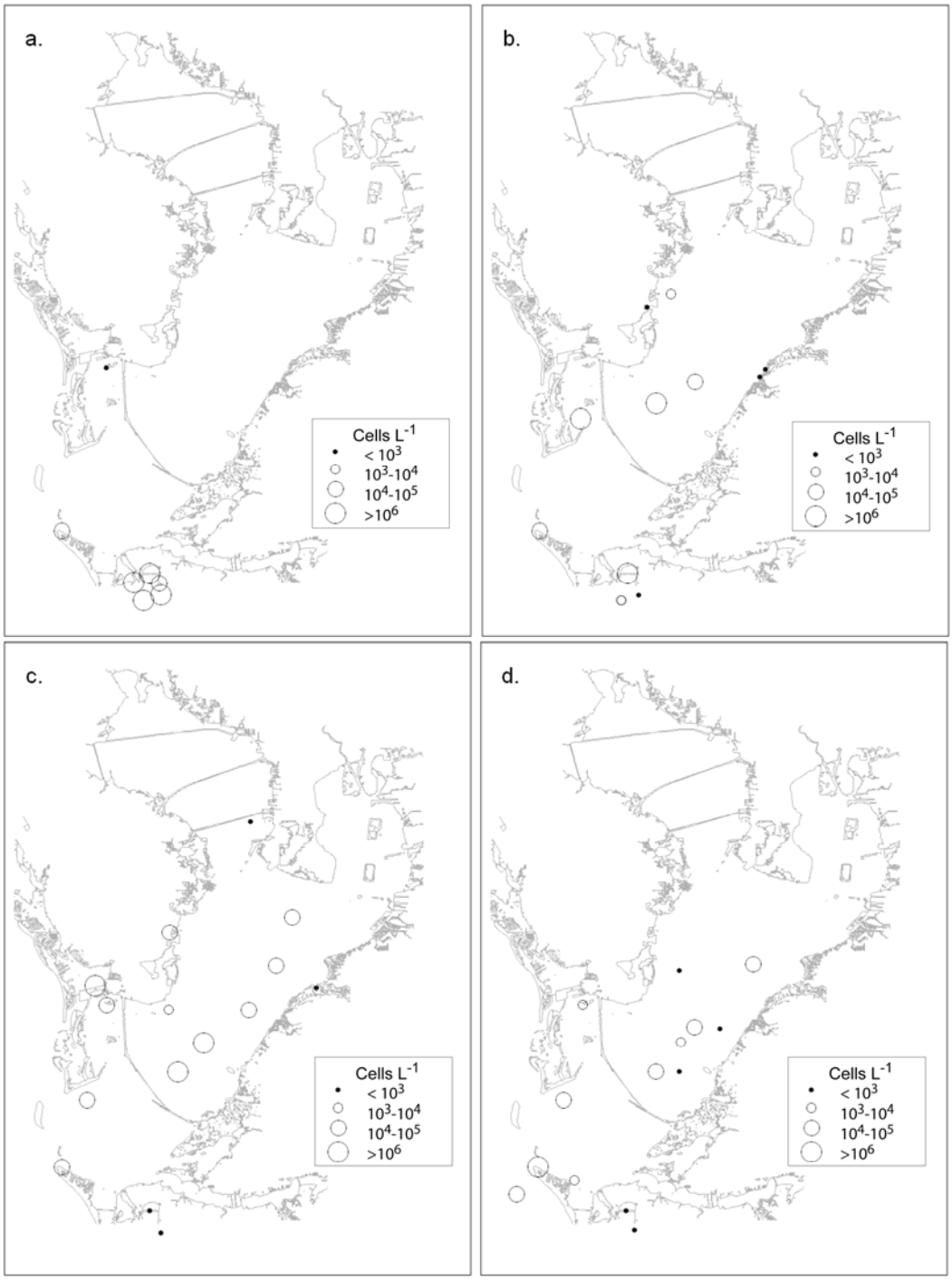

Figure 13 Figures showing concentrations of *Karenia brevis* collected from water samples at various locations throughout Tampa Bay for the months of (a) May (b) June (c) July (d) August 2005. The samples were collected by scientists at the Florida Fish and Wildlife Research Institute in response to reported bloom sightings and fish kills. The size of the circles indicate the concentration of *K. brevis* cells in that location and range from background ($<10^3$ cells L^{-1}), low (10^3-10^4 cells L^{-1}), medium (10^4-10^5 cells L^{-1}) and high ($>10^6$ cells L^{-1}) concentrations.

Chapter 3: Dispersion of Colored Dissolved Organic Matter

Introduction

Tampa Bay, the largest open water estuary in Florida, drains a mixed-use watershed about 4500 km^2 in size (Zervas, 1993) which plays a large role in determining the type of organic material deposited into the bay (Chen et al., 2007b). This organic matter enters into different regions of Tampa Bay through local rivers and other freshwater inputs.

Tampa Bay is comprised of four main regions: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB) and Lower Tampa Bay (LTB) (Figure 14). A dredged shipping channel, extending from LTB into MTB, bisects the bay before splitting into OTB and HB. Freshwater enters the bay primarily through HB and MTB setting up a buoyancy driven circulation system with mean flow of fresh water out of the bay at the surface and mean flow of saline Gulf of Mexico water into the bay along the bottom (Meyers et al., 2007; Weisberg and Zheng, 2006).

High amounts of organic matter in estuaries impact the levels of solar radiation penetrating the water column (Blough and Del Vecchio, 2002; Corbett, 2007; Moran et al., 2000). Tampa Bay is characterized by high organic content, therefore solar fluxes are

rapidly attenuated with depth (Hu et al., 2004; Kouassi et al., 1990). Colored or chromophoric dissolved organic matter (CDOM) is the primary factor controlling light attenuation in Tampa Bay (Chen et al., 2007b). CDOM in surface waters diminishes the amount of solar radiation able to penetrate the water column resulting in a reduction in the quantity and quality of the light that reaches the benthic habitat (Corbett, 2007) while also shielding organisms from UV exposure (Stabenau et al., 2004).

Exposure of CDOM to sunlight results in the photochemical degradation, or bleaching, of the absorption and fluorescence of CDOM (Blough and Del Vecchio, 2002; Kouassi et al., 1990; Morris and Hargreaves, 1997). Rates of photobleaching at the surface are controlled by the amount of light absorbed by the CDOM molecules. Several authors have described marine CDOM photobleaching rates under varying conditions and at different locations (Kieber et al., 1990; Kouassi and Zika, 1992; Miller and Zepp, 1995; Nelson et al., 1998; Shank et al., 2009; Shank et al., 2005).

Coastal areas exhibit varying levels of CDOM concentration depending on seasonal river flow (Blough and Del Vecchio, 2002). Rivers are the dominant source of CDOM in Tampa Bay (Stovall-Leonard, 2003), but other pathways include freshwater inputs such as runoff and groundwater (Coble, 2007; Corbett, 2007). Four major rivers discharge the bulk (about 85%) of the freshwater supply into Tampa Bay: the Hillsborough River, Alafia River, Little Manatee River and Manatee River (Boehme and Coble, 2000; Chen et al., 2007b; Swarzenski et al., 2007). Distribution of CDOM in Tampa Bay is

dominated by conservative mixing between inputs from the Hillsborough River and Alafia River (Chen et al., 2007b).

Climatological freshwater discharge rates show seasonally high flow from approximately June-October during which CDOM abundance is four times greater than during dry conditions (Chen et al., 2007b). Photobleaching acts as a sink for CDOM, especially during periods of increased freshwater input (Del Vecchio and Blough, 2002). During the wet season in Tampa Bay, the buoyancy input from freshwater reduces mixing and causes the water column to become highly stratified (Burwell, 2001). Decreased mixing results in a shallow mixed depth, prolonged exposure of CDOM to sunlight at the surface and greater photobleaching (Blough and Del Vecchio, 2002; Chen et al., 2007b; Nelson et al., 1998), provided that the light penetration depth is greater than the pycnocline depth. However, shorter residence times during the wet season act to flush out particles (Burwell, 2001) and result in greater amounts of "fresh", or un-bleached, CDOM.

During periods of low freshwater flow, increased vertical mixing limits exposure of CDOM to solar radiation at the surface (Blough and Del Vecchio, 2002; Chen et al., 2007b). Turbulent mixing acts to transport CDOM below the solar irradation depth, which can be shallow in estuaries depending on the organic content of the water (Kouassi et al., 1990). However, mixing also increases the light penetration depth potentially leading to photobleaching below the surface. Longer residence times during low flow conditions which would act to retain CDOM locally for longer periods than during the wet season.

An inverse relationship between CDOM and surface salinity in estuaries has been shown to vary seasonally and between rivers (Stovall-Leonard, 2003) indicating conservative mixing (Chen et al., 2007b; Coble, 2007; Del Vecchio and Blough, 2004; Hu et al., 2004). CDOM distribution in Tampa Bay in particular is determined by the concentration of riverine inputs and the subsequent mixing between river and estuarine waters (Chen et al., 2007b). For these reasons CDOM can be used as a proxy for mixing or to trace the freshwater inputs from different riverine sources (Coble, 2007). The use of CDOM in conjunction with its bleaching rate (on the seasonal time scale) may be an effective tracer for evaluating the residence time for surface water masses (Nelson and Siegel, 2002).

Numerical models offer powerful capabilities for prediction and simulation (Huthnance et al., 1993) and have been used to study and track organic matter in the Gulf of Mexico and Tampa Bay. The water quality model WASP (Water Analysis Simulation Program) is used to quantify nutrient loads and water quality in Tampa Bay (Wang et al., 1999). The Navy Coastal Ocean Model (NCOM) is used as a particle tracking model to follow river discharge and bio-optics in the Gulf of Mexico (Arnone et al., 2005). A similar particle tracking model, if applied to Tampa Bay and combined with photobleaching rates, would provide a better understanding of CDOM distribution and seasonality.

CDOM distribution maps are a tool to assist managers in determining the extent to which UV penetration, water quality and freshwater flux will affect estuaries and coastal areas

(Granskog et al., 2007). Hu et al (2004) examined the potential for using satellite technologies for assessing water quality parameters (including CDOM) and to create distribution maps in Tampa Bay for monitoring purposes. Knowledge of CDOM distribution from its source(s) enhances the monitoring of water quality (Chen et al., 2007b) and provides a better understanding of why some areas of Tampa Bay are more affected than other areas.

This study is part of the ongoing development of the Tampa Bay coastal prediction system. The prediction system, comprised of a three-dimensional circulation model coupled to a Lagrangian particle tracking model, is applied here to simulate CDOM dispersion in the Tampa Bay estuary during both dry and wet conditions in the bay. The parameterizations of the coastal prediction system are discussed in the following section. The incorporation of a CDOM photobleaching rate is discussed. Evaluations of distribution maps showing the likelihood of bay-wide CDOM dispersion are performed. Finally, conclusions are drawn as to the seasonal patterns of CDOM transport in Tampa Bay.

Methods

A numerical circulation model, based on the Princeton Ocean Model (Blumberg and Mellor, 1987), was developed for Tampa Bay (Galperin et al., 1991; Vincent, 2001) and produces three-dimensional fields of circulation, salinity and water level in the bay using

quality controlled boundary forcing conditions. Detailed model hydrodynamics and evaluation of the model are reported in Meyers et al. (2007).

The circulation model includes a particle tracking algorithm (Burwell, 2001) that advects dimensionless particles within the model domain, a 70 by 100 grid of cells in the horizontal and 11 sigma levels in the vertical (Meyers et al., 2007), according to the simulated three-dimensional circulation field. The particle tracking model incorporates random-walk diffusion (Dimou and Adams, 1993; Meyers and Luther, 2008) and follows the dispersion of material in tidal and meteorologically induced flows using a 4^{th} order Runge-Kutta scheme with model velocity linearly interpolated to position particles at each model time step. The addition of random displacement terms to the Lagrangian particle tracking model and the parameterization of eddy diffusivity allow for effective modeling of sub-grid scale particle motion (Burwell, 2001).

Boundary conditions from 2007 are chosen to perform a hindcast particle transport simulation, each particle representing a fraction of total CDOM discharge from four rivers in Tampa Bay, following the methods of Havens et al (2009). The 2007 model data set has undergone extensive quality control and 2007 is the last complete year that historical river flow data is available from the United States Geological Survey (USGS).

Averaged daily river flow rates for 2007 are obtained from USGS for the Hillsborough River, Alafia River, Little Manatee River and Manatee River and are plotted against USGS historical averaged flow (Figure 15) to determine whether river flow was typical

or anomalous during 2007 as compared to the historical trend. From these plots the period of average lowest flow in 2007 (here called "dry season") and the period of average highest flow (here called "wet season") in 2007 are determined. For purposes of this study differences in flow rates between the four rivers are neglected.

Each of the model grid cells across the mouths of each of the four rivers (Figure 14) are initialized with particles uniformly throughout sigma (throughout the water column) and centered on each cell center. The model outputs the total number of particles in every grid cell each day by summing the particles in a given grid cell at every internal time step (Burwell, 2001).

The particle tracking model is initialized both during the dry season and during the wet season. During dry season simulations 1000 particles are released at the mouths of each of the four rivers (for a total of 4000 particles). As reported by Chen et al. (2007b) approximately four times more CDOM is released during the wet season than during the dry season therefore 4000 particles are released during the wet season simulations from the mouths of each of the rivers (for a total of 16,000 particles). During the wet and dry season simulations the particles are allowed to mix for 60 days within the model domain. Particles flushed out of the model domain near the bay mouth are removed from the simulation and not allowed to re-enter the model domain.

The particle tracking model records the time and location of each particle within the model grid cells at each time step during the simulation. These spatial-temporal details

are written to files every 60 minutes during the 60-day-long simulations. Post-processing analyses of the particle counts and locations are performed on the output files after each simulation.

For each model day (every 24 h) post-processing decay rates are applied to particle counts contained within the surface levels of the model water column (two uppermost grid cells) to simulate CDOM photobleaching that occurs at the ocean surface (Clark and Zika, 2000; Vodacek et al., 1997; Whitehead and De Mora, 2000). Specific photobleaching rates are not available for Tampa Bay. However, a number of other studies have examined surface photobleaching rates of CDOM absorbance during dry (Miller and Zepp, 1995; Nelson et al., 1998) and wet (Kieber et al., 1990; Kouassi and Zika, 1992; Nelson et al., 1998; Shank et al., 2005) conditions in estuarine and oligotrophic settings (Table 1). Photobleaching rates for this study are determined from studies in areas with organic fluxes comparable to Tampa Bay. A dry season photobleaching rate was obtained from work by Miller and Zepp (1995) in a similarly organic-rich estuary along the Georgia coast during winter conditions. Their photobleaching rate of 0.0072 d^{-1} is applied to dry season simulations in this study. For wet season simulations, a photobleaching rate of 0.12 d^{-1} from a study by Shank et al. (2005) in the Cape Fear estuary in North Carolina, also a highly organic system, is applied.

Following the methods of Havens et al. (2009), post-processing transport quotients are calculated from the output files (see Appendix A) after photobleaching rates have been

applied. Transport quotients are ratios between the number of particles in each individual model grid cell and the total number of particles in the model domain at any given time of the simulations. Transport quotients are calculated in three-dimensions (x, y and z) for each model grid cell at each time step in the simulations. The transport quotients are then averaged over z and displayed in two-dimensions on maps to show locations in Tampa Bay with the highest CDOM abundance (throughout the water column) during the simulations.

The results of post-processing analyses (applied decay rate and calculated transport quotients) on the model simulation output files are maps of CDOM distributions with incorporated seasonal photobleaching decay rates. These probability maps show areas in Tampa Bay that are most likely to be affected by CDOM during dry versus wet conditions based on surface bleaching rates and circulation dynamics.

Results

USGS historical measurements from the four rivers examined in this study show, on average, 55 years of river flow rates (Figure 14). The lowest average flow rates for the Hillsborough River and Alafia River have historically been from April-June and November. In 2007 the lowest averaged flow rates for these two rivers were from April-June. For the Little Manatee River and Manatee River, the lowest average flow rates have historically been from April-May and from November-December. The lowest average flow rates in 2007 for these two rivers were from May-June and from November-

December. Based on the USGS data from all four rivers, a 60 day period in 2007, from April-May, is chosen to represent the dry season in this study.

The highest average flow rates measured by USGS at each river occur historically from August-September. The highest averaged flow rates for 2007 occur in August for the Hillsborough River and October for the other three rivers. The second highest flow rates in 2007 occur in August for each of the rivers except the Hillsborough River where the second highest rates are in September. Based on the overall historical and 2007 river flow data, the wet season for this study was determined to be a 60 day period from September-October.

Probability maps showing depth averaged transport quotients for the 2007 dry season generally show the highest transport quotients, and therefore the areas with the highest probability of containing CDOM, closest to the rivers from which the particles are released (Figures 16-19). Transport quotients averaged over the first 30 days of the dry season (Figure 16a) for particles (CDOM) entering Tampa Bay from the Hillsborough River are highest in HB at the mouth of the river, at a few locations along the western coast and above the northern dredge spoil island. Some particles are transported into MTB. After 60 days (Figure 16b) the areas with the highest CDOM probabilities are western HB and northern MTB. CDOM entering the bay from the Alafia River during the dry season is highest in southern HB and along northern MTB for the first 30 days of the simulation (Figure 17a). After 60 days CDOM is more heavily concentrated south of the river in HB (Figure 17b) and more widely distributed along northern MTB. CDOM

released from the Little Manatee River in the dry season is concentrated in northern MTB and extends southward into central MTB along the shipping channel after 30 days (Figure 18a). The CDOM distribution is more widespread in northern MTB after 60 days (Figure 18b) and has higher probabilities. Particles released from the Manatee River in the dry season remain tightly contained within the river and just north the mouth in LTB during the first 30 days of the simulation (Figure 19a) with a few particles being transported northward under the Sunshine Skyway Bridge. After 60 days (Figure 19b) the distribution of CDOM remains the same with slightly more particles entering MTB along the shipping channel.

Probability maps averaged over the 2007 wet season generally show more widespread CDOM dispersion throughout the study area than the simulations from the 2007 dry season. Transport quotients 30 days after particles are released from the Hillsborough River (Figure 16c) are highest along the western coast of HB. High CDOM concentrations extend across MTB and southwestward along the shipping channel. After 60 days (Figure 16d) the probability distribution is much more widespread with most of HB, MTB and portions of LTB containing very high to high concentrations of particles during the simulation. The probability of finding CDOM 30 days after it has been released from the Alafia River into Tampa Bay during the wet season is highest along the shipping channel and across northern MTB (Figure 17c). The proportion of particles in southeastern HB and throughout MTB increases after 60 days (Figure 17d). After 30 days particles released from the Little Manatee River (Figure 18c) are found in the highest proportion to the south of the river along the eastern coastline of MTB. High

concentrations are also found in LTB. The same is true after 60 days of the simulation (Figure 18d); particles are most likely to be found along the shipping channel to south of the river. The distribution of particles released from the Manatee River is tightly contained along the river and along the southern coast of LTB after both 30 days (Figure 19c) and 60 days (Figure 19d). Some particles are transported into MTB along the shipping channel.

Composite probability maps are constructed to show the total contributions from the four rivers during the dry (Figures 20a-b) and wet seasons (Figures 20 c-d) and the overall bay-wide distribution of CDOM averaged over 30 days and 60 days of model simulations.

The total riverine CDOM contribution during the dry season shows the highest transport quotients near the mouths of the four rivers after 30 days (Figure 20a). Moderate concentrations of CDOM are found throughout HB and extending into northern MTB. Low concentrations can be seen throughout most of the study area excluding northern OTB. After 60 days (Figure 20b) the CDOM distribution remains unchanged throughout the study area but with more transport into OTB. HB and northern MTB contain higher transport quotients.

The 30 day wet season composite (Figure 20c) shows the highest probabilities near the river mouths and moderate to high probabilities in western HB and in MTB along the shipping channel. CDOM distribution after 60 days (Figure 20d) does not change

drastically although portions of the shipping channel in MTB show slightly increased concentrations of CDOM as does northern MTB.

Surface salinity maps show average bay-wide salinity during the simulations (Figure 21). During the dry season, beginning in April (Figure 21a) and continuing through May 2007 (Figure 21b), most of the study area is in the high salinity range (≥35) with the exception of northern OTB and portions of LTB. CDOM released from the rivers during these months encounter high salinity water due to low freshwater input during this period in 2007. Salinities drop to the 30-35 range throughout LTB, MTB and HB for first 30 days of the wet season simulations (Figure 21c). Salinities in OTB range from 25-30. At the end of the wet season (Figure 21d) the proportion of the study area with salinities in the 25-30 range has increased. Northern OTB and HB become much more fresh with some areas having salinities <25. A portion of western MTB also becomes significantly fresher in October 2007.

Discussion

CDOM distribution in Tampa Bay is primarily controlled by mixing (Chen et al., 2007b) and becomes diluted the further it is transported away from its riverine source (Coble, 2007). The ability to discern CDOM away from the coastline is related to seasonal freshwater input (buoyancy) and the rate at which the CDOM photodegrades over time with exposure to radiation.

The surface probability maps, with applied photobleaching rates, show the effect mixing has on CDOM distribution during both low flow and high flow conditions. In the dry season salinities reflect the low amounts of freshwater entering the bay. Velocity profiles (not shown) show that particles are well-mixed and therefore have less exposure to the applied surface photobleaching rate. In the wet season stratification occurs due to an influx of freshwater (resulting in lower bay-wide salinities) and particles are exposed to surface radiation (simulated by the photobleaching rate) for longer periods at the surface. Higher CDOM concentrations are observed in the wet season than in the dry season and the distribution is more widespread throughout the study area. This is follows what has been reported in Tampa Bay (Chen et al., 2007b; Conmy et al., 2004), that CDOM concentration is inversely proportional to salinity and thus river input.

HB is an area known for its poor water clarity (Hu et al., 2004) and reduced rate of seagrass expansion (Johansson and Greening, 2000). The highest transport quotients are found in HB specifically near the Hillsborough River, an area with historical seagrass loss (Greening and Janicki, 2006) and where little mixing occurs. High transport quotients are also found in eastern HB near the Alafia River. This region encompasses an area known as the Kitchen where seagrass meadows have not expanded in recent years possibly due to poor water quality (Johansson, 2000). This area of eastern HB was shown by Burwell (2001) to have a significantly longer residence time, in both high and low streamflow conditions, than along the shipping channel to the west, implying that CDOM accumulates in this region.

The transport of particles southward out of HB along the eastern coast of MTB follows that observed by Havens et al. (2009) in a study which documented the presence of a strong southwestward flowing current to the east of the shipping channel. Water quality and color are optimal for seagrass growth in this region of MTB (Johansson, 2000) supporting the theory that strong currents prevent CDOM concentration in that portion of the bay, especially during the wet season.

This study is a first step in identifying CDOM seasonal distribution patterns from major freshwater sources, with the inclusion of a photobleaching rate, in order to determine which areas will most likely be affected by CDOM in Tampa Bay. The four largest freshwater sources in Tampa Bay (Hillsborough, Alafia, Little Manatee and Manatee Rivers) are chosen to represent the sources of CDOM although a significant amount of freshwater, in the form of runoff and groundwater (Tomasko et al., 2005), enters OTB as well. Debate exists over the amount of freshwater that enters Tampa Bay through OTB therefore that area was not considered in this study as a CDOM source. The scarcity of particles observed in OTB is likely a result of having no freshwater input into OTB; a separate study of CDOM transport in OTB is warranted (see Appendix B) given the lack of seagrass recovery in that portion of the bay (Greening and Janicki, 2006).

Photobleaching (or decay) is a function of the amount of radiation absorbed by CDOM molecules, primarily at the surface, and generally decreases with depth (Nelson et al., 1998). Given the highly organic nature of Tampa Bay and the degree to which high CDOM absorption in estuaries restricts photobleaching to a thin surface layer (Blough

and Del Vecchio, 2002), photobleaching was not considered below the uppermost grid cells in the model. The biological production (or growth) of CDOM *in situ* is not considered in this study.

No comprehensive CDOM datasets were available to ground truth the distribution maps. Sampling programs in Tampa Bay would need to begin to include CDOM measurements in their routine sampling in order to have *in situ* comparisons with the simulations (Chuanmin Hu, personal communication).

Among other things, knowledge of CDOM sources and distribution enhances our ability to monitor water quality (Chen et al., 2007b) and continue seagrass restoration efforts (Tomasko et al., 2005). Composite CDOM probability distribution maps are useful tools to guide sampling and ground truth satellite imagery. Tools, such as the prediction system used in this study, can track the effectiveness of efforts to restore water quality in Tampa Bay and move toward adaptive monitoring and ecosystem-based management in the bay.

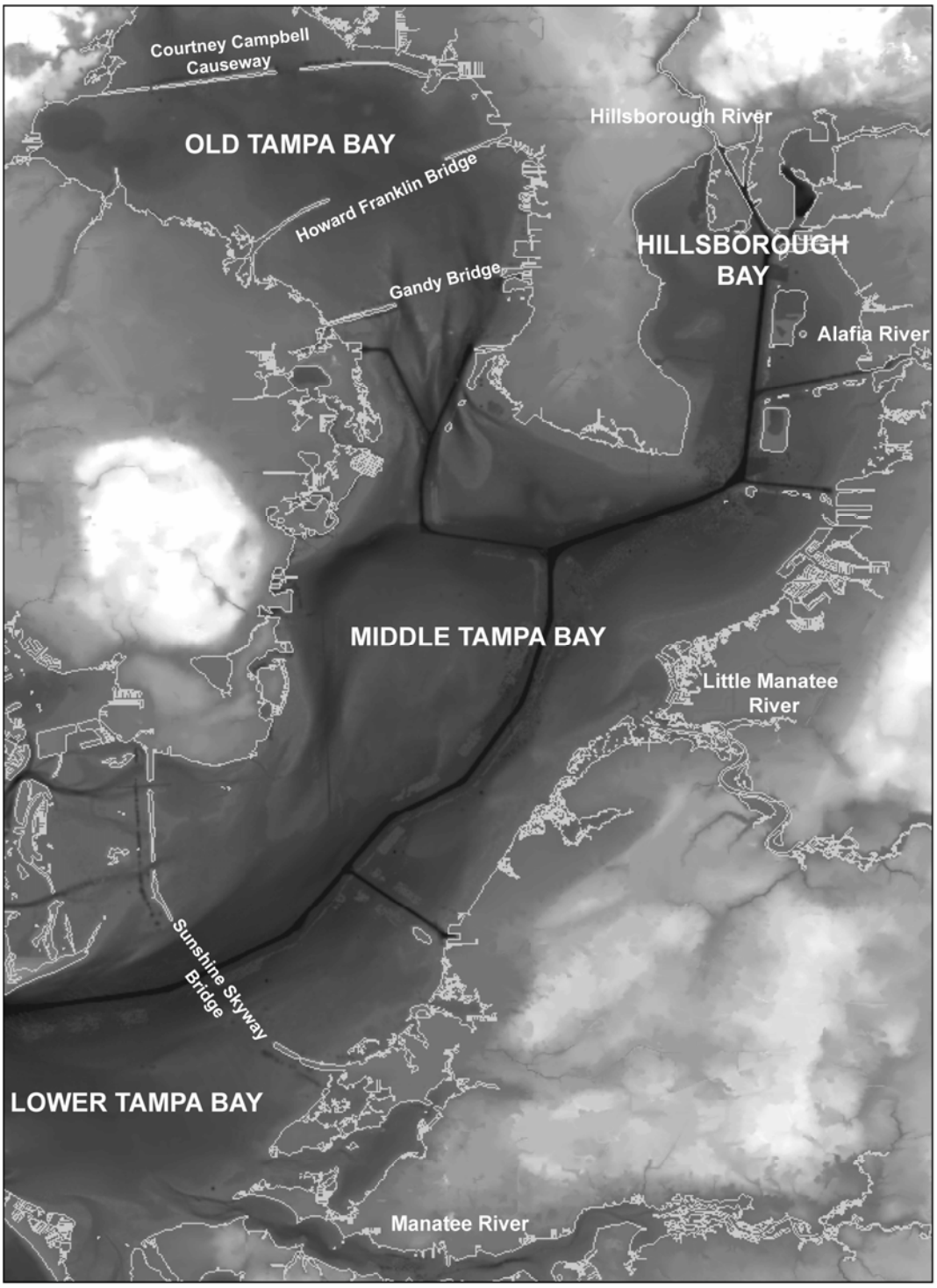

Figure 14 Bathymetric map of the Tampa Bay estuary. Tampa Bay can be divided into four quadrants: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB) and Lower Tampa Bay (LTB). A dredged shipping channel, running from LTB to MTB, bisects the bay before splitting into OTB and HB. The Hillsborough River and Alafia River empty into HB, the Little Manatee River empties into MTB and the Manatee River empties into LTB.

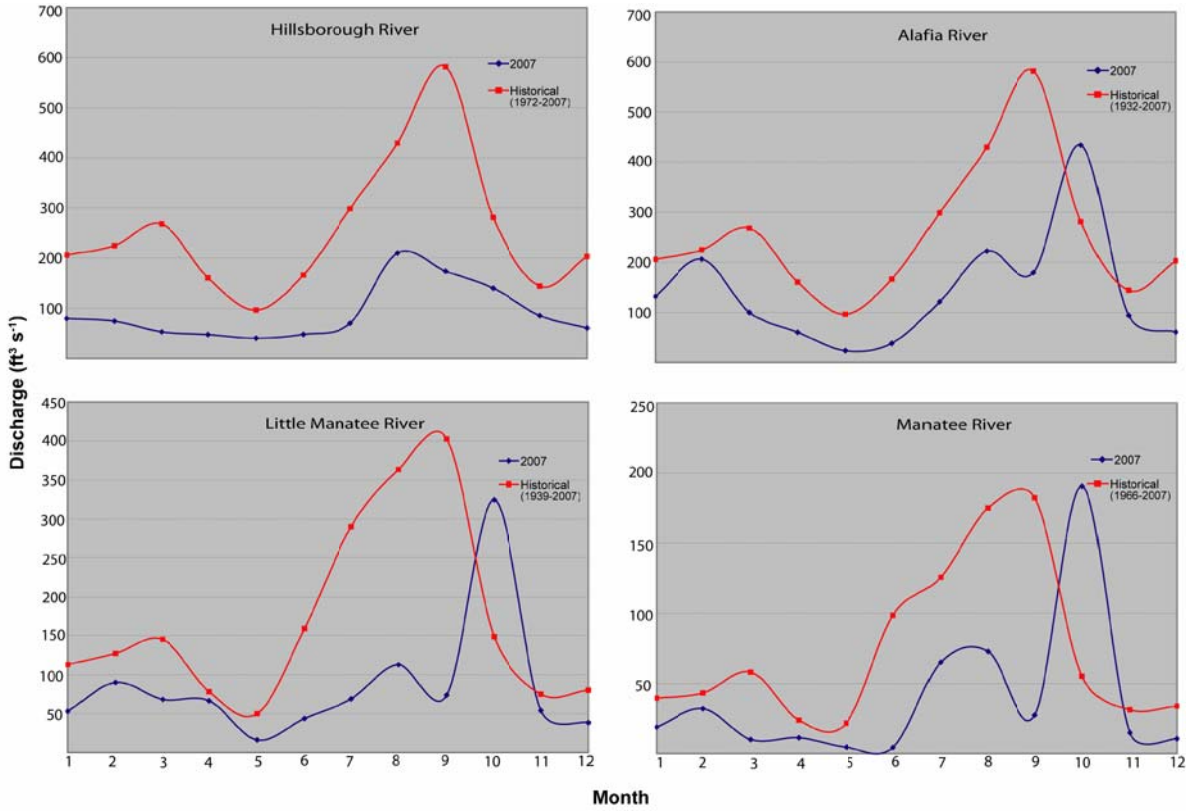

Figure 15 River discharge rates ($ft^3\ s^{-1}$) from the United States Geological Survey (USGS) for the Hillsborough River, Alafia River, Little Manatee River and Manatee River. The blue line represents monthly averaged daily discharge rates in 2007. The red line represents historical monthly averaged daily river discharge rates over various date ranges. The length of the USGS climatological dataset varies between rivers.

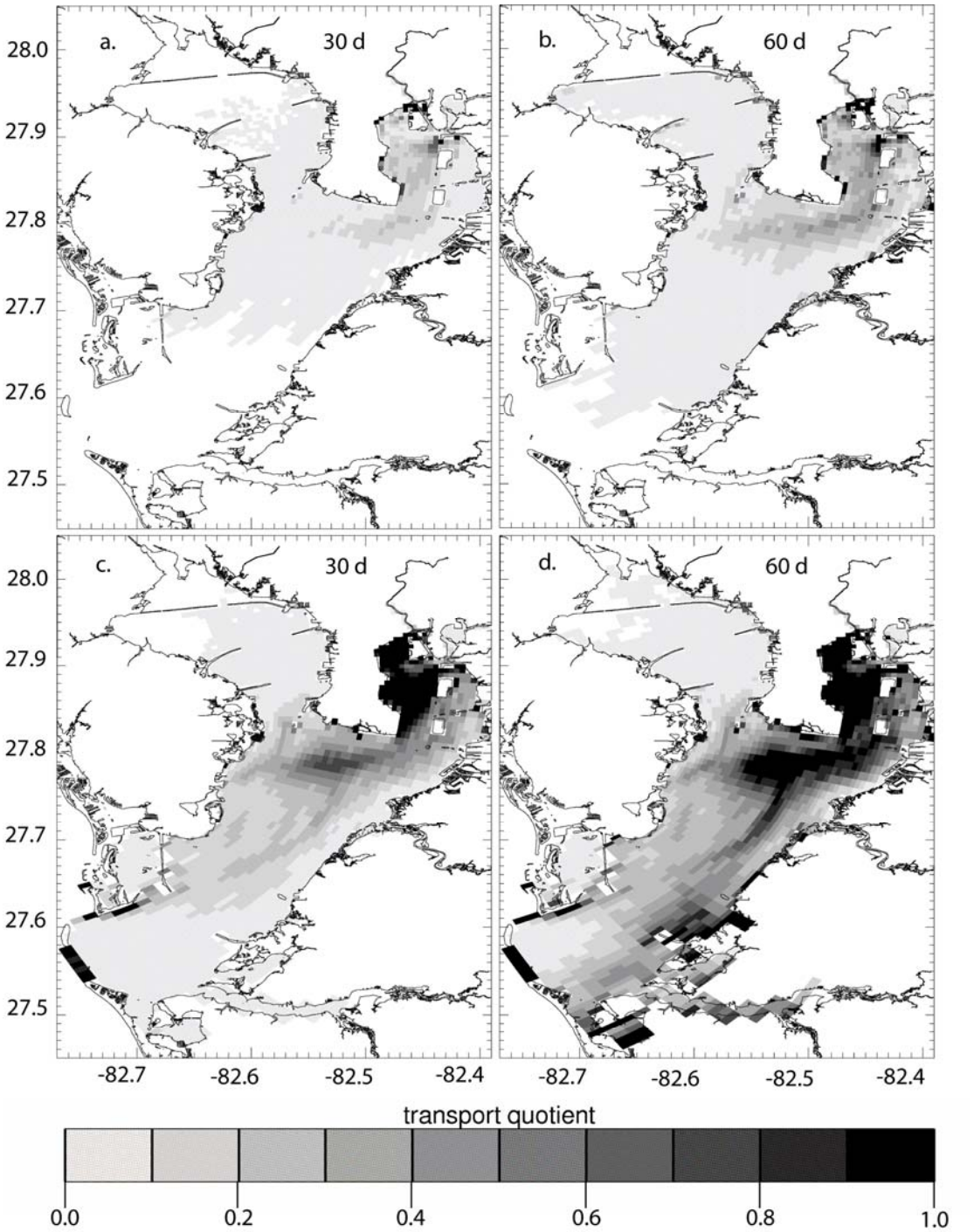

Figure 16 Transport quotients, with applied post-processing photobleaching rate, from the Hillsborough River simulations. The top two panels (a and b) show averaged transport quotients from the dry season simulations and the bottom two panels (c and d) from the wet season simulations. Transport quotients are calculated for each model grid cell and range in scale from zero (low probability of finding a particle in a grid cell) to one (high probability of finding a particle in a grid cell).

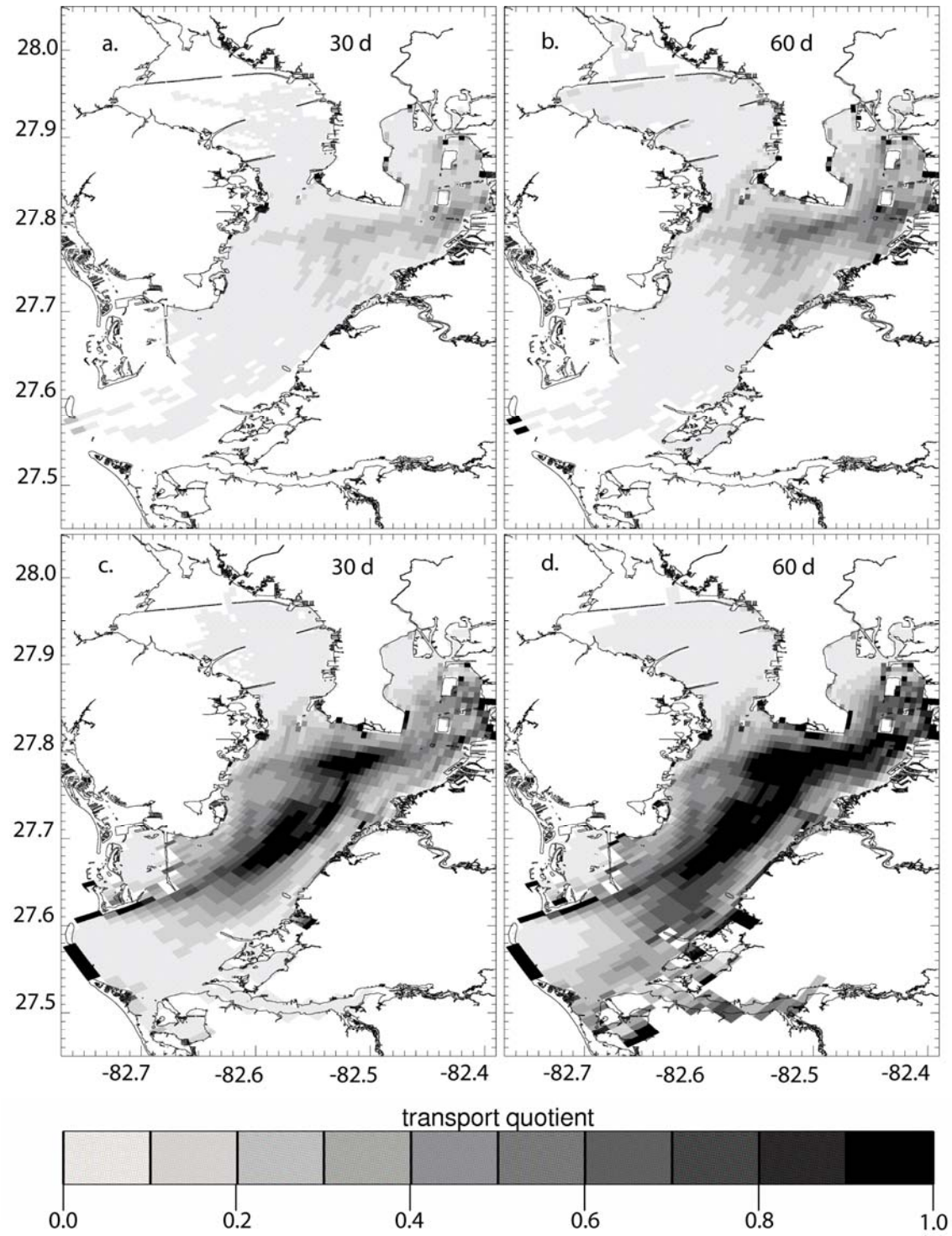

Figure 17 Transport quotients, with applied post-processing photobleaching rate, from the Alafia River simulations. The top two panels (a and b) show averaged transport quotients from the dry season simulations and the bottom two panels (c and d) from the wet season simulations.

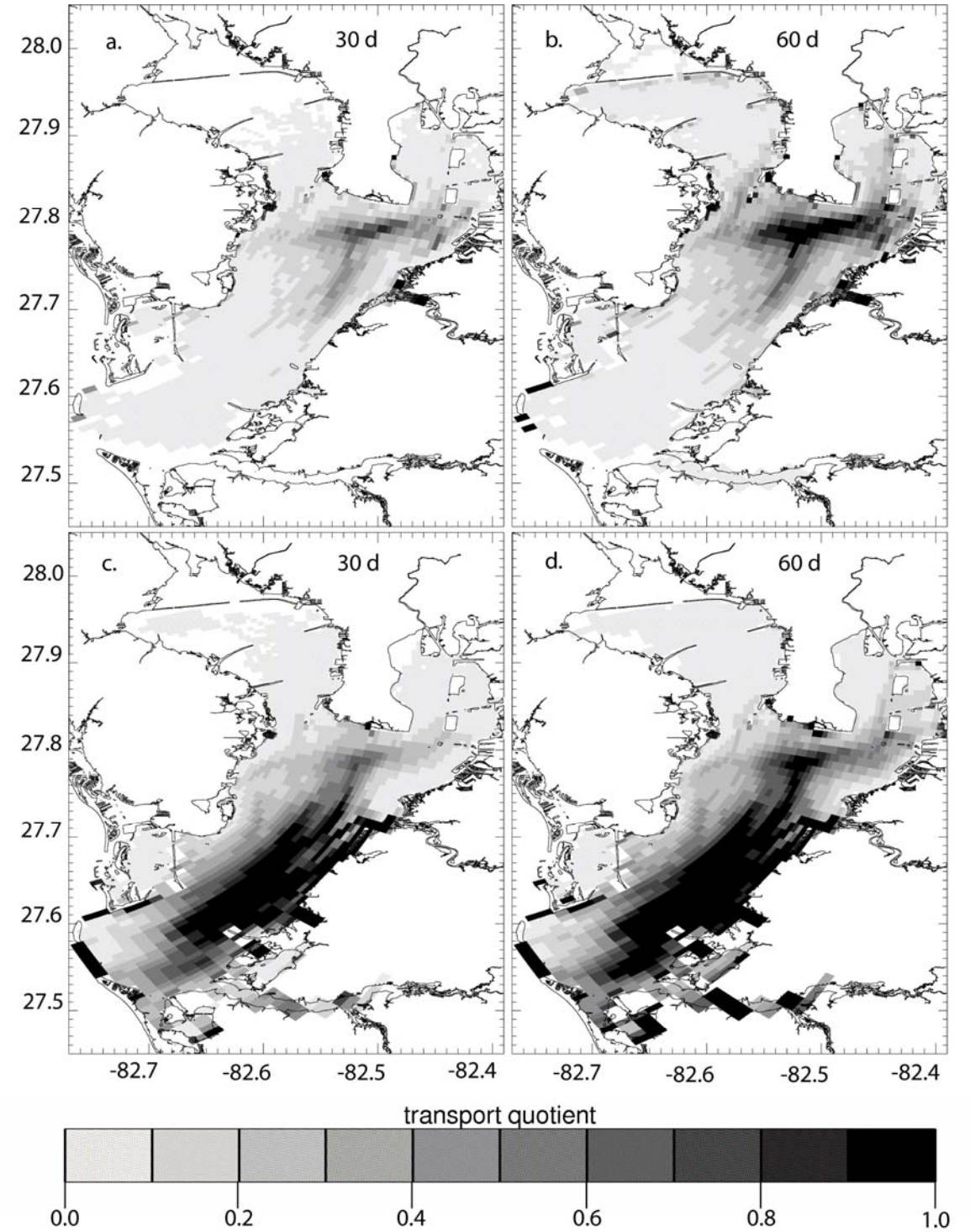

Figure 18 Transport quotients, with applied post-processing photobleaching rate, from the Little Manatee River simulations. The top two panels (a and b) show averaged transport quotients from the dry season simulations and the bottom two panels (c and d) from the wet season simulations.

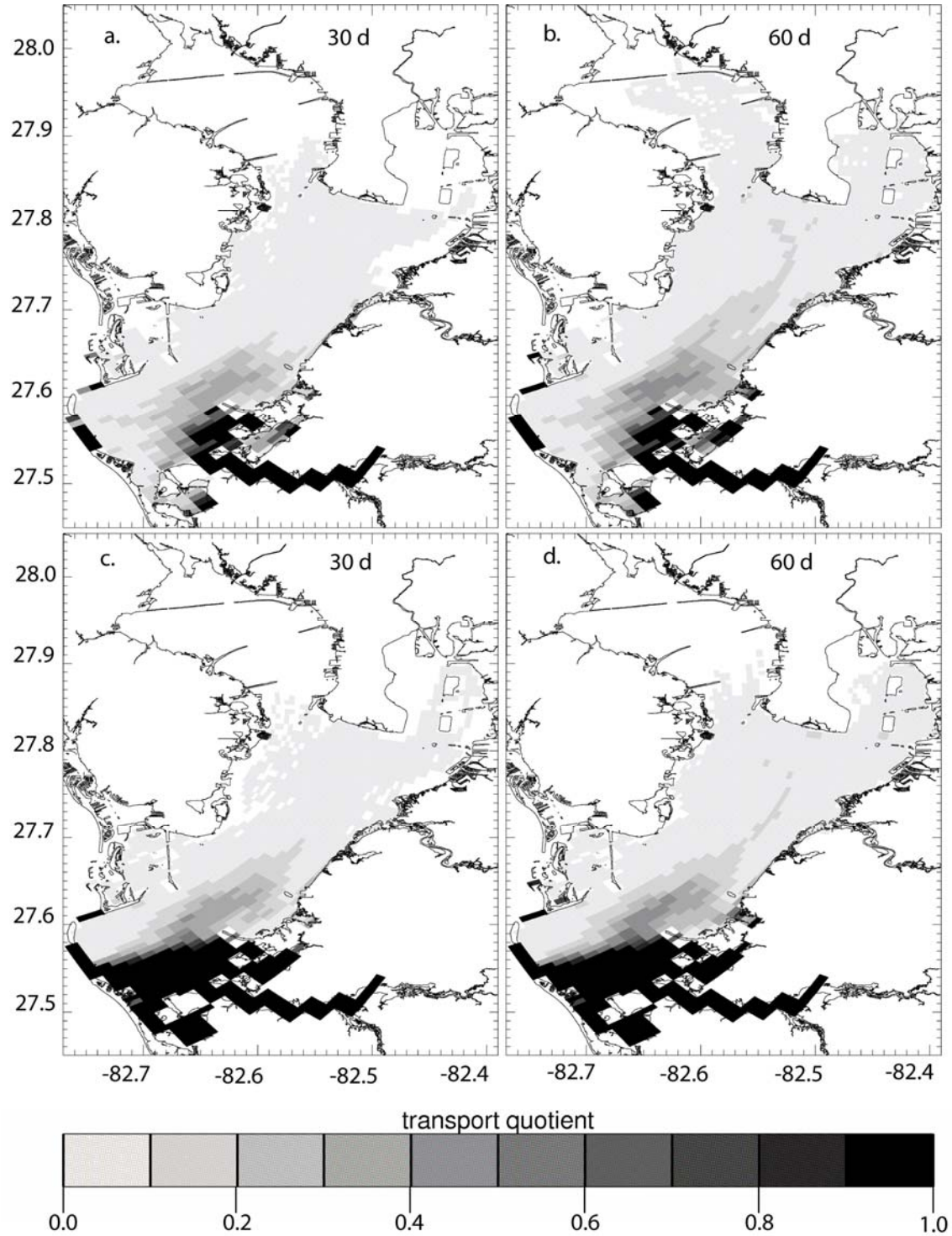

Figure 19 Transport quotients, with applied post-processing photobleaching rate, from the Manatee River simulations. The top two panels (a and b) show averaged transport quotients from the dry season simulations and the bottom two panels (c and d) from the wet season simulations.

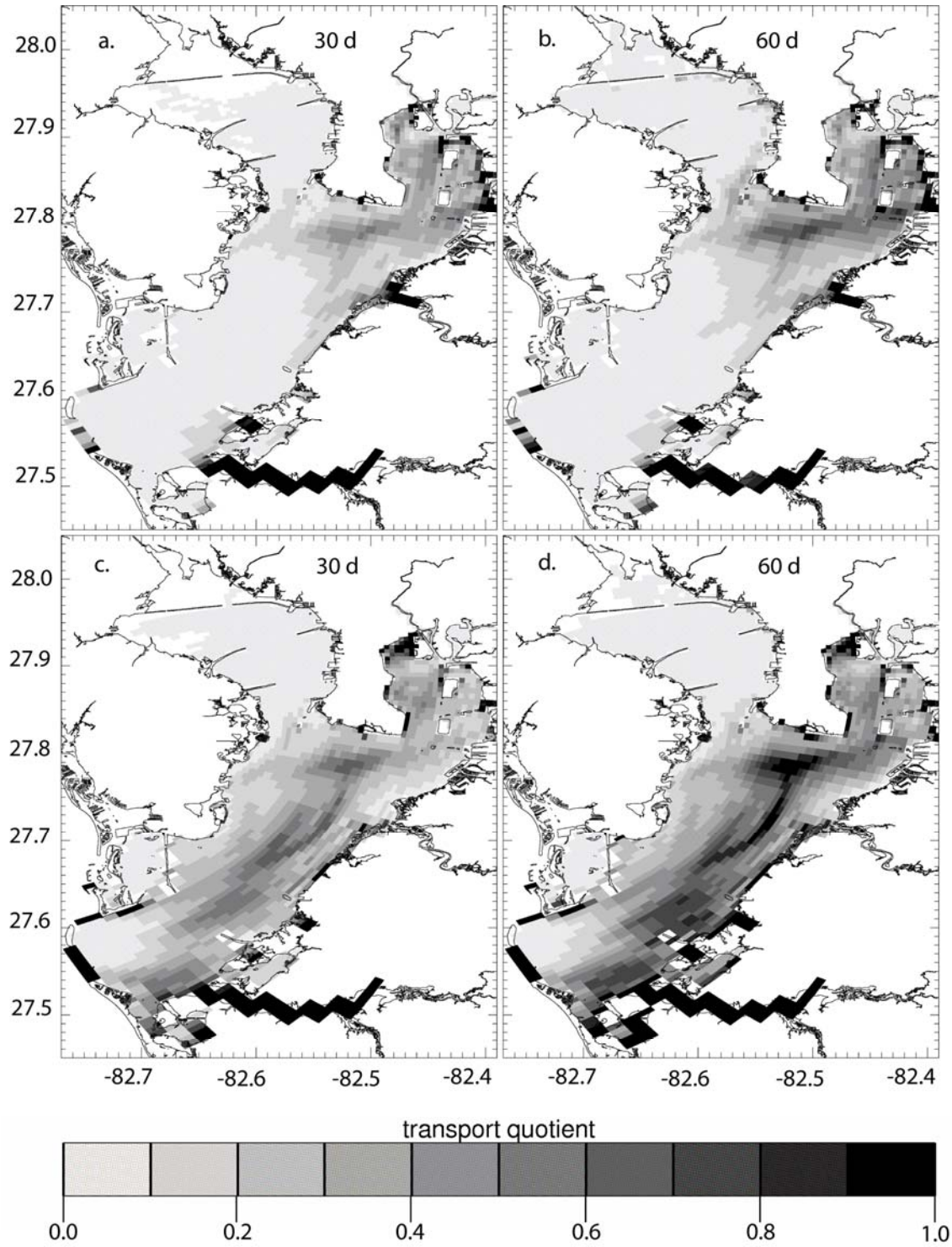

Figure 20 Composite showing the transport quotients, with applied post-processing photobleaching rate, from the four rivers (Hillsborough, Alafia, Little Manatee and Manatee) simultaneously. The top two panels (a and b) show averaged transport quotients from the dry season simulations and the bottom two panels (c and d) from the wet season simulations.

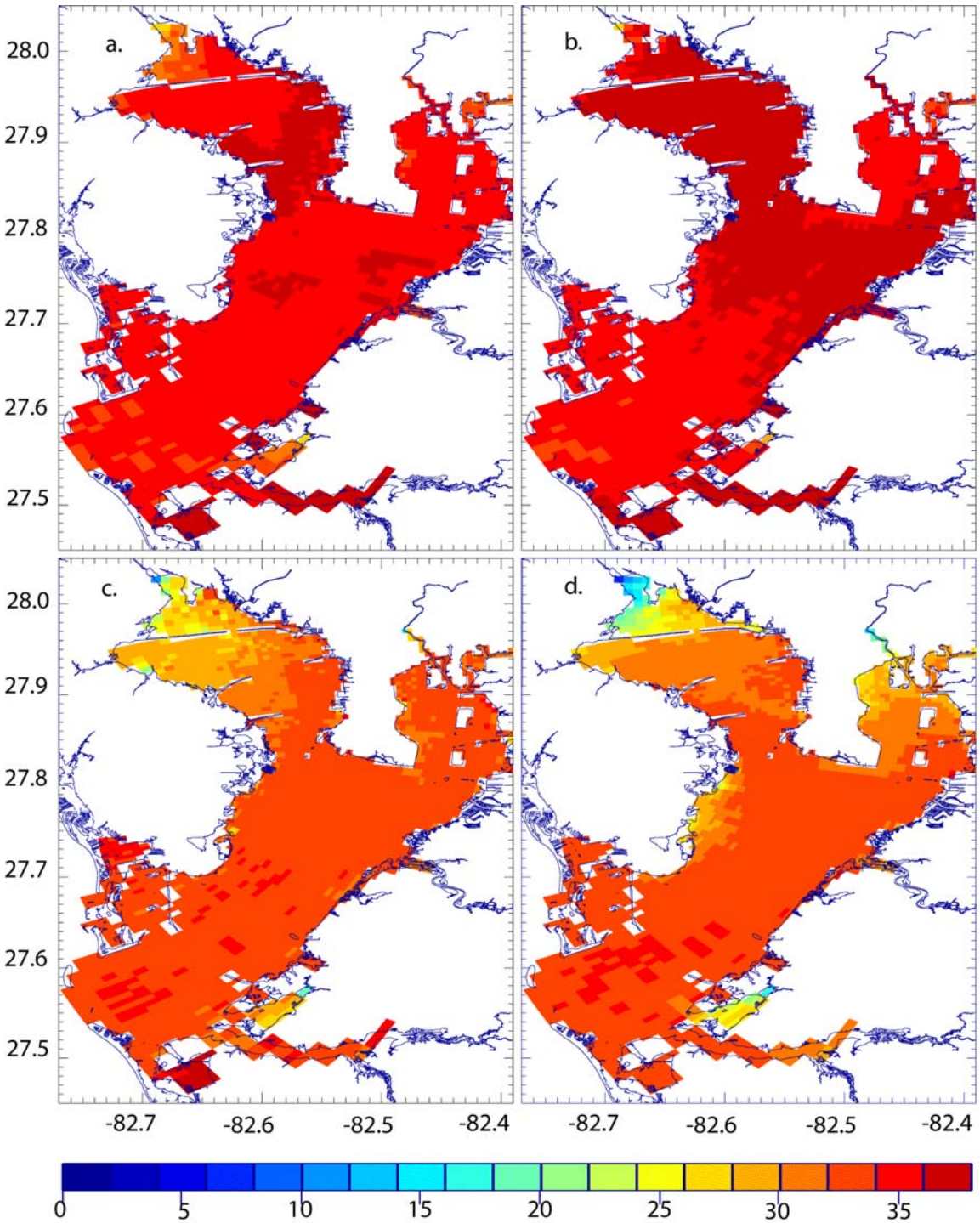

Figure 21 Bay-wide averaged monthly surface salinity. The top two panels show surface salinity in the dry season averaged for the months of (a) April and (b) May 2007; the bottom two panels show surface salinity in the wet season averaged for the months of (c) September and (d) October 2007.

Table 1 Surface photobleaching rates (d^{-1}) from the CDOM literature for wet and dry conditions at various estuarine and oligotrophic locations.

Location	Bleaching rate (wet season)	Bleaching rate (dry season)	Authors
Sargasso Sea	0.011	0.0023	Nelson et al. 1998
Everglades, FL	0.6		Kieber et al. 1990
Biscayne Bay, FL	0.15		Kouassi & Zika 1992
Cape Fear, NC	0.12		Shank et al. 2005
Sapelo Island, GA		0.0072	Miller & Zepp 1995

Conclusion

This dissertation expands on the work of Vincent (2001) to further develop and evaluate a coastal prediction system for Tampa Bay. The 3-D numerical circulation model underlying the prediction system has been extensively validated by Burwell (Burwell, 2001) and Meyers (2007). A particle tracking subroutine within the numerical model was developed and validated by Burwell (2001). His work determined that a Lagrangian based particle tracking method best approximates the true movement of particles in the bay. This study takes the theoretical application of the coastal prediction system a step further by incorporating basic biological characteristics onto particle simulations and evaluating the efficacy of those simulations in real world scenarios.

The prediction system is shown to accurately forecast the physical transport of a contaminant in Tampa Bay. Biological parameters are then incorporated one at a time in order to separately evaluate their accuracy for simulating the transport of biological material within the bay. The incorporation of both a tolerance parameter and a decay rate are successful in describing the basic transport mechanisms for algae and CDOM respectively from their sources into the bay.

This work introduces a probability calculation that allows for rapid analysis of bay-wide particle transport. Transport quotients are calculated at each time step of the simulation

and are used to compile probability maps of bay-wide particle transport. Providing environmental managers with these maps enables them to quickly assess areas of highest impact in the bay without requiring the detailed programming skills and oceanographic knowledge necessary to build the images. The probability maps can also be tailored to assist scientists in focusing their sampling efforts in the field.

The previous studies are numerical approximations to reality and should be treated as alternatives to costly *in situ* sampling. The forcing scenarios presented represent real world conditions and provide realistic interpretations of biological transport in Tampa Bay. The end result is a coastal prediction tool that can be used in real-time to support the management decisions of several environmental agencies in the bay area.

Future Work

1) Updated versions of the numerical model should include a larger model domain so as to incorporate some particle transport outside of the open boundary at the mouth of the bay. At present the open boundary condition is set at zero. This constraint traps particles at the open boundary and does not allow particles to exit the bay and then re-enter.

2) Further evaluations of the coastal prediction system, either by hindcasting previous events or a performing nowcast/forecast in real-time, will improve the accuracy

of model predictions. These evaluations should incorporate other biological parameters such as sedimentation and growth.

4) Further examination of the strong eastern current along the coastline of Tampa Bay is warranted given the presence of this current in the velocity profiles of all three studies.

3) An online component of the prediction system should be developed to allow environmental managers the ability to describe a specific spill or bloom scenario by entering a few initialization parameters. This would provide immediate access to model simulations to assist managers with clean-up or mitigation.

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Appendices

Appendix A: Transport Quotient Calculation

For any model grid cell within Tampa Bay, the transport quotient (Q) is defined as

$$Q(x,y) = \sum_T \sum_Z p(x,y,z,t) \qquad (1)$$

$$p(x,y,z,t) = \frac{n(x,y,z,t)}{N} \qquad (2)$$

where, x,y,z are spatial indices within the model grid; t is the time; n is the number of particles in a given cell at any time and N is the total number of particles released.

Appendix B: Application of the Coastal Prediction System

Feather Sound Project

Nutrient loading is a significant problem for coastal regions throughout Tampa Bay. The water quality in one region in particular has been determined to be worse than in the rest of the bay (Greening and Janicki, 2006).

Feather Sound is a body of water located in the northwestern portion of Old Tampa Bay (OTB), between the Courtney Campbell Causeway and the Howard Franklin Bridge (Figure 22). The watershed surrounding Feather Sound is primarily urban and residential with large areas of impervious cover. High levels of nutrients enter western Feather Sound via discharge from rivers, runoff from fertilizers applied to lawns and golf courses and sewage treatment plant outfall (Cross, 2007). Nutrients entering the region, especially nitrogen which is a limiting nutrient in coastal marine systems (Herbert, 1999), contribute to increased algal growth. Decomposition of the algal blooms causes eutrophication, potentially leading to hypoxic or anoxic regions. The result is that seagrass beds have not recovered as well in Feather Sound as in the rest of Tampa Bay despite efforts over the last several decades to reduce point and non-point sources of nitrogen into the bay (Bricker et al., 2007).

The acquisition of real-time data and the ability to perform nowcast/forecast simulations are becoming the standard for coastal observations and predictions. Referred to as

adaptive sampling by Robinson and Glenn (1999), this predictive method combines observations with model forecasts and has many applications in the marine user community. This study details an application of adaptive sampling and demonstrates the utility of a numerical model as part of a coastal observing network in Tampa Bay, Florida. The purpose of this study is to determine the extent of nitrogen transport in Feather Sound. From primary discharge locations the transport and fate of nitrogen is modeled to examine which regions of Feather Sound are most impacted by increases in nutrient input. A discussion of the results follows. This information will be beneficial to understanding the cause of seagrass fragmentation and loss in that region.

Methods

The Florida Department of Environmental Protection (FDEP) has been monitoring the water quality in Feather Sound for several years. They recently conducted field work using algal "sentinels" to detect nitrogen from different sources within Feather Sound (Cross, 2007). Five fresh water discharge locations in Feather Sound were selected in the FDEP study as the sites to anchor the algal sentinels (Figure 22). One site was selected to measure the outfall near the Clearwater wastewater treatment plant. Two sites were selected to measure the discharge from separate rivers, Alen's Creek and Cross Bayou. The final two sites measured runoff from two golf courses located along the Feather Sound coast. The algal sentinels were deployed at each of the five sites on May 14, 2007 and were recovered on May 22, 2007.

The goal of the FDEP algal sentinel study was to determine in what proportion nutrient sources (i.e. organic versus inorganic) were contributing to nitrogen enrichment in Feather Sound. By performing an isotopic analysis of the algal tissue a ratio between two isotopic forms of nitrogen, called the Delta 15-N ($\delta^{15}N$) ratio, was determined. Delta 15-N ratios have been shown to increase with population density in a watershed (Cabana and Rasmussen, 1996) and are related to sewage inputs (Hansson et al., 1997). Delta 15-N ratios were calculated by biologists at the FDEP based on isotopic analysis of the algal sentinels. A $\delta^{15}N$ ratio close to zero indicates an inorganic nitrogen source (e.g., fertilizer); a $\delta^{15}N$ ratio greater than 10 indicates an organic nitrogen source (e.g., animal or human waste) (Cross, 2007).

A coastal prediction system, comprised of a numerical circulation model and a particle tracking model, is used to simulate the transport of nitrogen from the five fresh water discharge points used in the FDEP study. Skill assessment of the circulation model as a forecasting tool was performed by Vincent (2001). A forecast simulation is run approximately one week prior to the deployment of algal sentinels at the five study sites. The results from the forecast are to be used to assist biologists from the FDEP with their nitrogen sampling project in Feather Sound and as an evaluation of the coastal prediction system as a forecasting tool.

An input file is constructed containing all of the boundary conditions necessary to run the model in a forecasting mode based on the method of Meyers et al. (2007). The predicted

open boundary water level is computed from local tidal harmonics (Table 1). The calculated amplitudes and phases are verified to be accurate with the water level from the Physical Oceanographic Real-Time System (PORTS) Egmont Key station. The forecast simulations are initially forced with long term averages for temperature (25ºC), salinity (surface: 33.8, middle: 34.1, bottom: 34.3), precipitation (0.42 cmd^{-1}), and winds (1.4 ms^{-1} from 67º true N). Fresh water fluxes are initialized at the beginning of the simulation with the most recent nowcast data transmission.

Eight hundred particles, each representing a fraction of the total nitrogen input, are simultaneously released from each of the five discharge locations at the beginning of the forecast. The particles are used to simulate nitrogen transport from those locations. The particles are released throughout the water column and are advected throughout the model domain by instantaneous model velocity fields. The spatio-temporal stamps of the particles are written to a data file every hour during the eight day simulation. It should be noted that the particles did not have a sedimentation rate associated with their transport.

Transport quotients are calculated for the model simulation to determine a probability distribution of nitrogen in Feather Sound (Appendix A). Cells with the highest transport quotient contain particles for the greatest amount of time during the simulation.

Results

Snapshots taken during the forecast simulation show that nitrogen released from the treatment plant and Alen's Creek quickly mix together throughout the water column (Figure 23). Similarly nitrogen from the two golf course runoff sites mixes together within a day after entering Feather Sound. Over time nitrogen is transported north and then west from all of the sites in Feather Sound. Some nitrogen is transported into northern OTB through a small gap under the western portion of Courtney Campbell Causeway.

The transport quotients from both simulations show that eight days after simulated nitrogen particles are released into Feather Sound the parcels of water containing nitrogen are most likely to remain close to the shore and are confined to western OTB (Figure 24). The areas to the north of the treatment plant outfall and Alen's Creek are forecasted to have the highest probability of containing nitrogen. A high probability also exists that nitrogen would be found in the area just north of the two golf courses during the study period.

The $\delta^{15}N$ average ratio near the Clearwater treatment plant outfall site is greater than ten and elevated values were found at the mouth of the two creeks (Table 2). The lowest average $\delta^{15}N$ ratios are found near the golf course sites.

Appendix B (Continued)

Discussion

The model forecast simulation of nitrogen transport supports the circulation patterns in OTB during conditions that were dryer than normal for that month historically (National Weather Service). The overall surface circulation in Feather Sound is reduced during periods of low rainfall and the weakened transport is westward into the coast (Meyers et al., 2007). Longer residence times (Burwell, 2001) are a possible explanation for the degraded water quality in Feather Sound as compared with the rest of OTB.

The results from the $\delta^{15}N$ ratios in northern OTB near the wastewater treatment facility suggest organic nitrogen sources, perhaps from animal or human waste found in runoff or wastewater systems. The ratios near the golf courses indicate that nitrogen in this area originated from inorganic nitrogen sources, such as from fertilizers used on the golf courses, in addition to organic sources.

This joint study with the FDEP confirms results from previous studies (Bricker et al., 2007; Burwell, 2001; Cross, 2007; Greening, 2004) suggesting that local retention of nutrient inputs from various sources (rivers, land runoff, and wastewater) could be impeding the successful resurgence of seagrass in Feather Sound. The nitrogen sources ranged from predominately organic to a mixture of organic and inorganic. This is to be expected in a mixed use watershed like the one surrounding Feather Sound. Further

circulation and flushing scenarios in Feather Sound are needed along with more rigorous sampling to fully understand the relationship between the transport of nutrients and the slow recovery of seagrass in western OTB. Further evaluations of the coastal prediction system as a forecasting are needed for the purpose of establishing sampling strategies prior to work in the field.

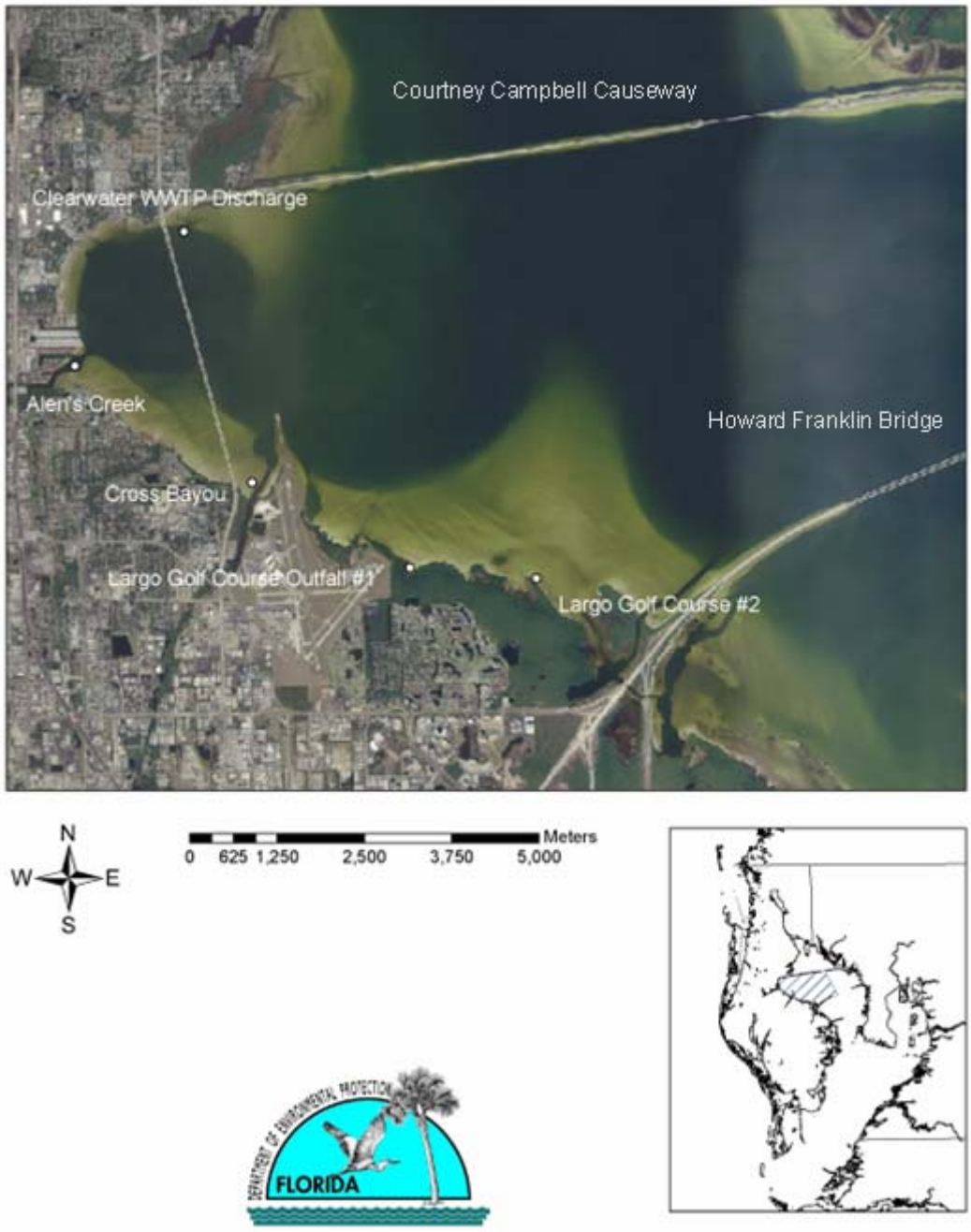

Figure 22 Location of discharge points in Feather Sound for nitrogen source tracking using stable isotopes.

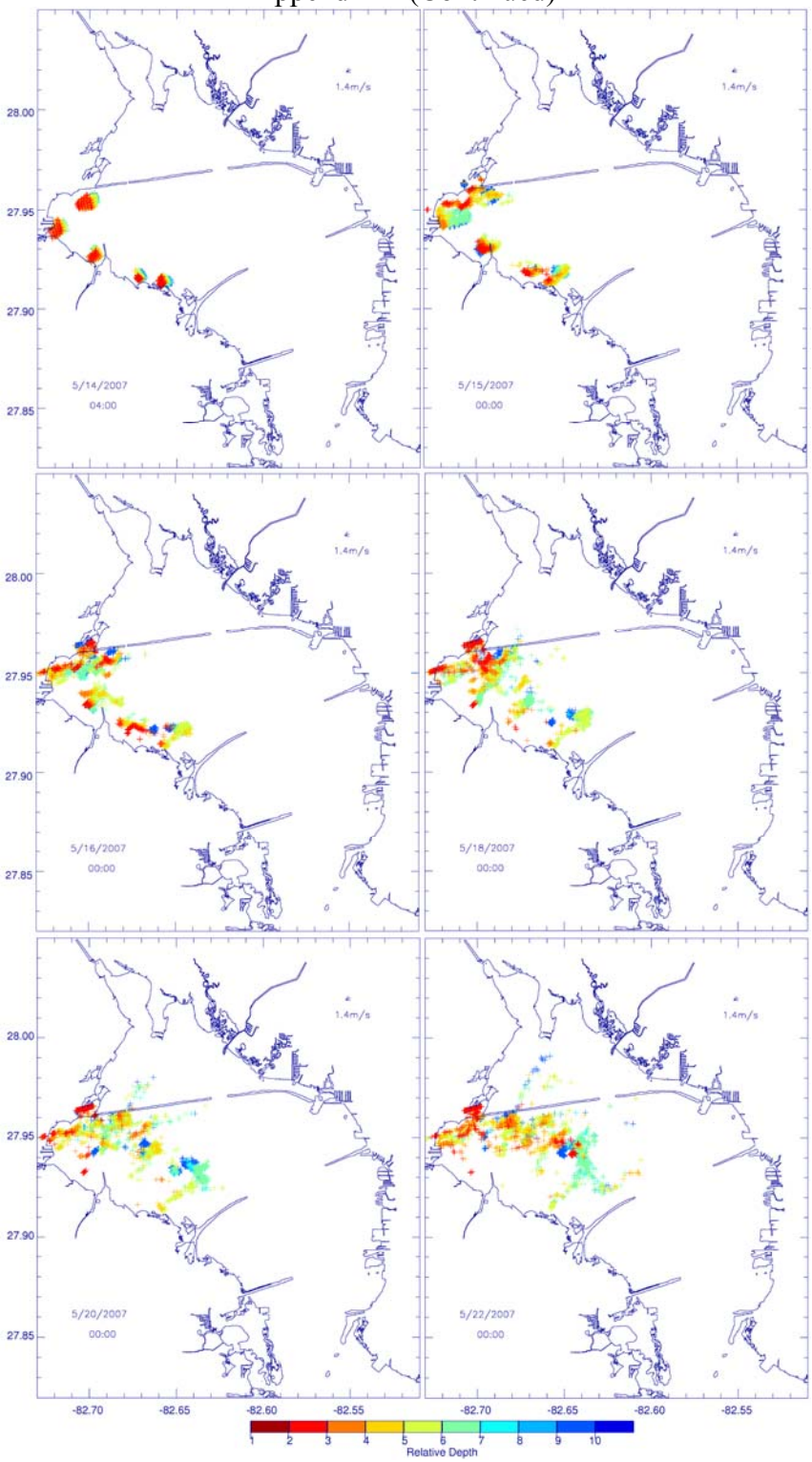

Figure 23 Snapshots of numerical model forecast simulation for nitrogen source tracking study (May 14-22, 2007). The scale represents the depth of the particles in the water column with red being at the surface and blue being at depth.

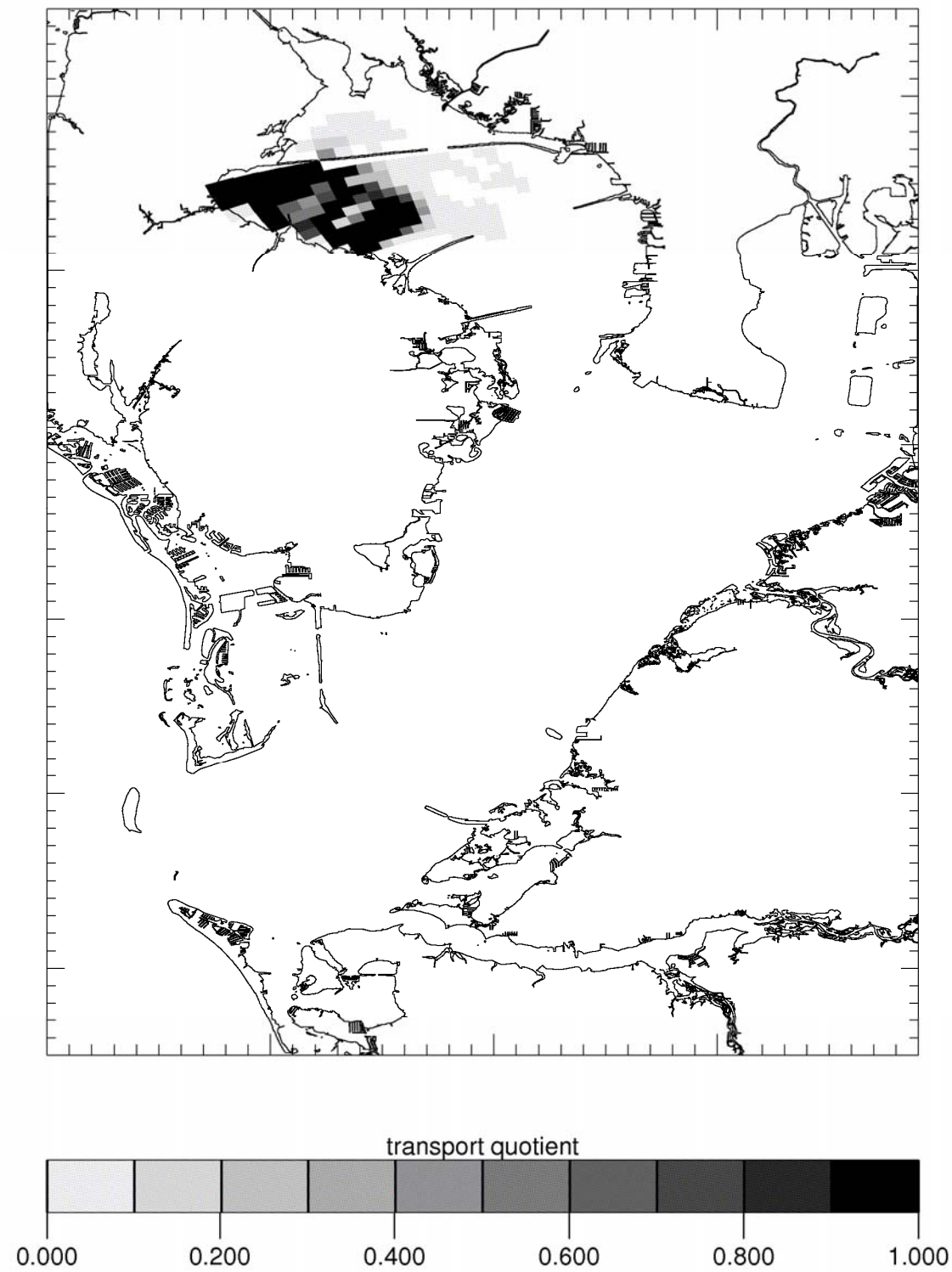

Figure 24 Probability distribution for nitrogen source tracking study based on forecast simulation run from May 14-22, 2007.

Table 2 Water level harmonics used in the numerical circulation model.

NOS Tidal Harmonics for St. Petersburg, FL			
Tidal Constituent	**Amplitude (m)**	**Phase (deg)**	**Speed (deg/hr)**
M2	0.175	197.0	28.9841042
S2	0.057	211.7	30.0000000
N2	0.030	191.3	28.4397295
K1	0.167	49.9	15.0410686
O1	0.155	37.7	13.9430356
P1	0.049	57.6	14.9589314

Table 3 Average delta 15-N values from discharge points in Feather Sound.

Sample Location	**Avg d15N**
Clearwater treatment plant	11.61
Alen's Creek	8.18
Cross Bayou	8.05
Golf Course #1	7.50
Golf Course #2	7.43

Appendix C: Old Tampa Bay *Karenia brevis* samples

During the 2005 *Karenia brevis* bloom no samples were collected within Old Tampa Bay (OTB) since no reported fish kills occurred in that area during the bloom. Samples were collected in OTB during a 2006 *K. brevis* bloom for comparison purposes with the 2005 *K. brevis* data. These samples, collected in August and September of 2006 from the mouth of OTB to the Howard Franklin Bridge, showed background concentrations of *K. brevis* during the 2006 bloom.

Figure 25 *Karenia brevis* samples collected in Old Tampa Bay during a 2006 *K. brevis* bloom. The samples are classified as background concentrations.

About the Author

Heather Havens received a Bachelor of Arts degree in biology from Agnes Scott College in 2001. While attending Agnes Scott, she participated in a marine science summer study program offered through Boston University's School for Field Studies. Through this program Heather spent a summer in the Turks and Caicos studying management of marine protected areas. She went on to pursue an advanced degree in marine science from the University of South Carolina where she earned a Master of Science degree in 2004. Under the advisement of Dr. Björn Kjerfve her master's research focused on the dispersion of snapper eggs from a spawning site within the Belize Barrier Reef. Heather entered the Ph.D. program at the University of South Florida in 2004. Under the advisement of Dr. Mark Luther her doctoral research focused on the evaluation of a coastal prediction system for guiding water quality monitoring in the Tampa Bay estuary.