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Solute Dispersion Modeling in New York Harbor

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EXECUTIVE SUMMARY

The hydrodynamic model within the Port of New York/New Jersey Operational Forecast System (NYOFS) has been used to simulate the tracer dispersion in the New York Harbor. With a concentration model added to the NYOFS, the hydrodynamic model simulates the movement of the passive tracer hexafluoride (SF_6) deliberately released at the Newark Bay in July, 2002 and at the East River in June, 2003 (two releases, one before the flood tide, flood injection, and one before the ebb tide, ebb injection) by Columbia University researchers. The tracer field experiments are used to study the dispersive characteristics of the inland waterways in the New York Harbor estuary, particularly at the Newark Bay, Arthur Kill, Kill van Kull, and the East River.

The hydrodynamic model has been set-up for simulating the tracer movement released in the field experiments. The model is forced with observed water levels at lateral open boundary Sandy Hook, NJ and Kings Point, NY and with observed winds on the surface. Observed discharges at Hudson and Passaic Rivers are used as the flow input to the model instead of climatology in NYOFS. A one-dimensional outflow and the constant spatial gradient inflow are specified for the concentration boundary condition at the northern end of the East River near Kings Point. The simulated water levels and currents are verified with observations to ensure the model accuracy. Model simulated tracer concentration distribution and the mass at model surface layer are compared with tidally daily synchronized measurements. The comparisons include: longitudinal tracer concentration distribution, vertical profile, mass inventory, center of mass movement, and residence time.

The simulated longitudinal tracer concentration distributions are qualitatively in agreement with observations. The simulated flushing rate is slower than the observations at the Arthur Kill and East River due to slower current velocity associated with coarse grid resolution. Since the model is barotropic without salinity and temperature, there is no structure in the simulated tracer vertical profile similar to observations found at Hudson River and northern East River.

For the July 2002 field experiment, the residence time from the mass inventory, within the inland waterways of Newark bay, Arthur Kill, and Kill van Kull, was estimated about 3.4 days for the data and 4.5 days for the model. For the June 2003 field experiment, the residence time within the East River was estimated 3.8 (flood injection) and 1.7 (ebb injection) days from the data, and 3.2 (flood injection) and 3.3 (ebb injection) days from the model, respectively.

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1. INTRODUCTION

Circulation in an estuary is the primary mechanism for transporting solute and pollutants in the water. The mixing process and dispersion characteristics with adjacent water parcel due to tidal circulation are essential to determine the short-term flushing and residence time for environmental and ecological management. In a coastal estuary, such as the New York Harbor and Galveston Bay/Houston Harbor, environmental assessment due to municipal pollutants requires detail transport characteristics in the area.

The Harbor and Port of New York and New Jersey (Figure 1.1) has a complex geometry with narrow navigation channels interconnecting the regional bays, for example, the Kill van Kull between the Upper Bay and the Newark Bay; the East River between the Long Island Sound and the Upper Bay; the Arthur Kill between the Newark Bay and the Raritan Bay. These channels are important for both safe navigation and hydrodynamics in the Harbor. Tidal currents through these channels play an important role in determining the dispersion characteristics. Flows from four major river systems provide freshwater to each of the three regional bays; the Raritan River to the Raritan Bay, the Passaic and Hackensack Rivers to the Newark Bay, and the Hudson River to the Upper Bay. These river inflows associated with the eddies and current shears generated by interacting with tidal currents further complicate the circulation and transport in the New York Harbor estuary.

The researchers in the Columbia University, New York conducted two field experiments in the New York Harbor to study the circulation, mixing, and the transport and the fate of solutes using sulfur hexafluoride (SF_6). In July 2002, an approximate of 0.9 mol of SF_6 was injected into Newark Bay, NJ. The SF_6 tracer was observed over 11 consecutive days using a high-resolution measurement system. In June 2003, two injections of approximate of 3.9 mol SF_6 each were made 8 days apart in the East River, NY. Measured data are processed and compiled for dispersion characteristics interpretation. Detailed experiment description and results are documented in two journal articles (Caplow, et. al., 2003 and Caplow, et. al., 2004).

National Ocean Service (NOS) of NOAA has developed the Port of New York/New Jersey Operational Forecast System (NYOFS) to simulate water levels and current velocities for use by mariners navigating in New York Harbor. Based on the Princeton Ocean Model (POM, Blumberg and Mellor, 1987), this forecast system (Wei and Chen, 2001 and 2002) has been running operationally since February 2003 utilizing the near real-time water level and current information from NOS' Physical Oceanographic Real-Time System (PORTS). The hydrodynamic model of this system will be used to simulate the SF_6 transport in the New York Harbor.

This report documents the modeling work performed to simulate the transport the SF_6. The model set-up, simulation procedures, and results comparison with measured data are described. Conclusions and future work based on simulation results are discussed.

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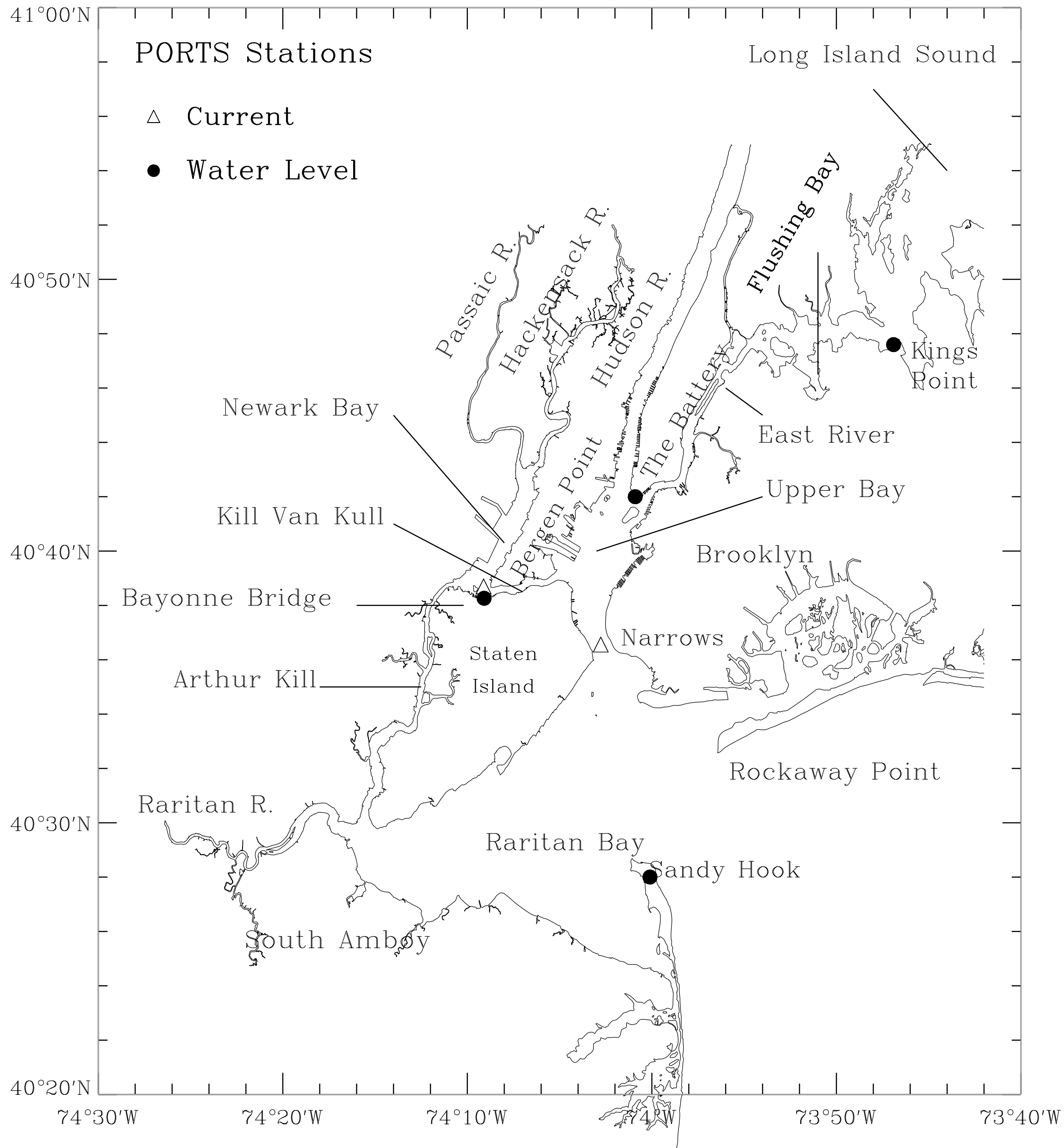


Figure 1.1. Map showing New York Harbor and The Port of New York/New Jersey including PORTS stations and major tributaries.

2. HYDRODYNAMIC MODEL

2.1. Governing Equation

The NYOFS hydrodynamic model is a three-dimensional barotropic circulation model, based on POM, for simulating water levels and current velocities. The model is forced with: water levels at the open boundaries at Sandy Hook, NJ and Kings Point, NY; freshwater inflows from the Raritan, Passaic, Hackensack, and Hudson Rivers; and surface winds. The governing equations in a vertical sigma coordinate are briefly given as follows. Detailed formulation is contained in Blumberg and Mellor (1987), and Wei and Chen (2001).

$$\frac{\partial \eta}{\partial t}+\frac{\partial UD}{\partial x}+\frac{\partial VD}{\partial y}+\frac{\partial \omega}{\partial \sigma}=0, \tag{1}$$

$$\frac{\partial UD}{\partial t}+\frac{\partial U^2 D}{\partial x}+\frac{\partial VD}{\partial y}+\frac{\partial U\omega}{\partial \sigma}-F_x-fVD+gD\frac{\partial \eta}{\partial x}=\frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial U}{\partial \sigma}\right]+\frac{1}{\rho}(\tau_{sx}-\tau_{bx}), \tag{2}$$

$$\frac{\partial VD}{\partial t}+\frac{\partial UVD}{\partial x}+\frac{\partial V^2 D}{\partial y}+\frac{\partial V\omega}{\partial \sigma}-F_y+fUD+gD\frac{\partial \eta}{\partial y}=\frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial V}{\partial \sigma}\right]+\frac{1}{\rho}(\tau_{sy}-\tau_{by}), \tag{3}$$

$$\frac{\partial q^2 D}{\partial t}+\frac{\partial Uq^2 D}{\partial x}+\frac{\partial Vq^2 D}{\partial y}+\frac{\partial \omega q^2}{\partial \sigma}=\frac{\partial}{\partial \sigma}\left[\frac{K_q}{D}\frac{\partial q^2}{\partial \sigma}\right]+\frac{2K_M}{D}\left[\left(\frac{\partial U}{\partial \sigma}\right)^2+\left(\frac{\partial V}{\partial \sigma}\right)^2\right]-\frac{2Dq^3}{B_1\ell}+F_q, \tag{4}$$

$$\frac{\partial q^2\ell D}{\partial t}+\frac{\partial Uq^2\ell D}{\partial x}+\frac{\partial Vq^2\ell D}{\partial y}+\frac{\partial \omega q^2\ell}{\partial \sigma}=\frac{\partial}{\partial \sigma}\left[\frac{K_q}{D}\frac{\partial q^2\ell}{\partial \sigma}\right]+E_1\ell\left[\frac{2K_M}{D}\left[\left(\frac{\partial U}{\partial \sigma}\right)^2+\left(\frac{\partial V}{\partial \sigma}\right)^2\right]\right]\widetilde{W}+F_\ell \tag{5}$$

where $\sigma = (z-\eta)/(H+\eta)$, H is the mean sea level water depth, U and V are horizontal velocities, K_M and K_H are the vertical kinematic viscosity and diffusivity, respectively, K_q is vertical turbulence mixing coefficient, q^2 is twice the turbulence kinetic energy, ℓ is the turbulence length scale, $\widetilde{w}=1+E_2(\ell/k\,L)$, k = 0.4 is the von Karman constant, $L^{-1}=(\eta-z)^{-1}+(H+z)^{-1}$, B_1, E_1, and E_2 are empirical constants (B_1, E_1, E_2)=(0.52, 1.8, 1.33), τ_s and τ_b are the wind stress and bottom friction, $D=H+\eta$ is the total water depth, g is the acceleration due to gravity, f is the Coriolis parameter, ρ is the water density, and ω is the transformed vertical velocity normal to a sigma surface. The relationship of ω with the Cartesian vertical velocity W is

$$W=\omega+U\left[\sigma\frac{\partial D}{\partial x}+\frac{\partial \eta}{\partial x}\right]+V\left[\sigma\frac{\partial D}{\partial y}+\frac{\partial \eta}{\partial y}\right]+\sigma\frac{\partial D}{\partial t}+\frac{\partial \eta}{\partial t}, \tag{6}$$

And the horizontal viscosity and diffusion terms F_x and F_y are defined as

$$F_x=\frac{\partial}{\partial x}\left[2HA_M\frac{\partial U}{\partial x}\right]+\frac{\partial}{\partial y}\left[HA_M\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)\right], \tag{7}$$

$$F_y = \frac{\partial}{\partial x}\left[2HA_M\left(\frac{\partial V}{\partial y} + \frac{\partial V}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[HA_M \frac{\partial V}{\partial y}\right] \tag{8}$$

where A_M, the vertically integrated horizontal eddy viscosity, is defined by the Smagorinsky formula

$$A_M = C_N \Delta x \Delta y \frac{1}{2}\left|\nabla V + (\nabla V)^T\right| \tag{9}$$

where C_N, a non-dimensional parameter, is set to be 0.2 in this study; u and v are the vertically-integrated velocities and Δx and Δy are the grid spacings in the x and y directions for each grid cell;

$$\left|\nabla V + (\nabla V)^T\right|/2 = \left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 / 2 + \left(\frac{\partial v}{\partial y}\right)^2\right]. \tag{10}$$

For the passive tracer SF_6, the concentration equation is

$$\frac{\partial CD}{\partial t} + \frac{\partial CUD}{\partial x} + \frac{\partial CVD}{\partial y} + \frac{\partial C\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial C}{\partial \sigma}\right] + F_C - L \tag{11}$$

where C is the concentration of SF_6,

$$F_C = \frac{\partial}{\partial x}\left[2HA_M \frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[HA_M \frac{\partial C}{\partial y}\right], \tag{12}$$

and L is the loss due to the gas transfer at the water surface, described in Section 2.3.

The boundary conditions for the continuity and momentum equations and other model parameter definition can be found in Wei and Chen (2001, 2002). The concentration lateral open boundary condition during the outflow is specified with one-dimensional advection,

$$\frac{\partial C}{\partial t} = \frac{\partial C\vec{V}}{\partial n} \tag{13}$$

where $\vec{V}$ is the velocity in the normal direction to the boundary n. The spatial gradient is used for the inflow,

$$\left.\frac{\partial C}{\partial n}\right|_b = \left.\frac{\partial C}{\partial n}\right|_{b-1} \tag{14}$$

where b denotes the cell at the lateral open boundary.

2.2. Air-Water Gas Transfer

After injection into the water column, part of the gaseous SF_6 tracer exits from the water into the air. The tracer loss L in the concentration transport equation (2.3) cam be expressed as

$$L = \frac{\partial}{\partial \sigma}\left[\frac{kC}{D}\right],$$

where *k* is the gas transfer velocity, a measure of the air-water transfer rate, can be defined as

$$k = \lambda_g D$$

where λ_g is the first-order gas transfer loss rate for the water column (with unit t^{-1}) and D is the total water depth. From many field and laboratory experiments (Ho et al., 2002, Caplow et al., 2003), λ_g is found to be approximately 0.170.01 day^{-1}.

2.3. Model Grid

The orthogonal curvilinear model grid used in NYOFS is also adopted here for the SF_6 concentration modeling. The model is constructed to cover the New York Harbor and vicinity estuaries from 74° 10' W to 73° 45' W and from 40° 24' N to 40° 52' N including the East River, Hudson River up to Poughkeepsie, Newark Bay, the Hackensack and Passaic Rivers, Arthur Kill, the Raritan River, and Raritan Bay (Figure 2.1). The horizontal resolution varies spatially and ranges from 150 to 1000 m, resulting in 134 by 73 grid points in the cross- and along- harbor direction. The model water depth ranges from 3 m in the shallow shoals to 25 m in the navigation channel near The Narrows (Figure 2.2). The Hudson River north of Spuyten Duyvil has been bent to take into account the river effect and to save on computational cost. For this simulation effort the nested fine grid in NYOFS is not included for the tracer concentration modeling.

In order to fully utilize information from NOS's Physical Oceanographic Real Time System (PORTS) as lateral boundary conditions, the NYOFS model grid open ocean boundary has been set at Kings Point, NY, and Sandy Hook, NJ.

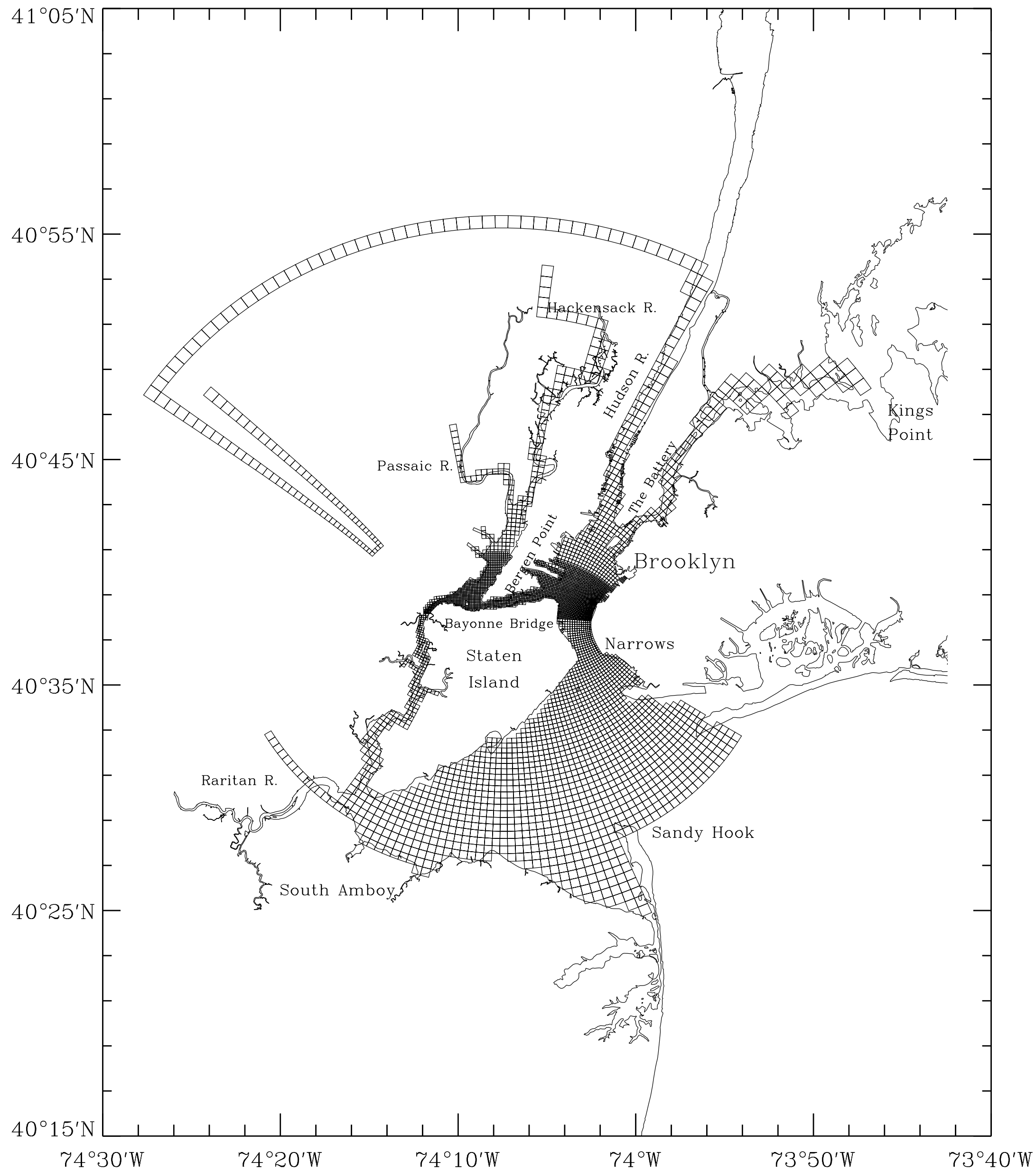


Figure 2.1. New York/New Jersey Harbor model grid showing locations of water level gages and current meter.

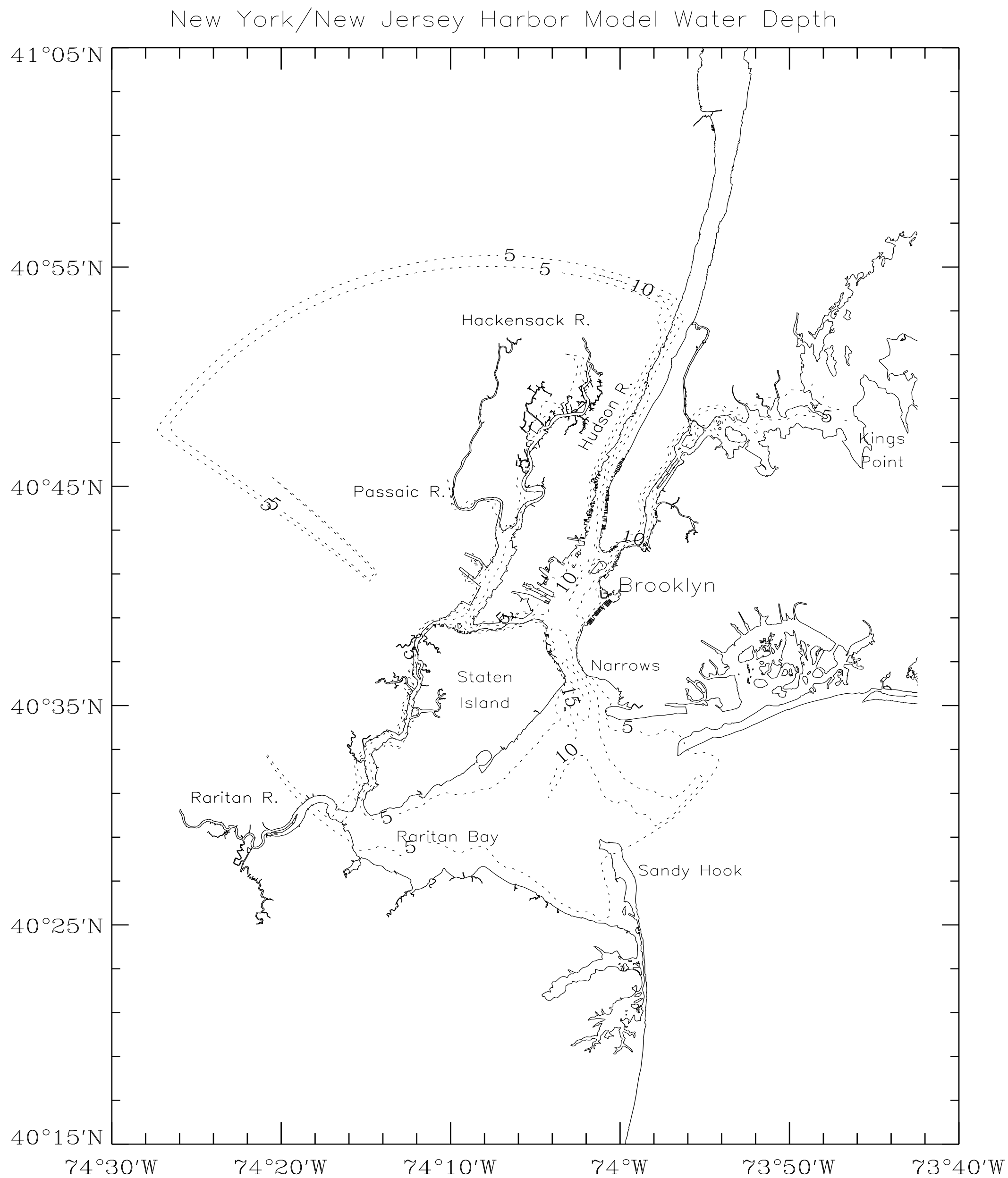


Figure 2.2. New York/New Jersey Harbor model bathymetry, contours in meter.

3. TRACER CONCENTRATION MODELING

3.1. July 2002 Newark Bay Field Experiment and Simulation

The first SF_6 field experiment was conducted from July 14 to July 25, 2002. Approximately 2.4 mol of SF_6 (in which approximately 0.9 mol was dissolved in the water and the rest immediately escaped from the water column into the air) was injected into Newark Bay, NJ (Figure 3.1). After the injection, the SF_6 tracer was then surveyed over 11 consecutive days using a high resolution measurement system (Ho et al., 2002, Caplow et al., 2003). The system includes a pump submerged at a depth of 1.2 m, a flow-through membrane contractor to extract gases from the water and a gas chromatograph equipped with an electron capture detector. A continuous measurement interval of 2 minutes was achieved. Figure 3.2 shows a typical survey boat track covering the Newark Bay, Arthur Kill, and Kill van Kull. Data were complied and processed for comparison with model results.

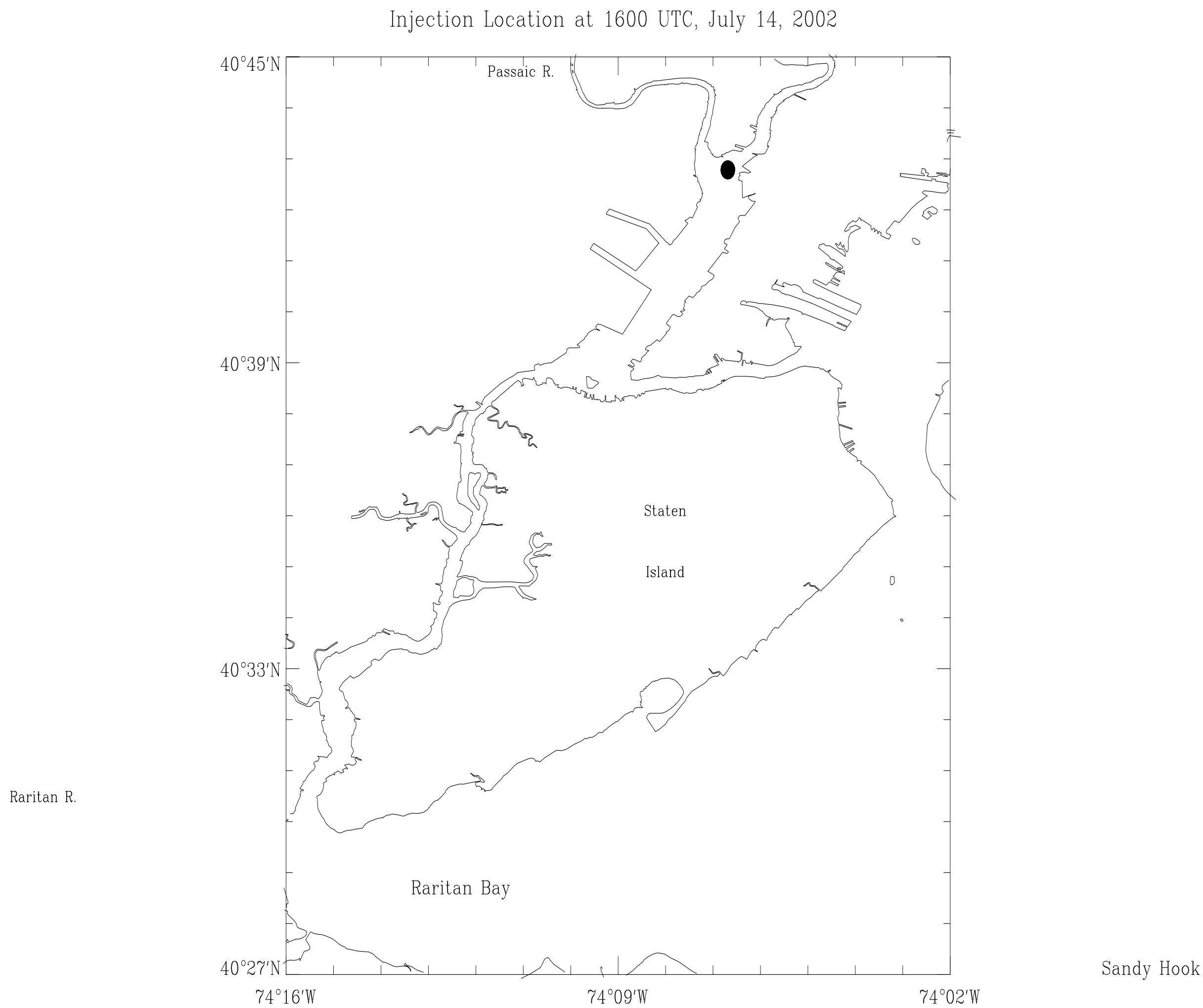


Figure 3.1. Injection location for July 14, 2002 field experiment**.**

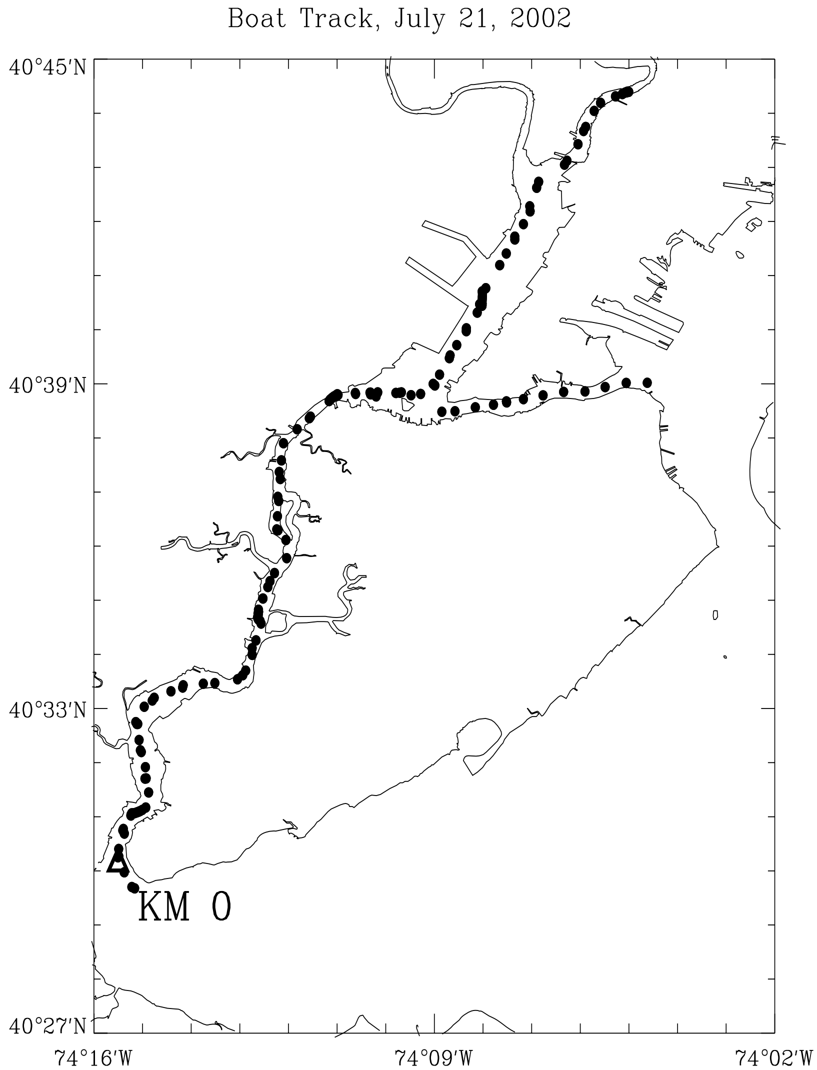


Figure 3.2. A typical boat track for July, 2002 SF_6 field experiment covering Newark Bay, Arthur Kill , and Kill van Kull. Dots indicate the tracer measurement location.

3.1.1. Simulation Set-Up

Observed river discharge in Passaic River was about 4 m^3s^{-1} during the field experiment period, which is much lower than the long-term average (Figure 3.3), except on July 20. The observed river discharges in Passaic River and long term average flows for Raritan, Hackensack, and Hudson rivers are used as river inflows to the model. Water level observations at Sandy Hook, NJ and Kings Pt, NY (Figure 3.4) from NOS water level gages are collected for open ocean boundary conditions at grid cells cross the harbor entrance (Sandy Hook, NJ) and the East River (Kings Point, NY). Detail open boundary condition specifications can be found in Wei and Chen (2001, 2002). The insignificant non-tidal components represent typical low river flow and summer winds during the experiment period.

The model was set up to simulate the SF_6 tracer concentration and to study the dispersion characteristics in the Newark Bay and inland waterways of the New York/New Jersey estuary. The model simulated the water levels, currents, and SF_6 concentration from July 12 to July 25, 2002. The model was spun-up from the rest at 1600 UTC, July 12, two days before the tracer injection at 1600 UTC, July 14. This two-day model spun-up allows the model reaches a quasi-steady state before the tracer injection. Simulated and observed water levels at the Bayonne Bridge and The Battery, shown in Figure 3.3, indicate that the model is accurately reproducing the water elevations at model interior locations. Figure 3.4 shows the simulated and observed current velocity in principle direction at Bergen Point at about 3 m (model layer 2) and 9 m (model layer 5) below the surface. Due to the insufficient model grid resolution, the model underestimates the maximum flood current velocity at a strong horizontal current shear location. However, the simulated current phase agrees with the data.

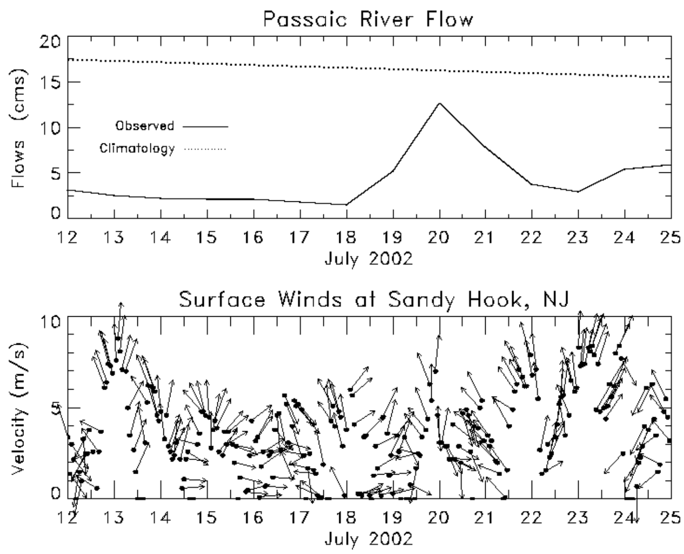


Figure 3.3. Observed and climatological freshwater input from Passaic River, NJ (upper) and surface wind at Sandy Hook, NJ (bottom) for July 2002 model simulation boundary forcing.

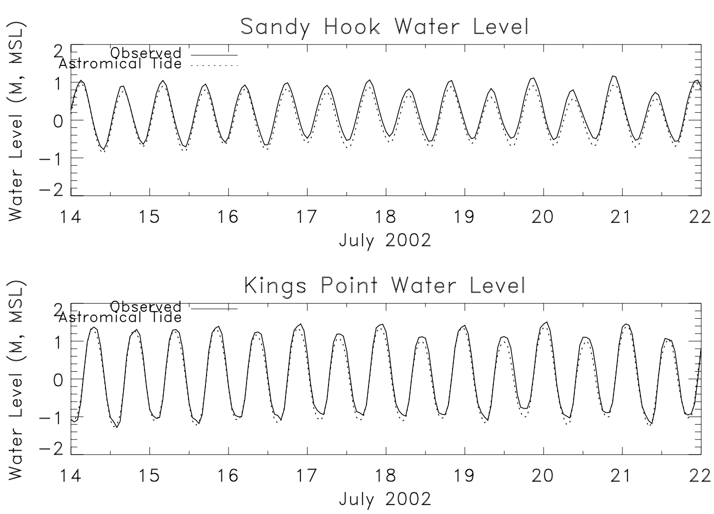


Figure 3.4. Observed water levels and astronomical tides at Sandy Hook, NJ and Kings Point, NY during July, 2002 Sf_6 field experiment.

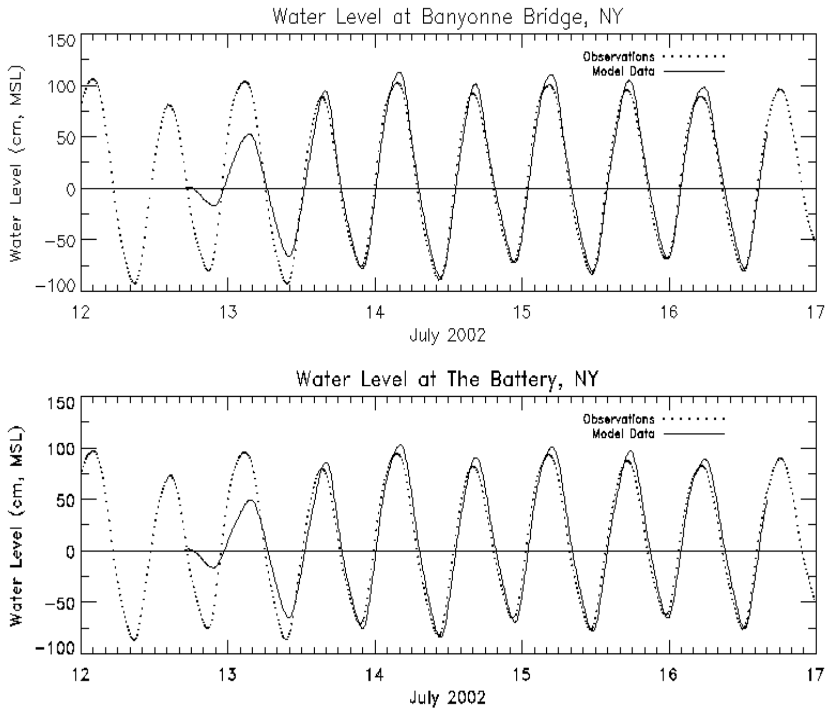


Figure 3.5. Model simulated water levels and observations at Bayonne Bridge, NY and The Battery, NY showing the model is capable of reproducing the water levels within the mod grid.

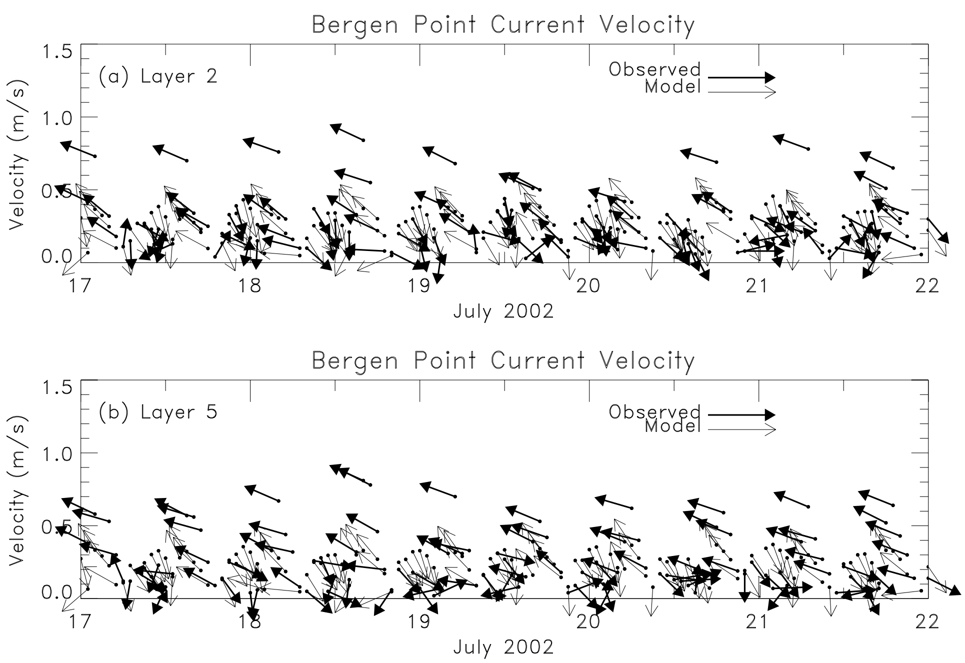


Figure 3.6. Hourly model simulated current velocity (light line and open arrow head) and observations (heavy line and solid arrow head) at Bergen Point, Newark Bay at (a) Layer 2, about 3 m below the surface; and (b) Layer 5, about 9 m below the surface.

3.1.2. Daily Averaged Concentration

Figure 3.7 to 3.9 shows the observed tracer concentration and simulated daily averaged surface SF_6 concentration contours for July 15, 19, and 23, 2002. The concentration contour plots not only show the tracer distribution and gradient over the area but also reveal the tracer advancement. In general, the model simulated tracer concentration distribution is in good agreement with the observations. The simulated tracer leading location along Arthur Kill lags behind the observations, probably because of a slower simulated current velocity. One day after the injection, July 15, the survey reveals the tracer moving from the Kill van Kull to the Upper Bay. However, the model simulated tracer has extended through The Narrows to Raritan Bay, an area not covered by the survey. The tracer was carried by the tidal currents north of the injection location in the Passaic and Hackensack rivers. Transport into and through the Arthur Kill was much slower. In Newark Bay, maximum concentration was reduced from approximately 8000 fmol l^{-1} to about 2000 fmol l^{-1} in two days. This behavior can also be seen from the tracer mass inventory plot (Figure 3.10) which shows an exponential decay of approximate total mass over inland waterways including the Newark Bay, Kill van Kull, and the Arthur Kill. The model simulated tracer exits the inland waterways slower than the observed tracer mass.

Since the observed concentration contours shown in Figures 10 are obtained by averaging data measured from two boat track surveys through the inland waterways, there exists concentration contour errors because of the averaging process and because of the area not covered by the survey boat tracks. The observed total mass calculation was performed on the average over a "box" ranging from 100 m to 400 m and based on a presumed vertical distribution derived from limited vertical observations. The simulated total tracer mass is computed from the averaged tracer concentrations in each of the 3-dimensional model grids within the inland waterways at 15 minute interval. Therefore, it is not surprising that the model simulated total mass is greater than the measurements.

3.1.3. Longitudinal Concentration Profile

Simulated SF_6 concentrations in the longitudinal direction along the survey boat track were compared with the survey data. Figures 3.11 and 3.12 show the boat tracks along the channel from Newark Bay to Arthur Kill and simulated longitudinal SF_6 concentration compared with data for Days 1, 2, 5, and 7. Distance km 0 is defined at the junction of Arthur Kill and Raritan Bay. Overall, the simulated tracer advanced slower than the data. The tracer gradients, however, match with the data.

3.1.4. Residence Time

The residence time for SF_6 in the inland waterways is defined as the time required for the total tracer mass to be reduced to 1/e of the original injection concentration. Therefore, the mean residence time is estimated as 3.4 days for the observed data and 4.7 days for the simulation model results. The residence time at each model grid cell in the inland waterways is assumed to be the time between when a grid cell is first exposed to the tracer and when the tracer concentration is reduced to 1/e of the peak concentration. The residence time in this definition refers to the relative time of tracer exposure, as an indication of flushing rate in a specific area, and not as a measure of the concentration history. A model-derived residence time contour plot is shown in Figure 3.13. The figure shows that the residence time in Newark Bay and the Kill van Kull is on the order of one day, indicating a greater tidal current flushing rate there than in the Arthur Kill, where the residence time is in the order of 3 to 5 days in the lower kill. Low flushing rates are found upstream in the Passaic River and in channels near the marine terminals.

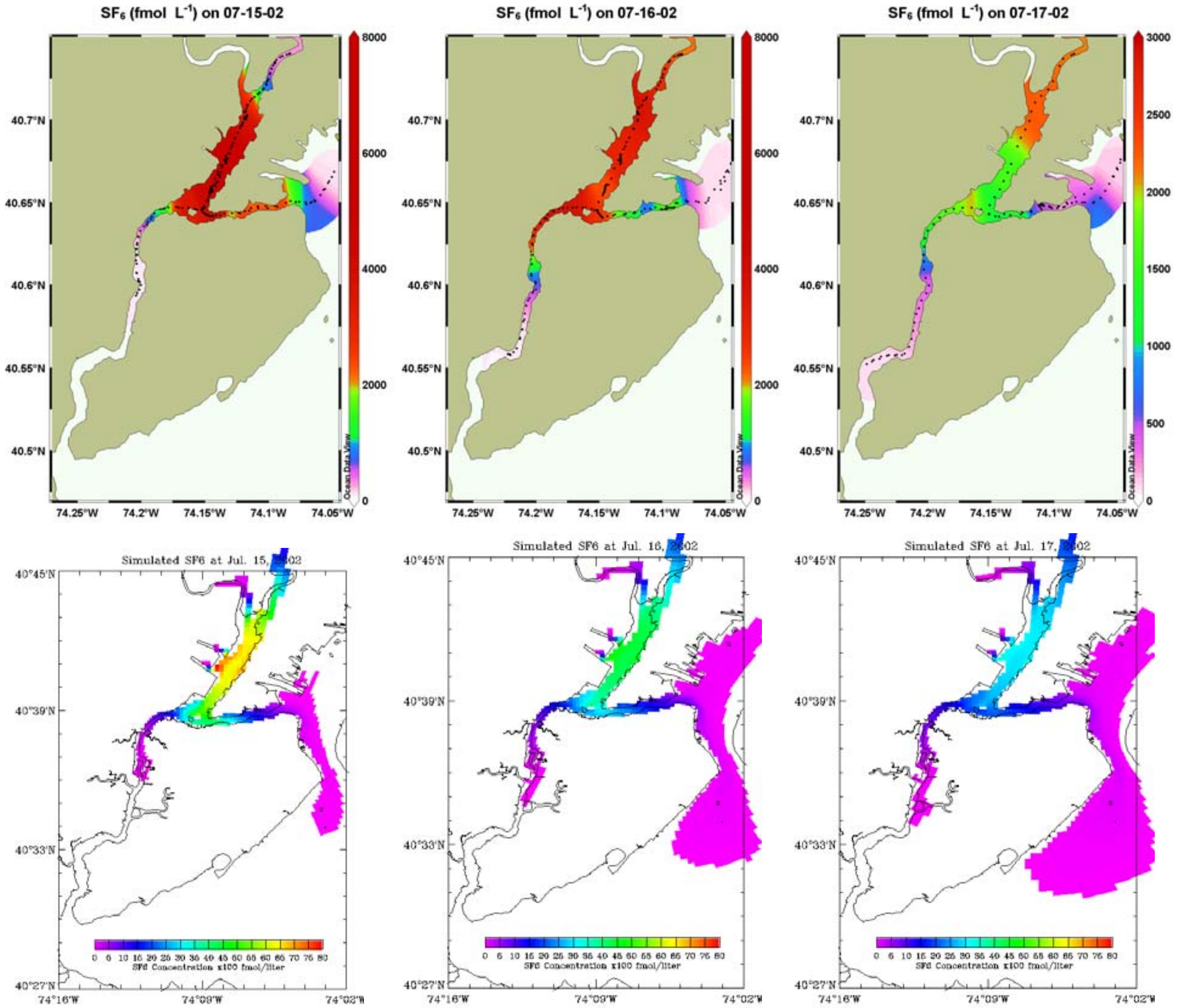


Figure 3.7. Observed (top, Caplow, et. al., 2003) and model simulated (bottom) daily averaged surface SF_6 concentration contour plots for July 15, 16, and 17, 2002. Dotted lines indicate the survey tracks.

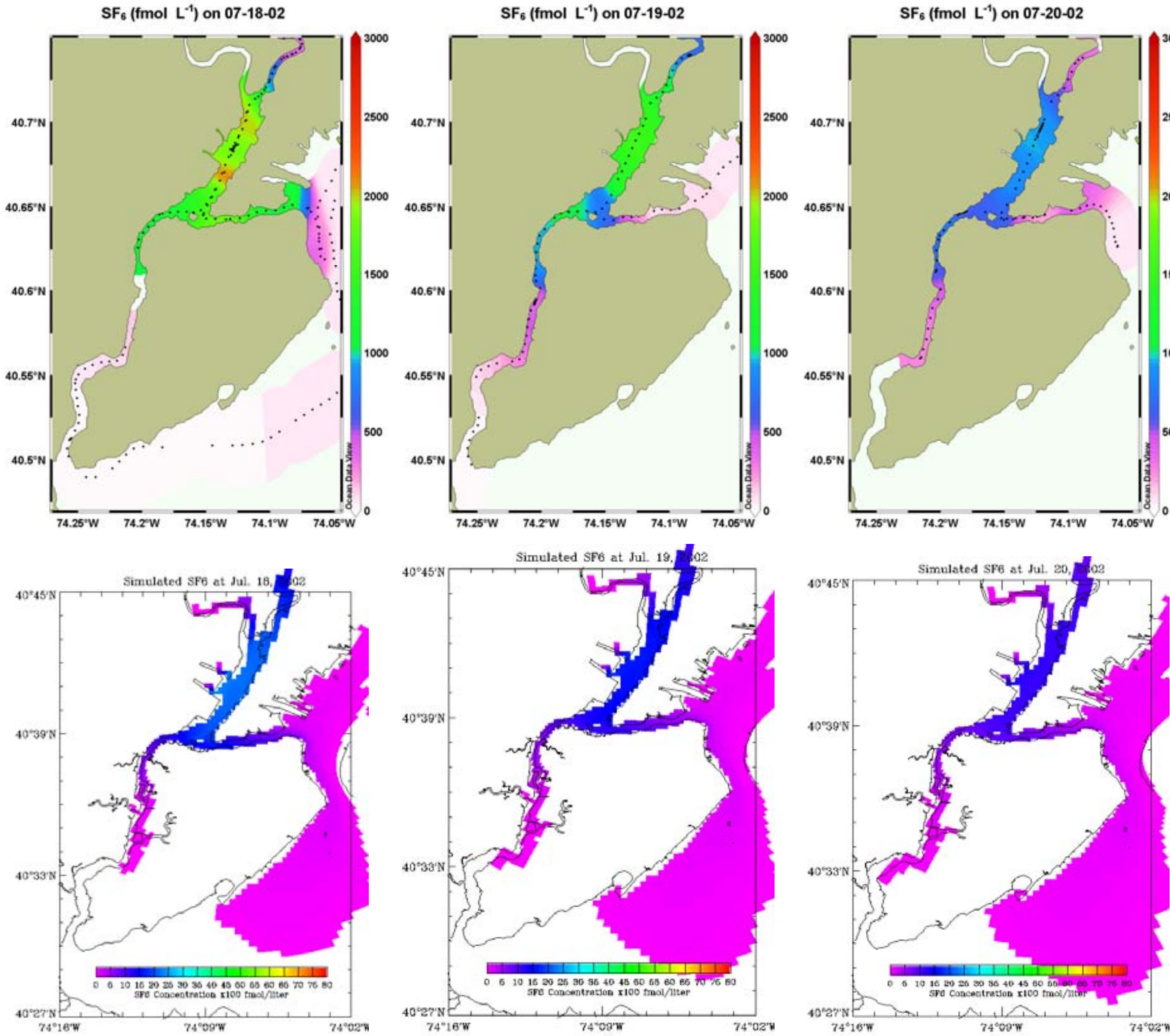


Figure 3.8. Observed (top, Caplow, et. al., 2003) and model simulated (bottom) daily averaged surface SF_6 concentration contour plots for July 18, 19, and 20, 2003. Dotted lines indicate survey tracks.

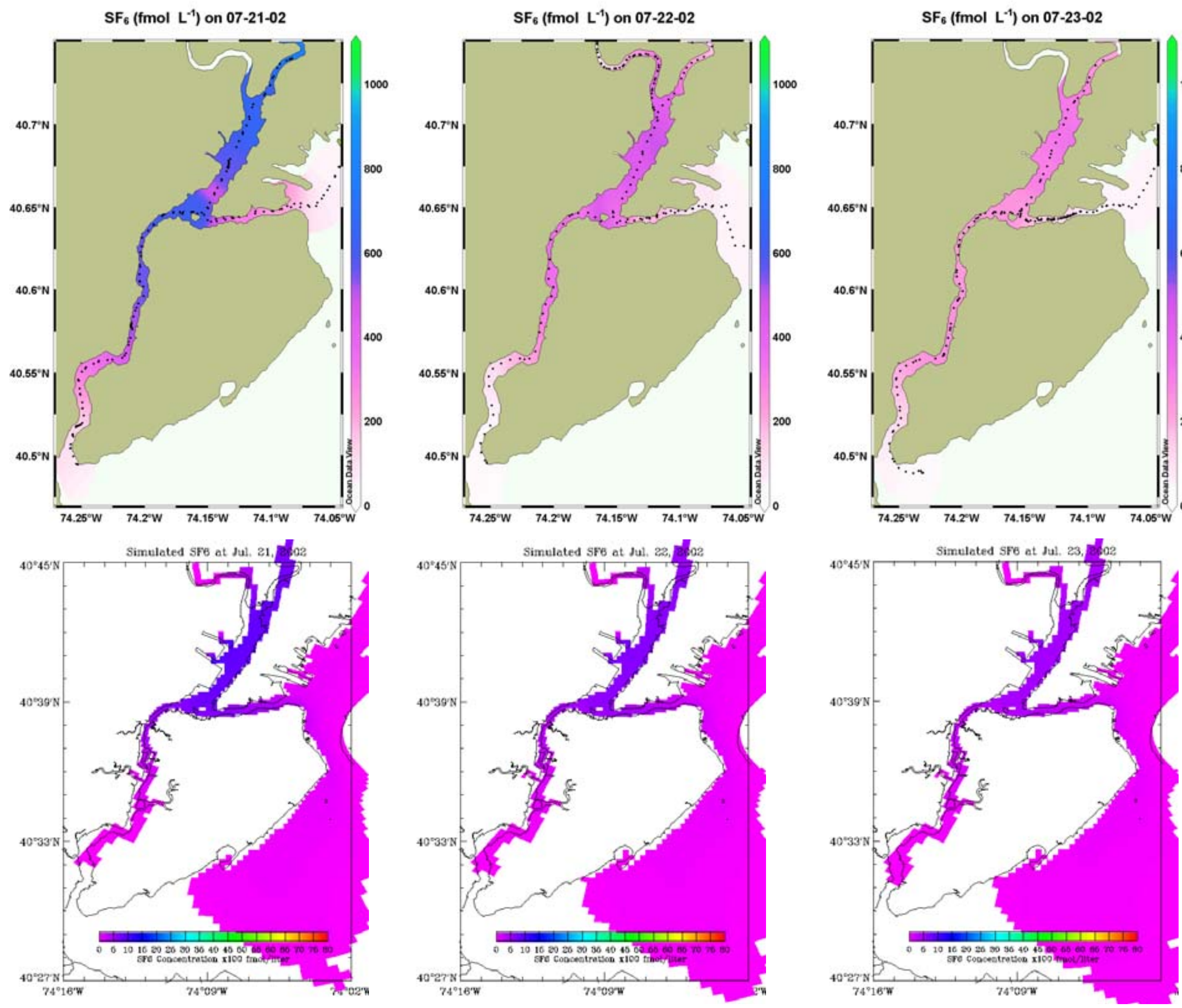


Figure 3.9. Observed (top, Caplow, et. al., 2003) and model simulated (bottom) daily averaged surface SF_6 concentration contour plots for July 21, 22, and 23, 2002. Dotted lines indicate survey tracks.

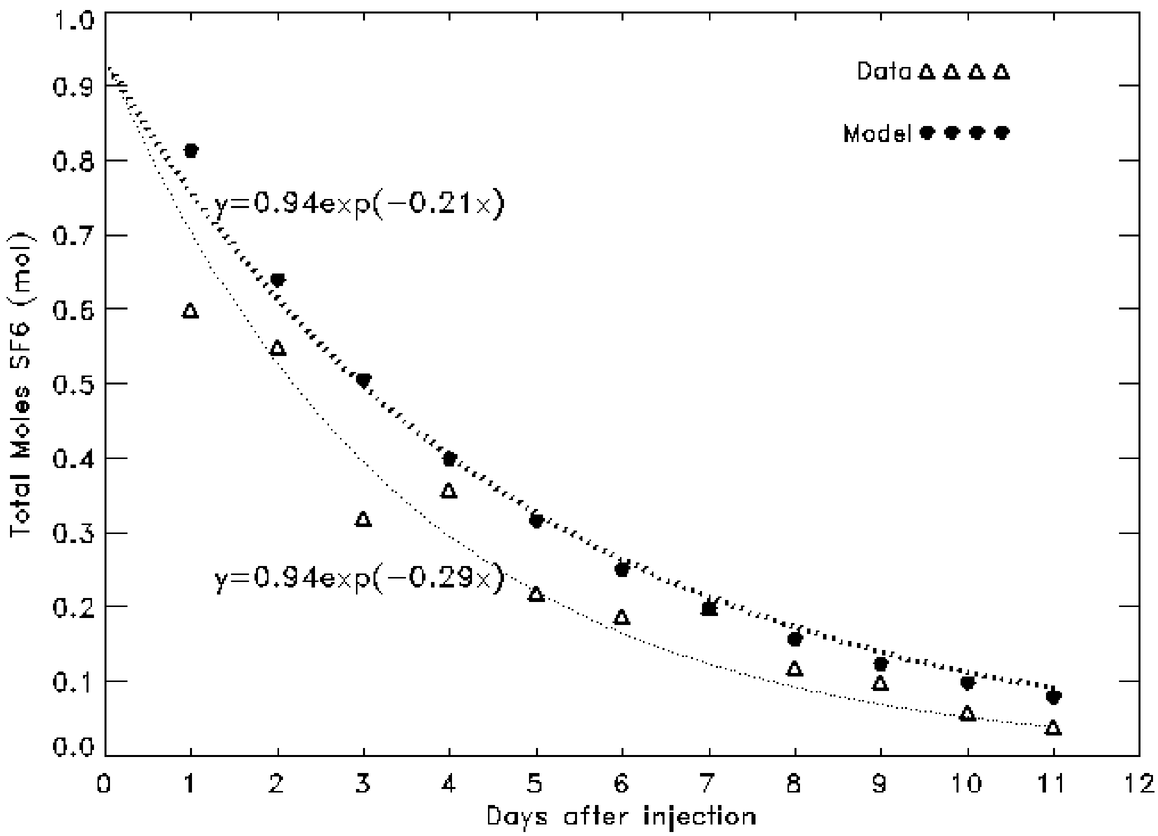


Figure 3.10. Total measured and model simulated SF_6 inventory in the inner waterways (Newark Bay, Arthur Kill, and Kill van Kull) over 11 days, with fitted exponential decay curves, indicating a decay constant of 0.29 day^{-1} and 0.21 day^{-1} for observed and simulated tracer dispersion.

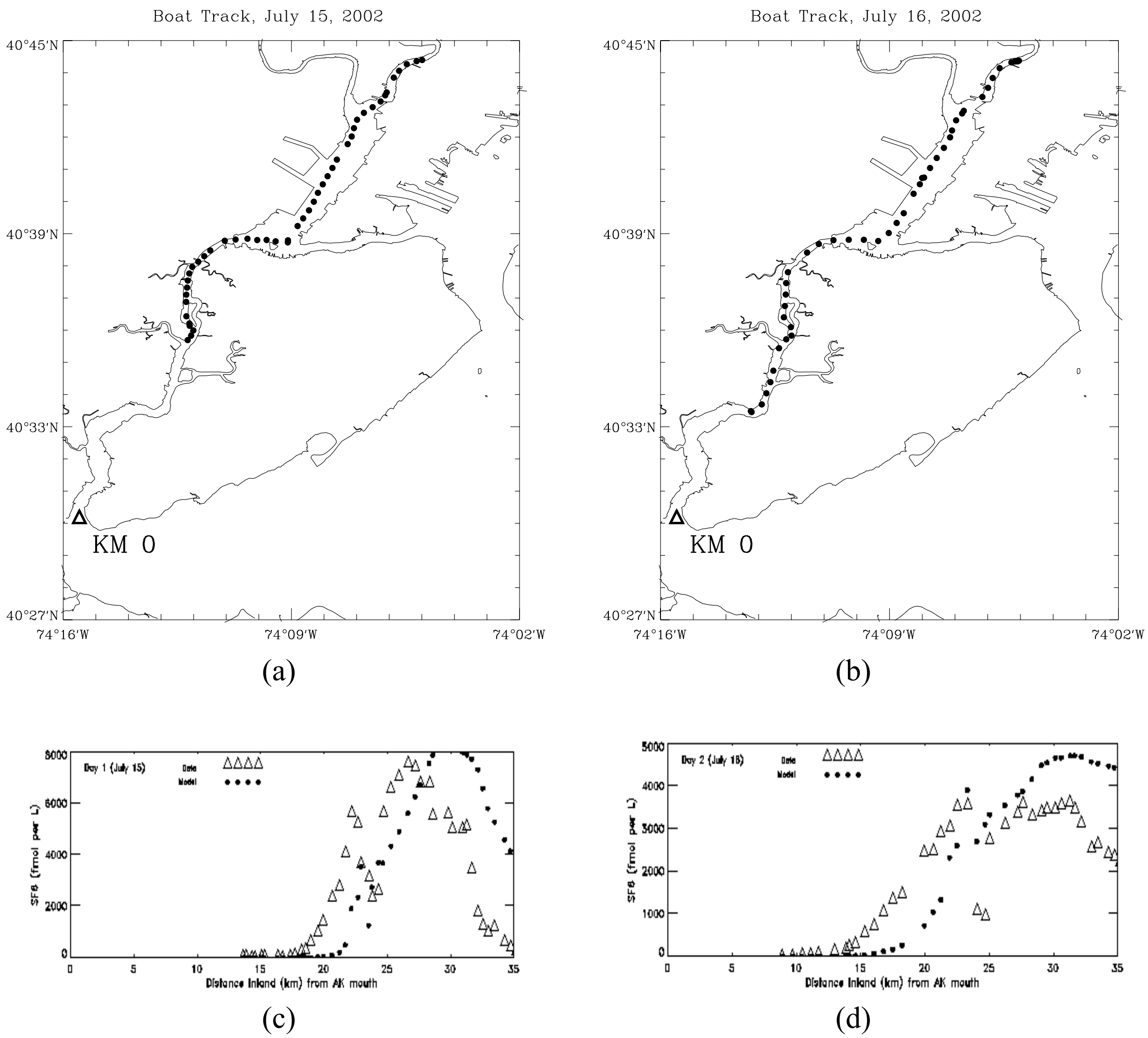


Figure 3.11. Boat tracks from Newark Bay to Arthur Kill and simulated longitudinal SF_6 concentration (solid circle) compared with observations (open triangle) for Day 1 ((a) and (c), July 15, 2002) and Day 2 ((b) and (d), July 16, 2002).

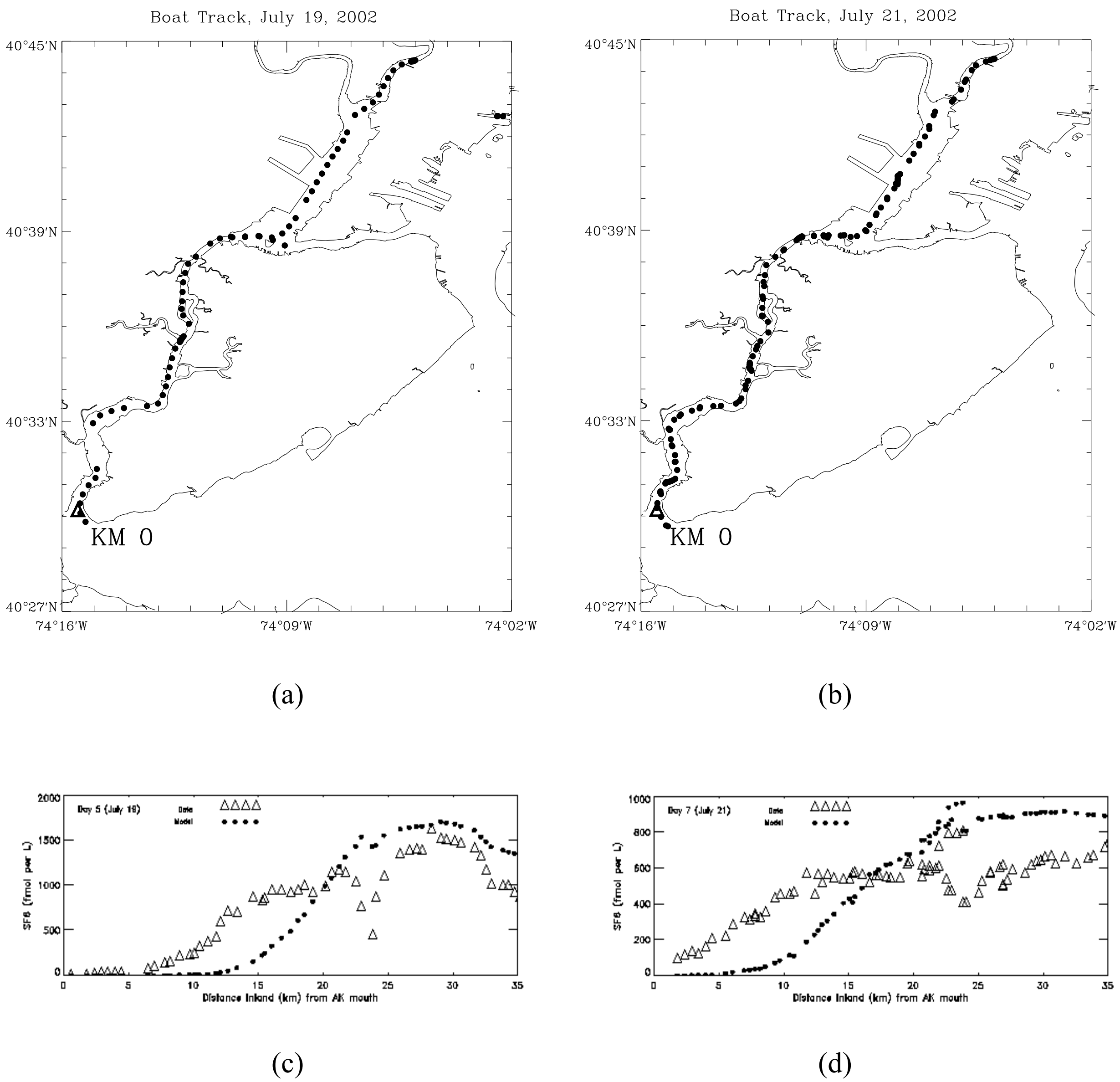


Figure 3.12. Boat tracks from Newark Bay to Arthur Kill and simulated longitudinal SF_6 concentration (solid circle) compared with observations (open triangle) for Day 5 ((a) and (c), July 19, 2002) and Day 7 ((b) and (d), July 21, 2002).

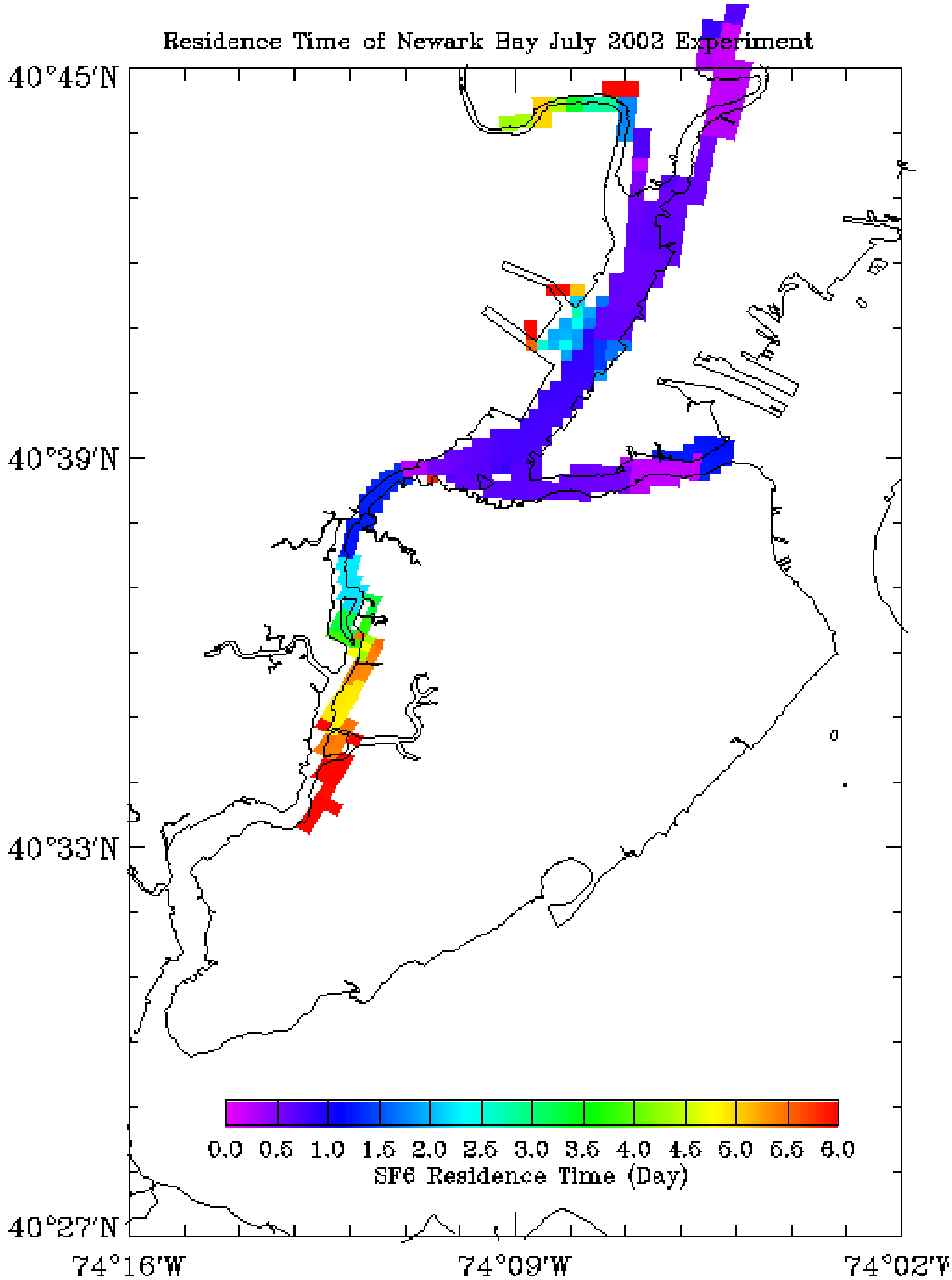


Figure 3.13. Contour plot of residence time for the inland waterways including Newark Bay, Kill van Kull, and Arthur Kill.

3.2. June 2003 East River Field Experiment and Simulation

The other SF_6 field experiment was carried out from June 18 to June 30, 2003 in the East River, a tidal channel connecting Long Island Sound and New York Harbor. This field experiment was designed to study the dispersion and flushing characteristics of the river between The Battery and Throgs Neck (near Kings Point, Figure 1.1). Two initial injections were made 8 days apart in the East River (Figure 3.14), the first at 1230 UTC, June 17, 2003 about one hour after slack-before-flood (flood injection) and the second at 1300 UTC, June 25, 2003, about one hour before slack-before-ebb (ebb injection, Figure 3.15). In each injection, there was about 3.9 mol of SF_6 dissolved into the water column. In addition to the determination of the dissolved material dispersion and flushing rate of the East River, this experiment paid particular attention to the effects of the tidal phase on the flushing rate. Starting on June 18, tidal synchronized boat surveys were conducted each day for a tidal cycle in order to measure the near surface (1.2 m below the water surface) SF_6 concentration at 2 minute intervals. The boat track usually started from the City Island marina, traveled north toward Long Island Sound then turned south through the East River to the Upper Bay (Figure 3.16). Thus, each survey covered the entire East River, and often went beyond the river limits. On June 21 and 29, the survey was extended to cover the Hudson River from the conjunction with the Harlem River to The Battery. On June 21, 24, 25, and 29, SF_6 concentration in the Harlem River was also measured. Concentration and salinity vertical profiles were also taken at several key locations in the East and Hudson Rivers in order to study the vertical structure (Caplow et al., 2004).

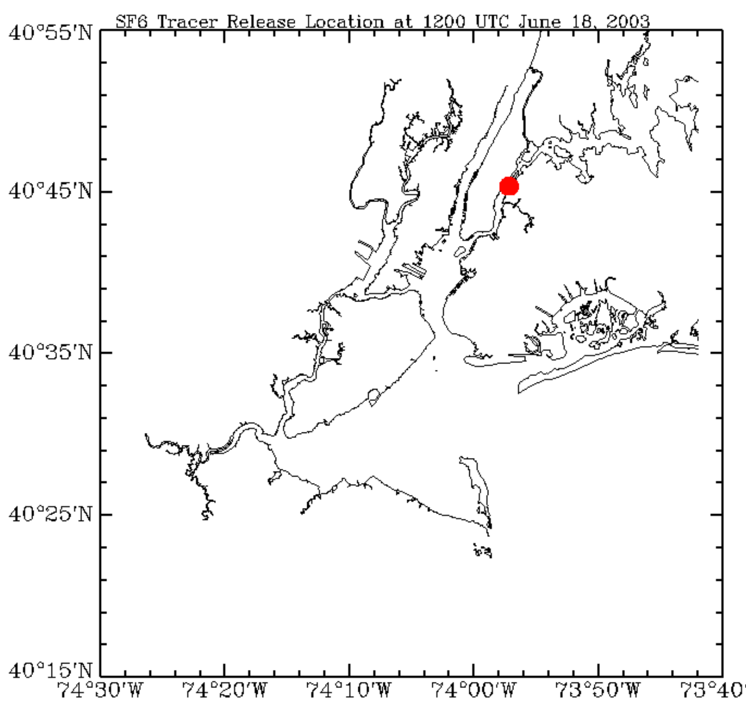


Figure 3.14. Injection location at East River for June 2003 SF_6 field experiment.

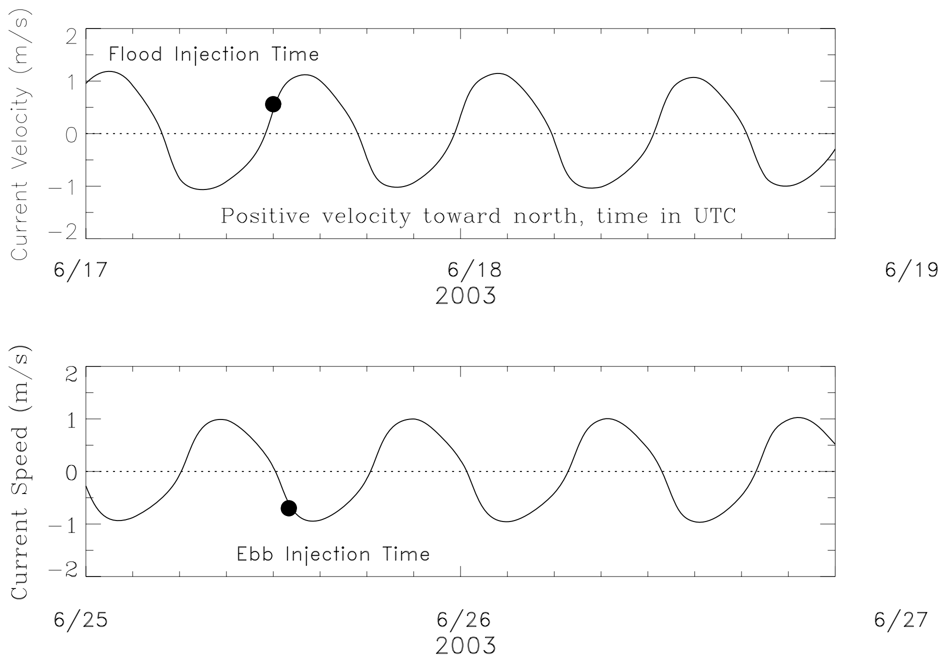


Figure 3.15. Time for flood and ebb injections relative to model tidal current at injection location near Hell Gate a NOS tidal current reference station.

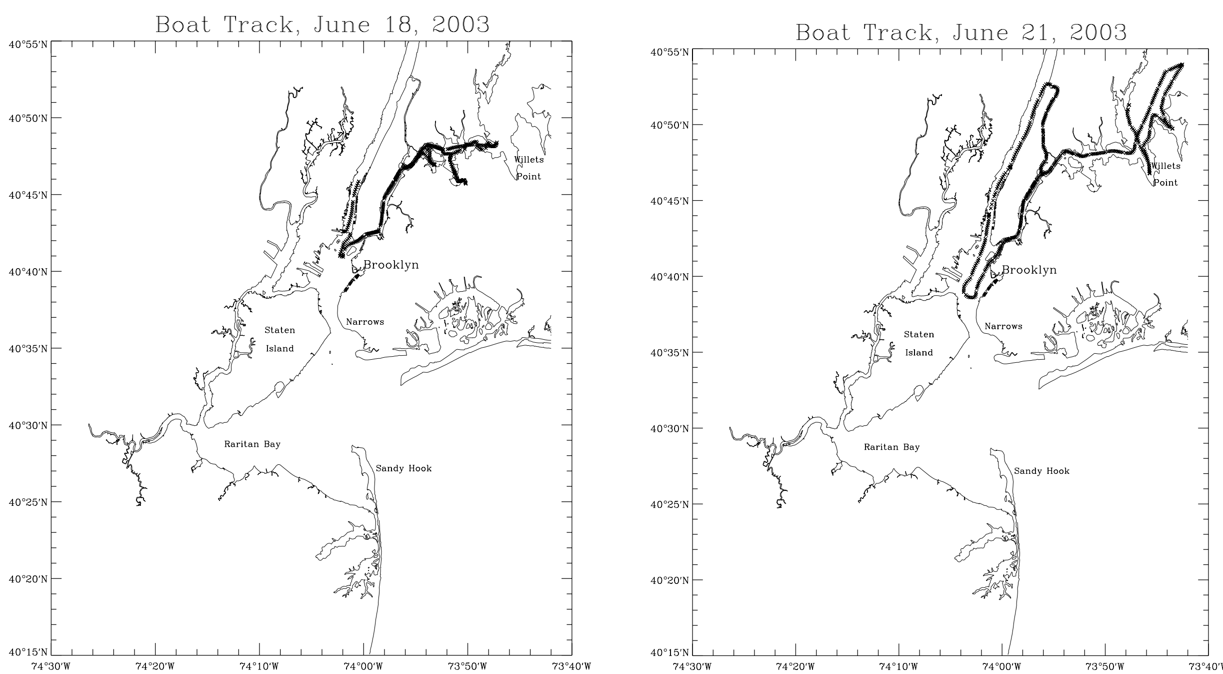


Figure 3.16. Typical survey boat tracks of June 2003 SF_6 field experiment, June 18 and 21. The survey boat covers entire East River each Day. Surveys also cover lower Hudson River conducted on June 21 and 29 and Harlem River on June 21, 24, 25, and 29.

3.2.1. SF6 Concentration Measurement

Tidally synchronized longitudinal surveys of concentration were carried out in the East River extended into Western Long Island Sound to the north and the Upper Bay and Raritan Bay through The Narrows in the south. Measurements from a portion of the survey are plotted as Figure 3.17 (Caplow, et. al., 2004). Daily survey concentration plots show the dispersion and decay of the tracer. Note the tracer spreading difference at the Upper Bay and The Narrows one day after the flood (Day 1F) and ebb (Day 1E) injections. Not shown in the plots is that just one tidal cycle after the tracer injection the tracer was carried to the lower Hudson River from the Upper Bay by the flooding tidal current.

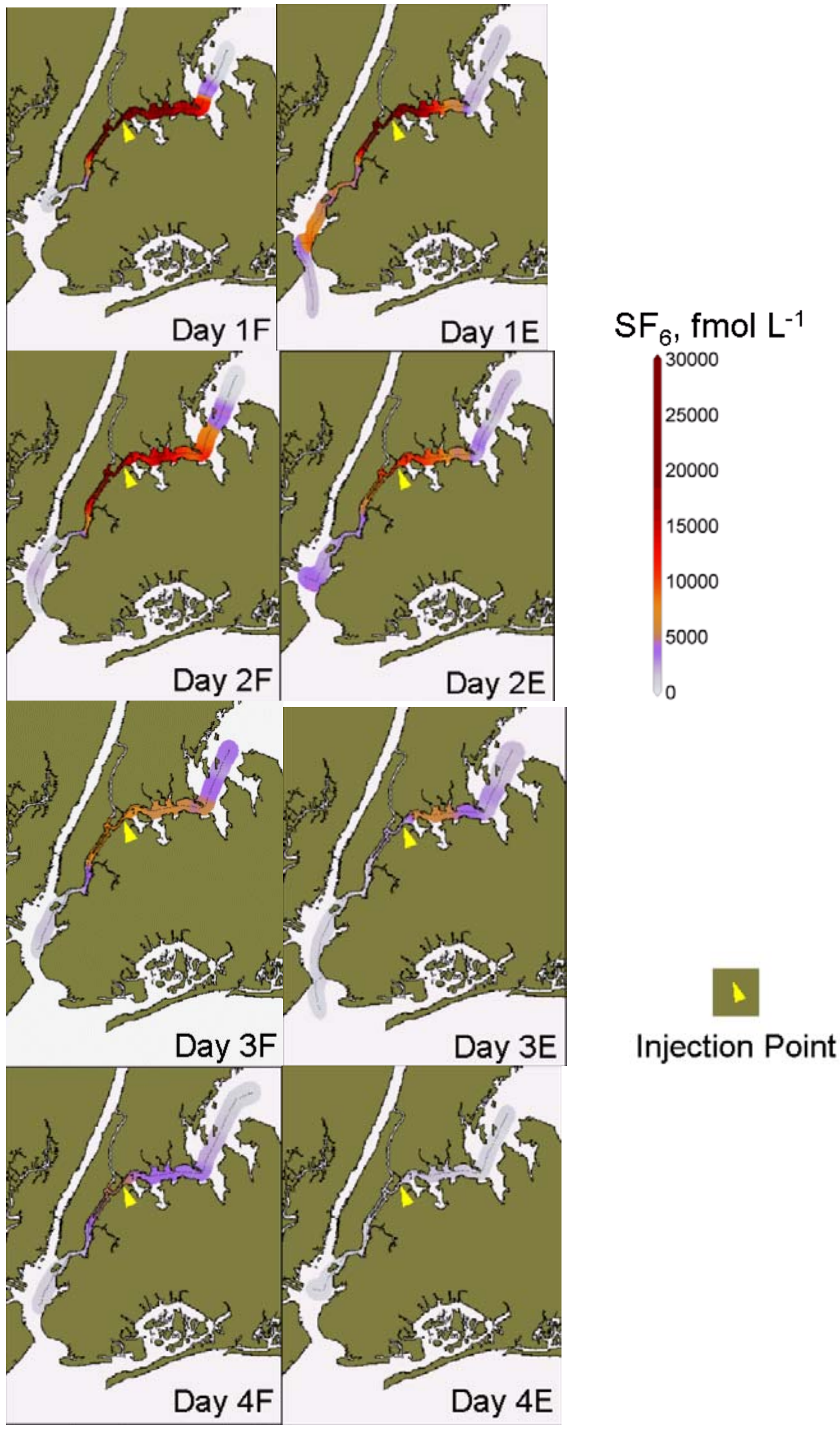


Figure 3.17. Tidally synchronized longitudinal tracer concentration contour plots, in the East River and in the Upper Bay and The Narrows, after the flood (left) and ebb (right) injections (from Caplow et al., 2004).

3.2.2. Model Simulation Set-Up

The model was set up to simulate the SF_6 tracer concentration movement in the East River and the New York/New Jersey estuary from June 15 to June 30, 2003 to study the tracer transport and dispersion characteristics. The observed Hudson River discharge, which is dynamically close to the East River (climatology for other rivers), and surface winds at Sandy Hook, NJ are used for model river inflow and surface boundary conditions. Figure 3.18 shows the Hudson River flow observations along with climatology. High flows occurred on June 22 and 23 due to rainfall in the upper Hudson River watershed. Open ocean boundary conditions are specified with observed water levels at Sandy Hook and Kings Point (Figure 3.19) comparable to the July 2002 model simulation.

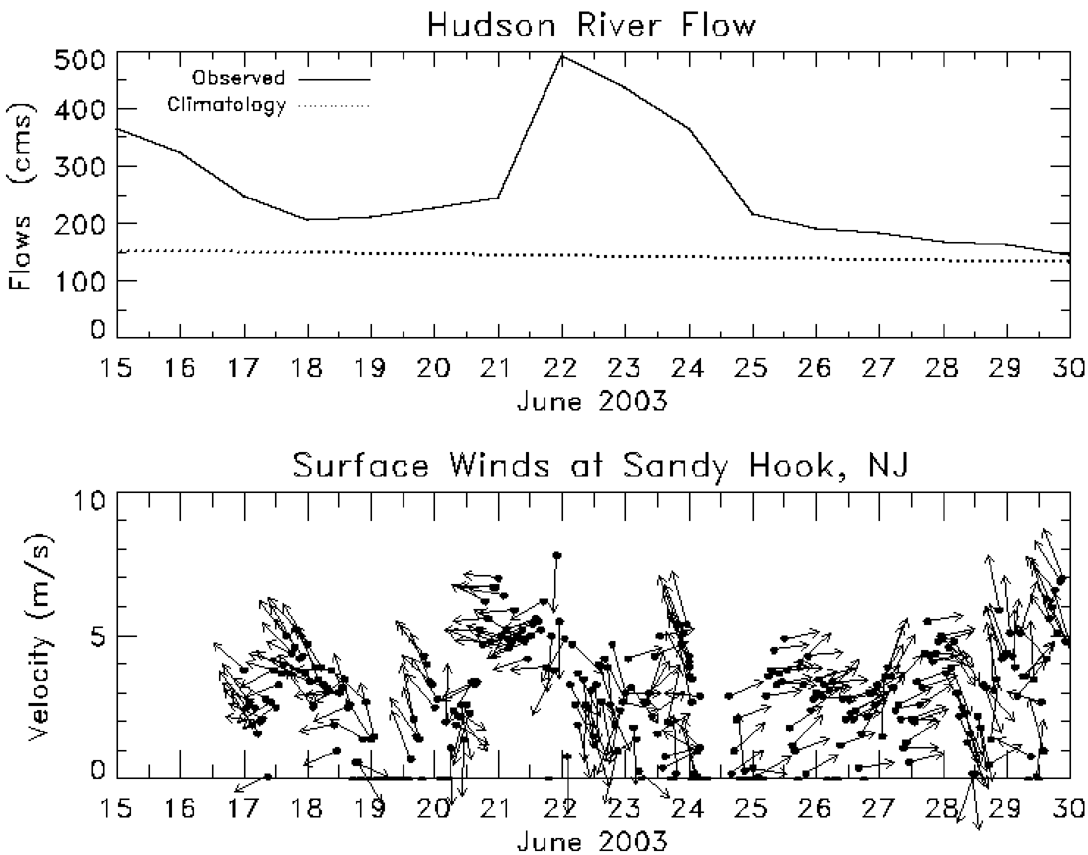


Figure 3.18. Observed and climatological freshwater input from Hudson River, NY (upper) and surface wind at Sandy Hook, NJ (bottom) used for June 2003 model simulation.

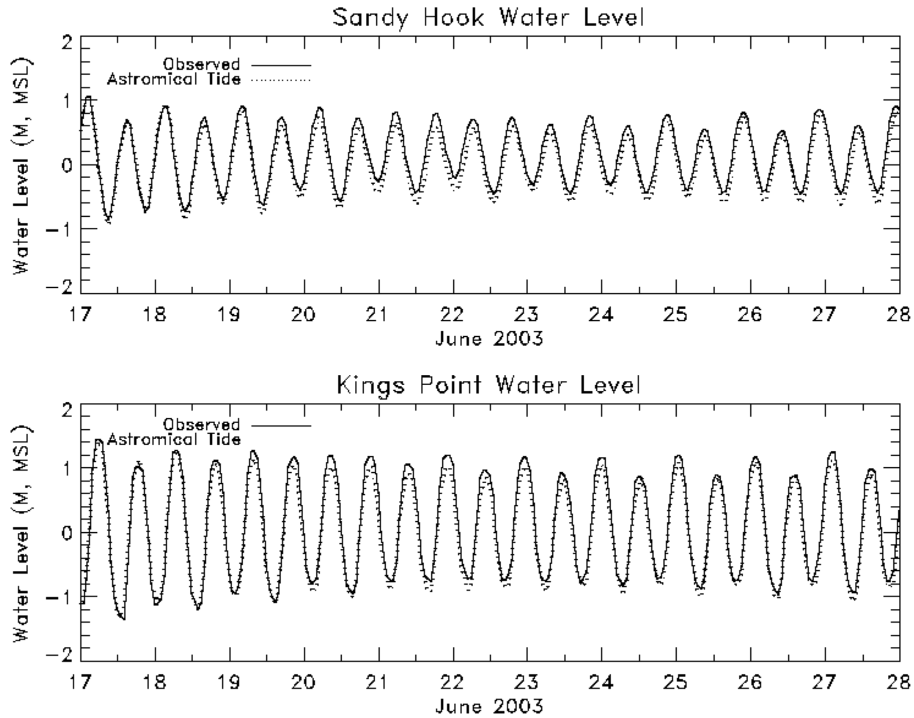


Figure 3.19. Observed water levels and astronomical tides at Sandy Hook, NJ and Kings Point, NY during June 2003 SF_6 field experiment.

The injection location (Figure 14) of this experiment allows the tracer to exit the model grid open boundary at Kings Point (Figure 2). Therefore, the boundary condition for concentration equation (Eq. 11) needs to be carefully specified. There is no time series measurements at the model open boundary. During the outflow (flood), the concentration at the boundary is specified with an one-dimensional advection scheme similar to the current velocity specified at the open ocean boundary. During the inflow, the concentration is specified based on the concentration spatial gradient at the previous time step. Besides the SF_6 tracer loss at the air-water interface, the tracer also exits from the model domain and there is a net loss of the tracer mass due to the way the boundary condition is treated. This loss will have to be accounted for in the total mass inventory calculation.

The model simulated water levels at The Battery and Bayonne Bridge are in good agreement with observations (Figure 18). There were no current velocity observations available within the East River during the experiment. However, the coarse model grid configuration (one model grid cell for most of the river width) for the East River indicates the model could significantly underestimate the maximum current velocity in this area. The simulated tracer concentration accuracy may be decreased due to the inaccurate model simulated current velocity field.

Simulated tracer concentration fields were analyzed and compared with the observed data by examining daily averaged concentration contours, longitudinal concentration profiles, mass inventory and residence time estimation, movement of the center of mass (COM), and concentration vertical profiles.

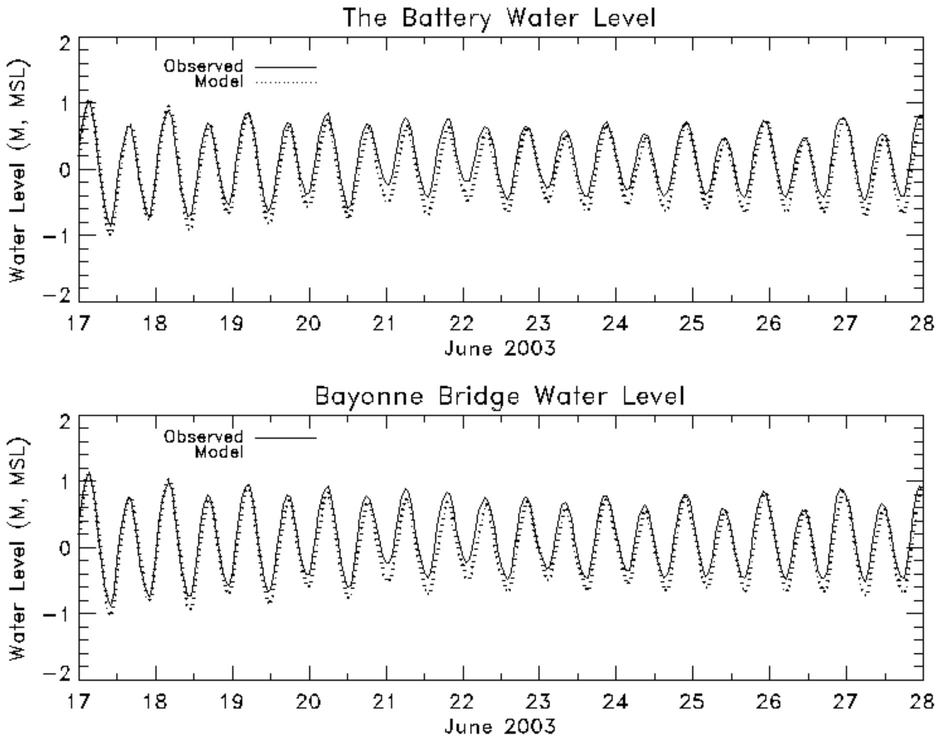


Figure 3.20. Model simulated water levels and observations at Bayonne Bridge and The Battery.

3.2.3. Longitudinal Concentration Distribution

After the tracer was injected into the water column before the flood tide, the tracer moved to the north with the tidal current into the Western Long Island Sound. Figure 3.21 shows the concentration distribution, after flood injection, in the longitudinal direction for the East River, from the intersection of the East River and the Upper Bay to The Battery in the south and to the Throgs Neck (also the model grid boundary) in the north. The concentration for days 1F, 3F, and 5F after the flood injection are plotted as heavy lines, while lighter lines represent concentrations for days 2F, 4F, and 6F. The narrow width and the strong current velocities associated with the East River ensure a good mixing of tracer concentration in the transverse direction. The tracer remained maximum at Hell Gate, the injection location, and dropped sharply near The Battery, indicating the high dispersive characteristics where the narrow East River flows into the wider Upper Bay. Tracer concentrations in the river decreased daily due to flushing of the East River into the Upper Bay at The Battery and into the Long Island Sound at Throgs Neck, as well as exiting through air-sea interaction. Note the observed concentration plateau in Flushing Bay, a semi-enclosed bay (Figure 2.1) which serves as a solute storage area. The simulated tracer concentrations for the longitudinal profiles and the observations are similar. But there are distinct differences. The tracer loss from the model northern boundary following the flood injection on Days 1F and 2F results in lower concentrations than the measurements. After Day 3F, the simulated concentration agrees with the observations between The Battery and the Throgs Neck.

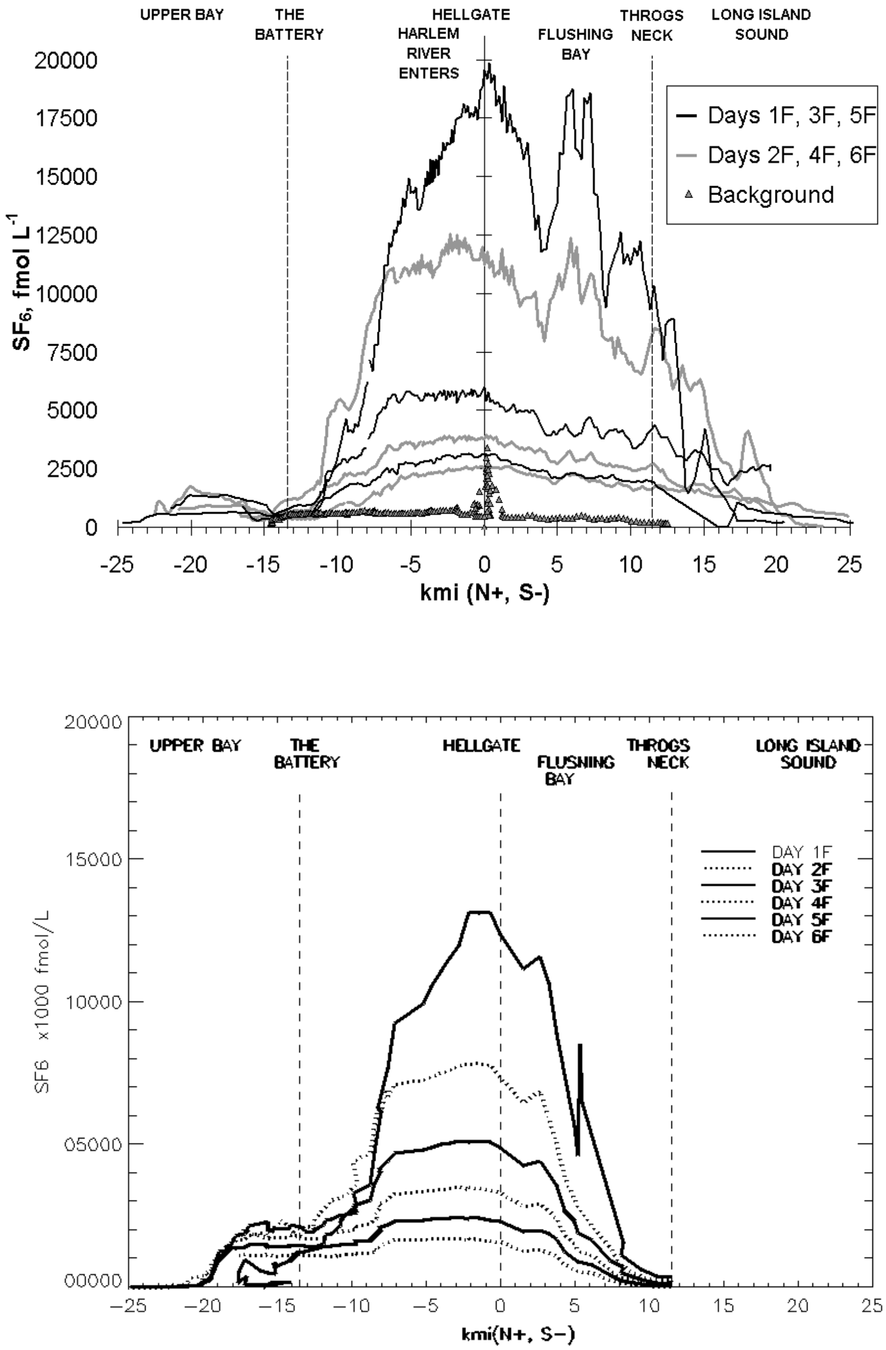


Figure 3.21. Observed (top) and simulated (bottom) longitudinal SF6 concentration distribution after the flood injection from The Battery to the Throgs Neck, heavy lines for Days 1F, 3F, and 5F and light lines for Days 2E, 4E, and 6E. Note the model grid boundary location at Throgs Neck.

On July 25, 2003 the tracer was injected into the water column the same location at the time before the ebb tide (ebb injection, Figure 3.15). Thus, simulated daily tracer longitudinal distributions following the ebb injection are compared with the flood injection and with observations shown in Figures 3.22 and 3.23. The flood injection simulated concentrations in the river are lower than the observations; however, the ebb injection simulated concentrations compare well with observations. During the ebb injection, the simulated tracer dissipates much slower than the measurement from The Battery to the Upper Bay.

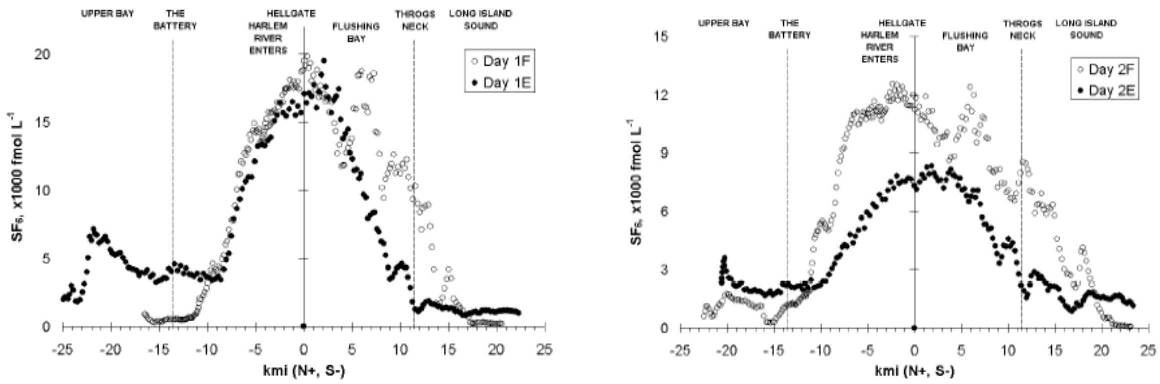
3.2.4. Simulated Daily Averaged Tracer Concentration Contours

The longitudinal tracer distribution following the flood and ebb injections reveals the tracer dispersion and decay in the East River. For the model simulation, the daily tracer concentration fields in 15 minutes interval are averaged to produce daily averaged concentration contour plots shown in Figures 3.24 and 3.25. Tracer exiting the model domain at northern boundary is apparent in the first 2 days. The tracer started to spread into the Upper Bay on June 18 (Day 1F) and then to the Hudson River by tidal excursion on June 19 (Day 2F). Instant hourly tracer contours (not shown here) indicate that the tracer movement is well synchronized wit the tidal currents. It is worth noting that a higher concentration tracer is observed in the Buttermilk Channel between Governors Island and Brooklyn, probably due to high current velocity.

3.2.5. Vertical Profiles

The SF_6 field survey focused on measuring longitudinal surface tracer distributions in the East River, the lower Hudson River, Upper Bay, The Narrows, and Western Long Island Sound. In addition, vertical concentration profiles at selected locations were also measured to better understand the tracer distribution in the vertical. Figure 3.26 shows the observed and simulated concentrations (normalized to the vertical average) at the injection point, and in the northern and southern East River (locations shown on the map). In the northern East River, the data shows a significant vertical gradient on Days 2F and 2E (2 days following the flood and ebb injections), while the model reveals a smaller vertical gradient than the observed data on Day 2E, and almost zero vertical gradient on Day 2F. Possible causes for these differences are the lack of density flow in the model, and the tidal current velocity phase discrepancy between the observations and model. At the injection point and in the southern East River, the tracer is well-mixed. The profile in the lower Hudson River, shown in Figure 27, reveals a high tracer concentration in the middle of the water column during the flood injection, suggesting that the tracer is trapped between the classic estuarine 2-layer top and bottom flows. The salinity at this depth, ranges from 16-22 ppt (Figure 27c) matching salinities in the East River (~20 ppt), suggesting that water from the East River is carried into the Hudson in the mid-depth layer.

Observations



Model

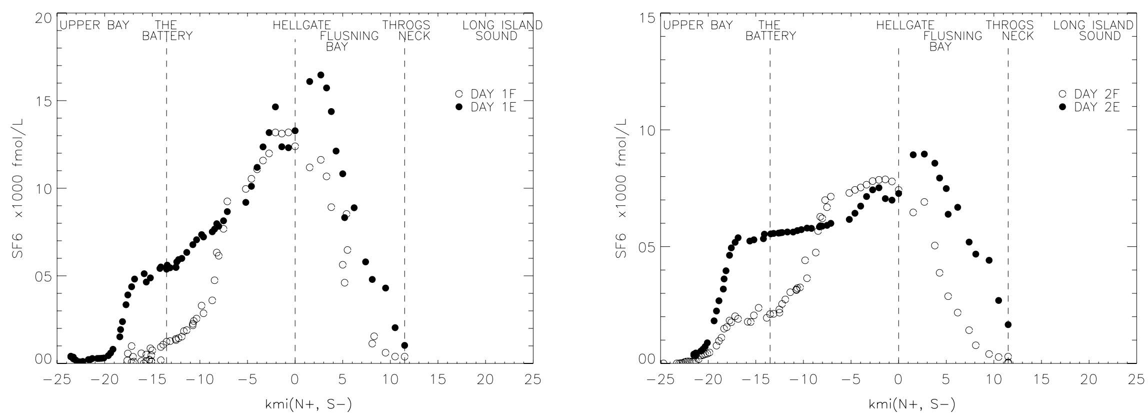
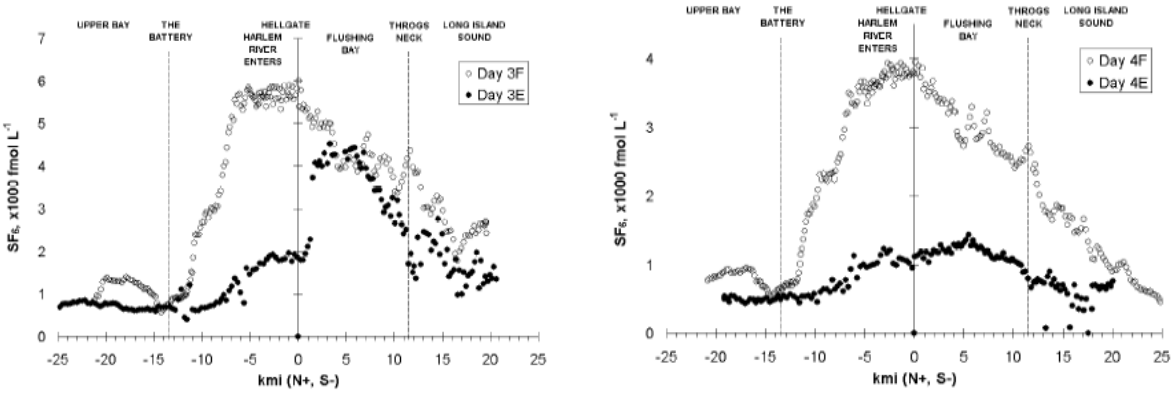


Figure 3.22. Observed (upper panels) and simulated (lower panels) longitudinal tracer concentration for days 1 (left panels, Days 1F and 1E, July 18 and 26) and 2 (right panels, Days 2F and 2E, July 19 and 27) after the flood (open circle) and ebb (filled circle) injections.

Observations



Model

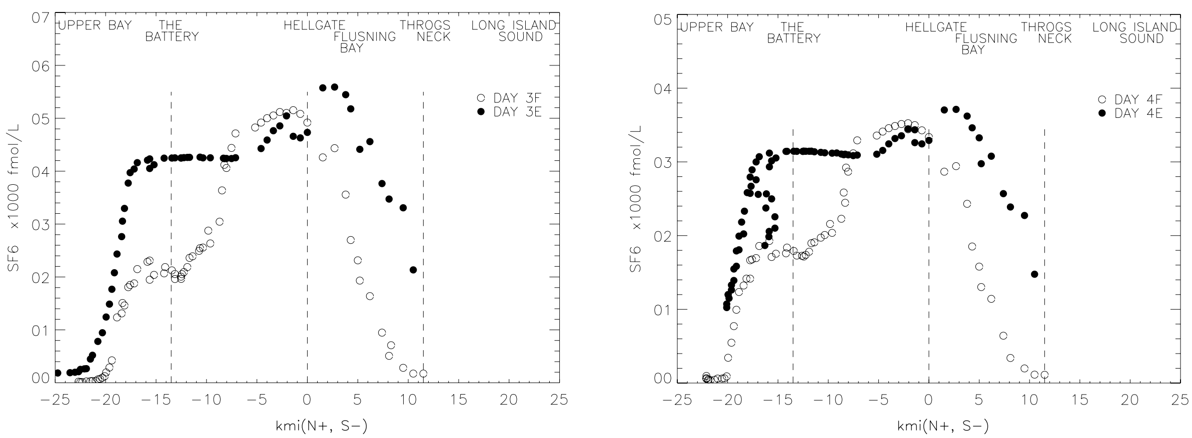


Figure 3.23. Observed (upper panels) and simulated (lower panels) longitudinal tracer concentration for days 3 (left panels, Days 3F and 3E, July 20 and 28) and 4 (right panels, Days 4F and 4E, July 21 and 29) after the flood (open circle) and ebb (filled circle) injections.

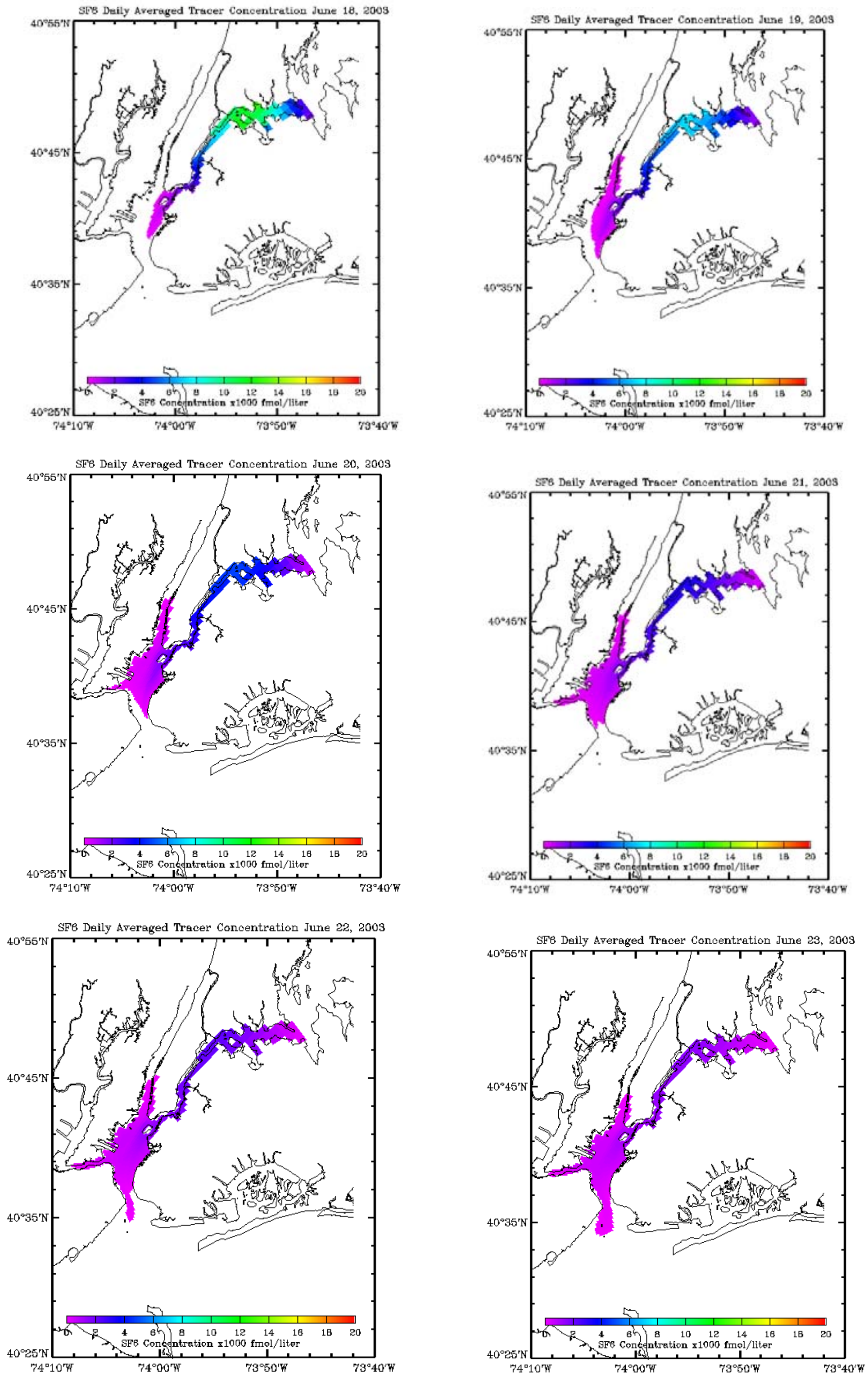


Figure 3.24. Simulated daily averaged tracer concentration contour plots, June 18 (Days1F) to June 23 (Day 6F) after the flood injection. Tracer exiting the model domain at northern boundary is especially apparent during the first 2 days.

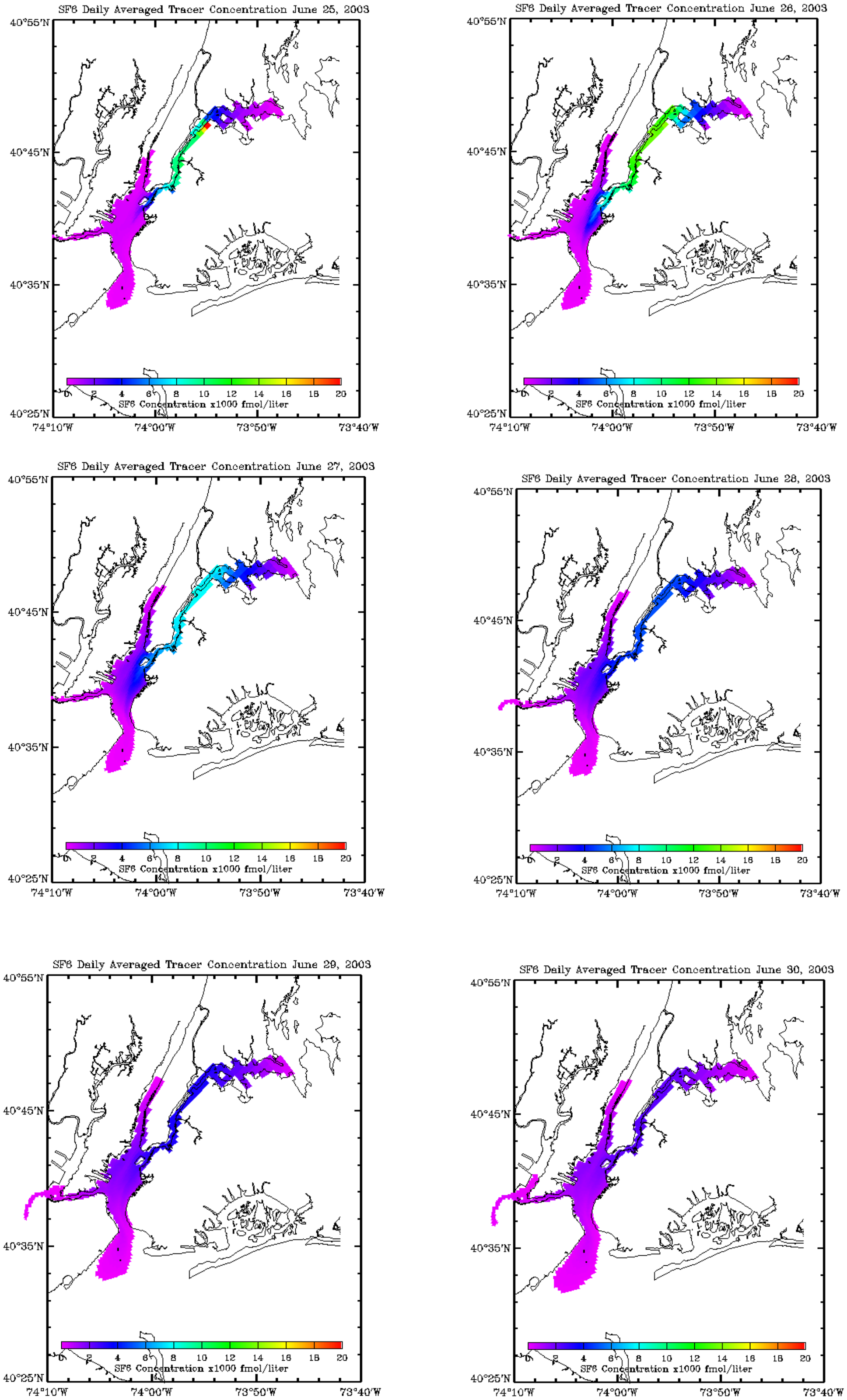


Figure 3.25. Simulated daily averaged tracer concentration contours for June 25 (Day 0E) to June 30 (Day 5E) after the ebb injection.

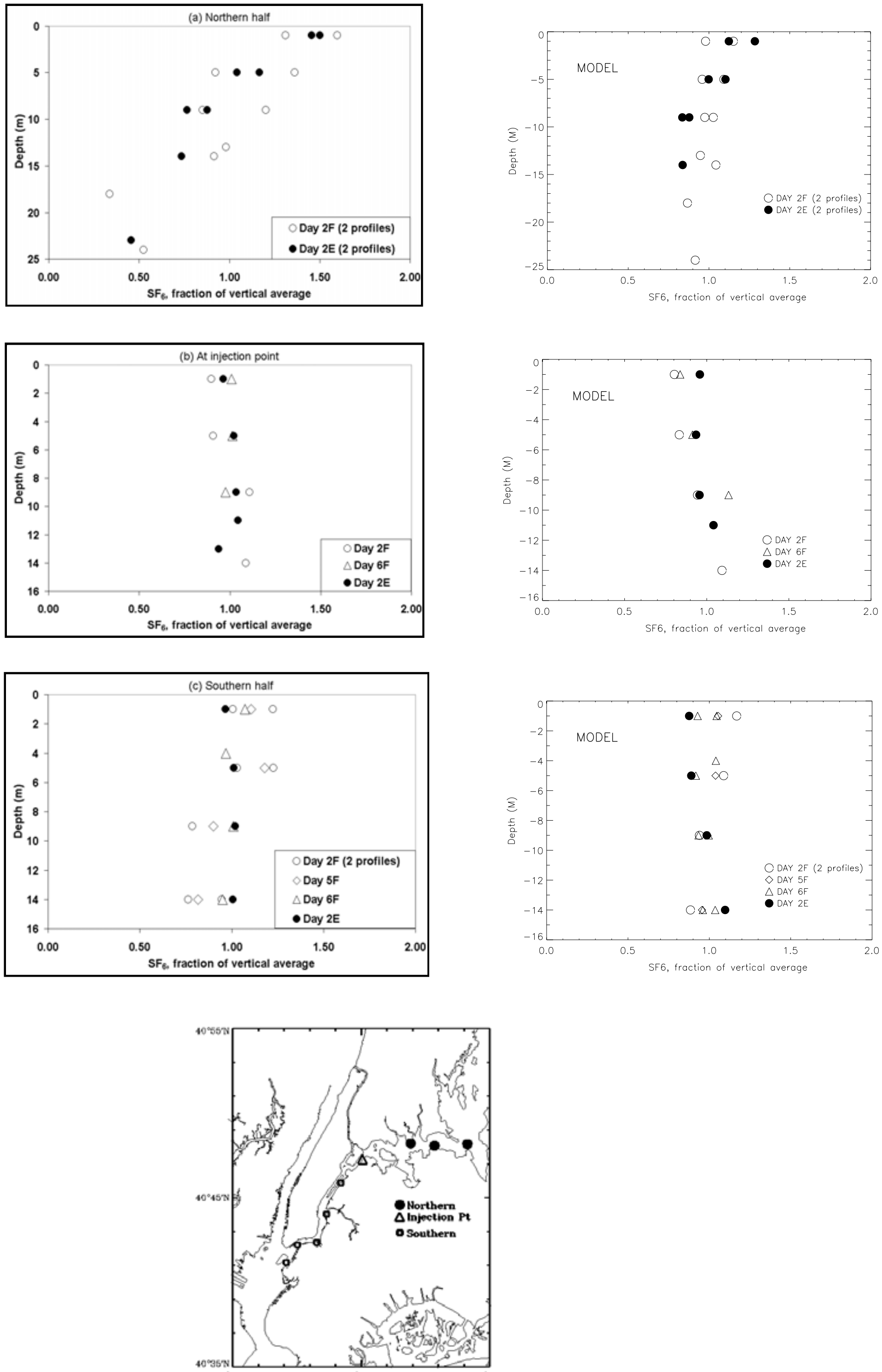


Figure 3.26. Observed (left, Caplow, et. al., 2004) and model simulated (right) vertical profiles of SF_6 concentrations (normalized to the vertical average) in the East River from three regions: (a) northern, (b) injection point, and (c) southern of the river. Profiles locations are shown on the map.

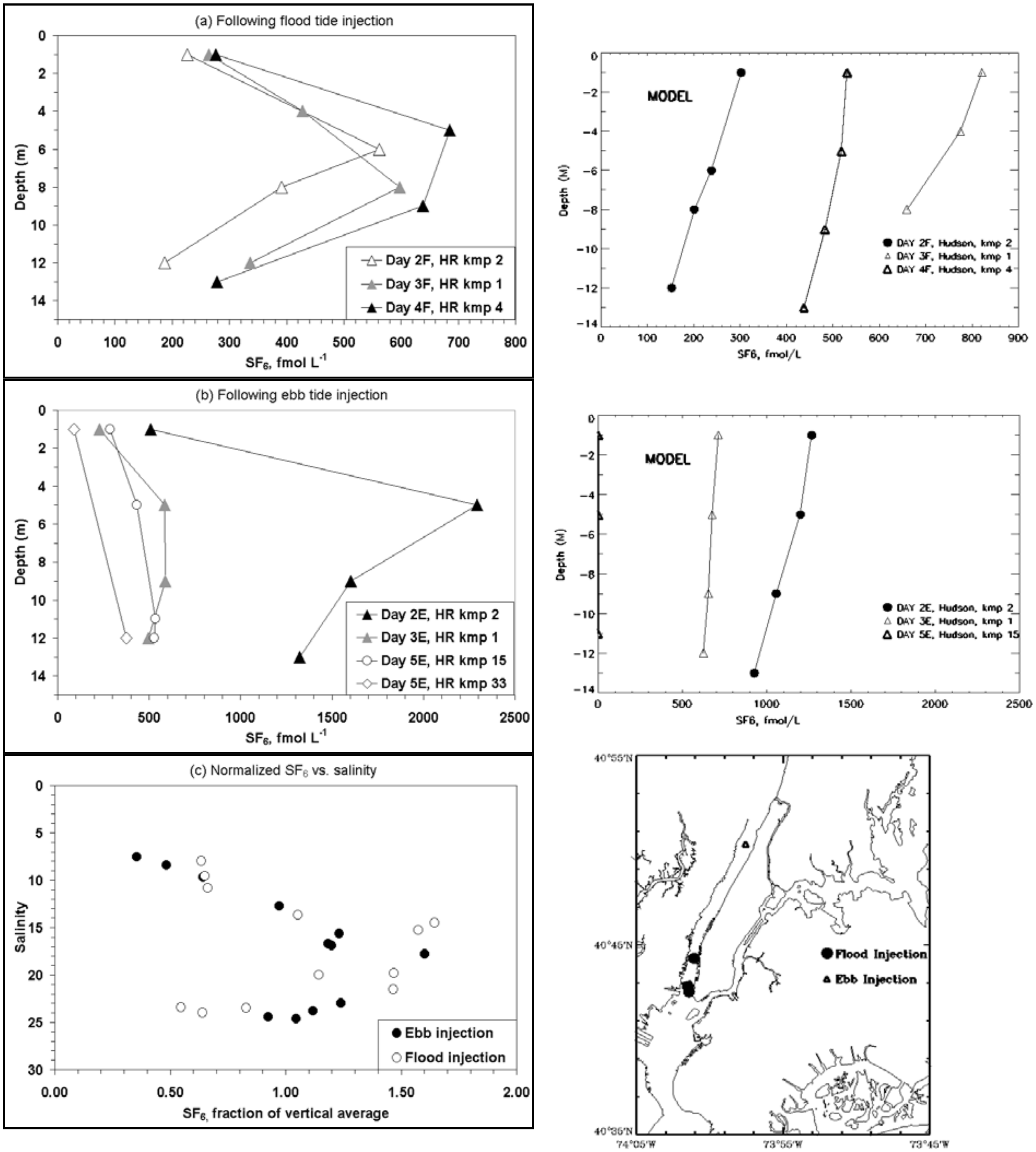
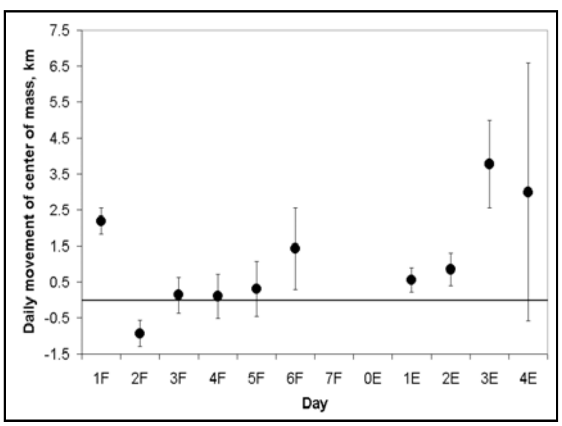


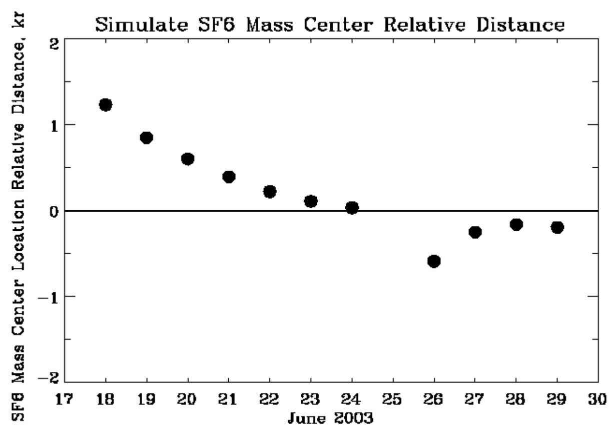
Figure 3.27. Observed (left column (a) and (b), Caplow, et. al., 2004) and model simulated (right column) vertical SF_6 profiles in the Hudson River following the flood and ebb injections, respectively. Normalized SF_6 concentration vs salinity (left (c)) for all profiles indicating peak SF_6 concentrations at mid-depth matches salinities in the East River.

3.2.6. Center of Mass Movement

The movement of the center of mass (COM) was calculated from the survey mass inventory each day in the East River. Figure 3.28(a) shows the observed COM movement for the flood and ebb injections (Caplow, et. al., 2004). The mean displacement was northward for both injections although initially it is southward for the flood injection. Although the distribution of background SF_6 from the survey has been subtracted before the COM calculation, the calculation could result in a significant error due to unknown background variability (Caplow et al., 2004). The model simulated tracer COM can be calculated at any model output time by a two-dimensional moment method, as the simulated tracer concentration is available over the entire model grid. Figure 3.29 shows surface layer COM time series at the model output interval (15 minutes) for flood (top) and ebb (bottom) injections. The COM locations coincide with a semi-diurnal tidal current, and a southward net movement for the flood injection can be seen. To calculate the COM net movement for comparison with the observations, the daily averaged COM calculated based on the model surface layer tracer concentration is presented in the right plot of Figure 3.28(b). In contrast to the data, the COM movement in the model is southward for the flood injection. The cause of discrepancy between the model and the observations is probably due to the mass loss at the model northern boundary in the model. For the ebb injection, the simulated net COM movement is northward, consistent with the observations because the flushing rate is higher than the flood injection from the East River to the Upper Bay (Figures 3.22 and 3.23).



(a)



(b)

Figure 3.28. Movement of the center of mass (COM) of SF_6 in the East River; (a) observed and (b) model. The COM of the SF_6 background has been subtracted. Note that distance 0 located at the injection location (near Hell Gate) and positive distance toward north. Note that June 18 and 26 correspond to Days 1F and 1E, respectively.

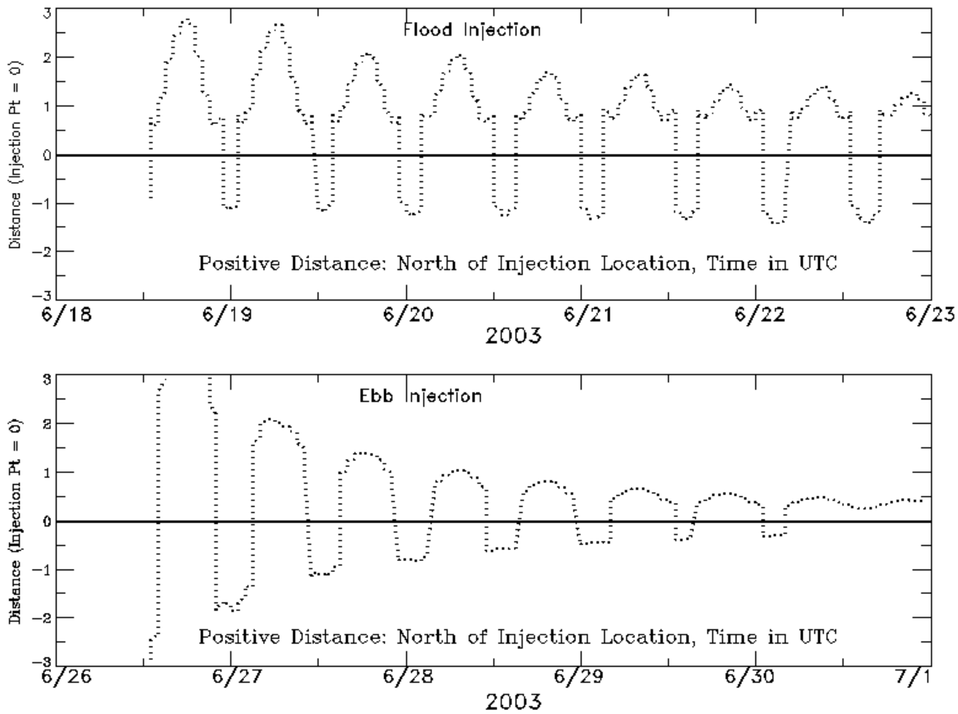


Figure 3.29. Location of the center of mass time series from model simulated tracer in the East River, relative to the injection point (distance 0) near Hell Gate for the flood (top) and ebb (bottom) injection.

3.2.7. Tracer Mass Inventory

The tracer injected into the water column in the experiment eventually either exits through the water surface into the air or flushes out to the Western Long Island Sound to the north and the Upper Bay to the south. The tidal flushing rate in the East River can be estimated from the total mass inventory. Some of the tracer that moves out of the East River (from The Battery to Throgs Neck) to the Long Island Sound will move back into the East River by the flooding tidal current. However, there are no data to evaluate the tracer inflow into the East River at the northern open boundary (near Throgs Neck) during the ebb tide (toward the south). There will be errors associated with the inflow boundary condition specified in the model. For this model simulation experiment, the tracer mass loss due to the difference between the outflow and the " concentration spatial gradient inflow boundary condition specified at Throgs Neck, can be estimated from the velocity and concentration information at the model boundary. Daily mass loss following the flood and ebb injections is calculated and tabulated in Table 3.1. There is significant mass loss during the first 2 days following the flood injection. Daily mass loss following the ebb injection is almost invariant after day one. Figure 3.30 shows the total mass decay for flood and ebb injections. For the observed data the ebb injection flushing rate is greater than the flood injection flushing rate. For the model, the tracer flushes out of the East River to the Upper Bay so quickly on the first two days that the mass decay in the ebb injection (square) is greater than the flood injection (triangle) despite the tracer mass loss at the northern boundary. For the ebb injection, the mass loss for the model (square) is much less than the data (diamond) probably due to: (1) significantly underestimating mixing in the Upper Bay by the mode, (2) low simulated current velocities caused by the coarse grid resolution; and (3) no Harlem River configuration in the model. Significant amounts of tracer were found in Harlem River from the survey (Figure 3.31, from Caplow et al., 2004).

The residence time is defined as the time it takes for the mass to decay to 1/e. Table 3.2 shows the residence time between the data and the model for the flood and ebb injections, respectively, based on the mass inventory decay curve in Figure 3.30. As mentioned previously, the model residence time is slightly less than that for the data following the flood injection because of the mass loss at the northern boundary. The model residence time is much greater than that of the data following the ebb injection.

Table 3.1. Model simulated daily tracer mass loss at model grid boundary, Throgs Neck, following the flood and ebb injections.

	Flood Injection		Ebb Injection	
Day	Loss (mod)	% of Total	Loss (mol)	% of Total
1	0.050	9.4	0.010	1.9
2	0.039	10.4	0.015	4.0
3	0.022	8.7	0.013	4.8
4	0.013	7.3	0.009	5.0
5	0.008	6.4	0.007	5.1
6	0.005	5.6		

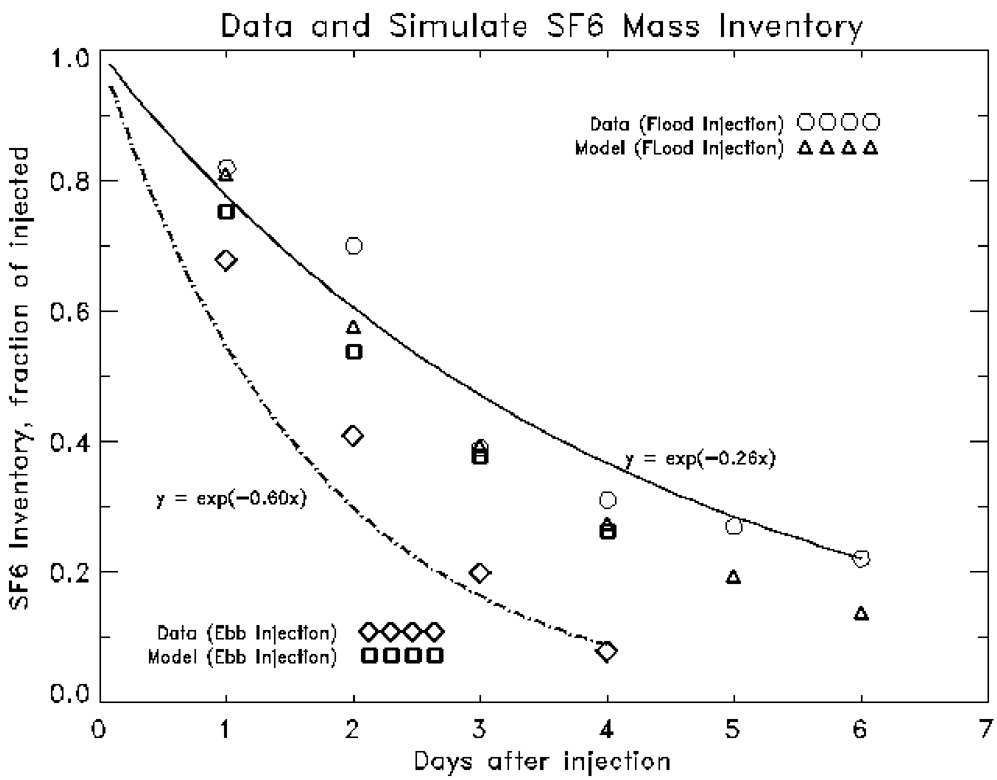


Figure 3.30. Observed and model simulated daily SF_6 mass inventory within the East River from The Battery to Throgs Neck following flood and ebb injections. Observed data (circle for flood injection and diamond for ebb injection) with regression curves for flood (solid line) and ebb (dot-dashed) injections are also plotted. Ebb injection decays are much faster than the flood injection.

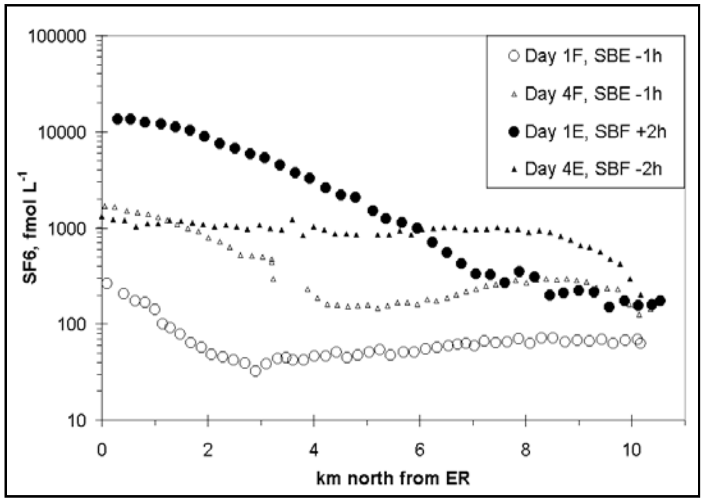


Figure 3.31. Longitudinal surveys of SF_6 in the Harlem River 1 and 4 days following the flood and ebb injections in the East River (Caplow, et. al., 2004).

Table 3.2. Residence time of observed and model simulated tracer for flood and ebb injections, respectively.

	Flood Injection	Ebb Injection
Data	3.8 day	1.7 day
Model	3.2 day	3.3 day

4. CONCLUSIONS AND FUTURE WORK

The estuarine dispersion characteristics of inland waterways in the New York Harbor have been investigated by the movement of a deliberately released gaseous SF6 tracer at Newark Bay (July, 2002) and the East River (June, 2003). The flushing rate and residence times were estimated by tracer concentration data collected at the surface by tidally synchronized boat surveys for about two weeks following the tracer release.

With the addition of a concentration subroutine to the NYOFS hydrodynamic model and forcing with proper boundary condition, the model has been set up to simulate the tracer movement during the two field experiments. The simulated SF6 concentration characteristics not only have been verified with observations collected from the field experiments but also extended beyond the area covered by the field survey. The simulated longitudinal tracer concentration distributions are qualitatively in agreement with observations obtained field experiments (Caplow et al., 2003 and Caplow et al., 2004). In the Newark Bay experiment, the simulated and observed maximum concentration and distribution shapes are similar but have mismatches in the phase. The simulated tracer advances less than the observed tracer in the Arthur Kill and the East River, probably due to slower current velocity associated with the coarse grid resolution. A finer model grid resolution such as the nested fine grid in NYOFS for Kill van Kull and Newark Bay is needed to improve the current velocity accuracy in these channels. In the East River experiment, the simulated maximum longitudinal concentration for the flood injection is less than the observed data due to the tracer loss at the northeastern boundary. Extending the model grid to the Western Long Island Sound would cover the entire tracer movement for this experiment. The vertical profiles observed in the Hudson and East Rivers in the East River experiment show peak SF6 concentrations at the mid-depth associated with classic two layer estuarine flow. The model is barotropic without salinity and temperature components, so there is no structure in the simulated tracer vertical profile comparable to the observed data. The model requires the density effect and fully 3-D baroclinic structure in order to produce accurate concentration structure in the vertical.

The residence time can be defined as the time it takes for the tracer mass to decreases to 1/e of the original mass, i.e., the e-folding. In the Newark Bay experiment, the simulated residence time for the inland waterways including the Newark Bay, Arthur Kill, and Kill van Kull is about 4.7 days, compared with 3.4 days for the observed data. Again, the slower current velocity associated with the coarse grid is the probable cause. For the East River experiment, the residence time following the flood injection in the model is about the same as the data (3.8 days for the observed data and 3.2 days for the model). However, the residence time following the ebb injection from the observed data (1.7 days) is much shorter than that from the model (3.3 days). This is probably due to the mixing in the Upper Bay is significantly underestimated by the model. Slower simulated current velocities and the lack of a Harlem River configuration in the model may also contribute the tracer out flushing from the East River. The grid resolution needs to be increased in the East River and the grid needs to be extended beyond the present boundary to more accurate tracer simulation. The Harlem River should also be included in the model configuration.

Analysis of the survey data reveals a high flushing rate from the East River to the Upper Bay following the tracer ebb injection, suggesting the optimal outfall time for wastewater management. However the model shows about the same residence time in the East River between flood and ebb injection. The model performance accuracy needs to be improved with model grid modification and more thorough verification of transport. By then, the verified model can be efficient and cost effective tool for environmental and ecological management in the New York Harbor estuary. For example, the model can be used to effectively study the dispersion of multiple pollutant sources, to evaluate their long term impacts, and for sensitivity studies of the forcing variables including river discharge, surface winds, and the coastal signal at the harbor entrance.

Concentration modeling is a cost effective tool for characterizing the dispersion features of a soluble substance in an estuary. For other pollutants, particle tracking may be a more appropriate approach. This report only documents the model simulation of the SF6 tracer dispersion using the concentration approach. Lagrangian trajectory modeling, for example the 4th order Runge-Kutta method (Wei, 1994), can also be applied to study the SF6 tracer dispersion experiments and to compare with results from the concentration modeling.

The model grid configuration to match the shoreline is very important for conserving mass and momentum. An un-structured grid is capable of matching the shoreline with higher accuracy than curvilinear grids. The finite volume models such as FVCOM (Chen et al., 2003), UnTRIM (Casulli et al., 2000), or ELCIRC (Zhang et al., 2004) using un-structured grids have been proven to be more accurate in circulation modeling than the orthogonal grid models in a complex estuary. Such model applications should improve the accuracy required for environmental management.

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REFERENCES

Caplow, T., P. Schlosser, D. Ho, and M.E. Rica, 2004. "Effect of tides on solute flushing from a strait: imaging flow and trasport in the East River with SF_6. (Accepted by Environmental Science & Technology)

Caplow, T., P. Schlosser, D. Ho, and N. Santella, 2003. "Transport Dynamics in a Sheltered Estuary and Connecting Tidal Straits: SF_6 Tracer Study in New York Harbor." Environmental Science & Technology, Vol 37, No 22, 2003, 5116-5126.

Casulli, V., and R.A. Walters, 2000. An Unstructured Grid, Three-Dimensional Model Based on the Shallow Water Equations, Inter. J. For Num. Methods in Fluids, Vol. 32, p. 331-348.

Chen, Changsheng and Hedong Liu, 2003. "An Unstructured Gid, Finite-Volume, Three-Dimensional, Primitive Equations Ocean Model: Application to Coastal Ocean and Estuaries", Journal of Atmospheric and Oceanic Technology, American Meteorological Society, January, 2003, Volume 20, p159-186.

Blumberg, A.F. and G.F. Mellor, 1987. A Description of a Three-dimensional Coastal Ocean Circulation Model. In: Three-dimensional Coastal Ocean Models, Coast and Estuarine Science, Vol. 4 (Heaps, N.S. ed.), American Geophysical Union, Washington, D.C., 1-16.

Ho, D.T., P. Schlosser, and T. Caplow, 2002. "Determination of Longitudinal Dispersion Coefficient and Net Advection in the Tidal Hudson River with a Large-Scale, High Resolution SF6 Tracer Release Experiment". Environmental Science & Technology, Col 36, No. 15, 3234-3241V

Wei, Eugene J. 1994. Lagrangian Drifter Trajectory Modeling. NOAA Technical Report NOS OES 004, NOS, NOAA, Silver Spring, MD, 57p.

Wei, E. And M. Chen, 2002. NOS Experimental Nowcast/Forecast System for the Port of New York/New Jersey (NYEFS): Requirements, Overview, and Skill Assessment, NOAA Technical Report, NOS CS 15, NOAA/NOS, 53p.

Wei, E. and M. Chen, 2001. Hydrodynamic Model Development for the Port of New York/New Jersey Water Level and Current Nowcast/Forecast Model System , NOAA Technical Report, NOS CS 012, NOAA/NOS, 46p.

Zhang, Y.-L. and Baptista, A.M. (2004) "A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: I. Formulation and skill assessment". Cont. Shelf Res. (accepted).