Title: Mixing in the Hudson Estuary: The Role of Estuarine Circulation and Tidal Trapping

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Abstract: The effect of estuarine circulation and tidal trapping on mixing in the Hudson Estuary is investigated by a numerical model simulation of a tracer release. The data set used in this study was obtained from a large-scale SF$_6$ tracer release experiment conducted during July/August 2001. It consists of over 2,000 measurements taken over a period of two weeks and distance of 110 km with a typical resolution of 400 meters. The model is based on the three-dimensional, time-variable, estuarine and coastal circulation modeling framework (ECOM), and consists of over 10,000 mass balance segments with a 600 m horizontal and 1 m vertical resolution in the study area. The ability of the model to reproduce the observed fate and transport of the tracer (model skill) is quantified using a new set of metrics. The model can reproduce the data over four orders of magnitude with a mean relative agreement (MRA) factor of 2.0. The modeled and measured longitudinal tracer concentration profiles (plumes) differ from the ideal Gaussian shape in two ways: (1) On a large scale the plume is asymmetric, with the downstream end stretching out farther. (2) Small-scale (1-2 km) peaks are present at the upstream and downstream ends of the plume. A sensitivity analysis is used to understand the processes responsible for these features. The model forcing functions (e.g., freshwater flow, boundary salinity, geometry) and process parameterizations (e.g., gas transfer velocity) are modified systematically and the resulting tracer profiles are compared to those from the unmodified model (base case). It is demonstrated that the large-scale asymmetry is due to salinity intrusion, which sets up an estuarine circulation. In the presence of an estuarine circulation, tracer in the surface layer is diluted to a larger degree with water from the lower layer causing increased longitudinal dispersion. Since the salinity intrusion is confined to the downstream end of the tracer plume, only that part of the plume is subject to a larger dispersion,
which leads to the large-scale asymmetry. The small-scale peaks are due to tidal trapping. Small embayments along the estuary trap water and tracer as the plume passes by in the main channel. At a later time, when the plume in the main channel has passed, the tracer is released back to the main channel, causing a secondary peak in the longitudinal profile.

Introduction

Understanding the transport characteristics of the Hudson Estuary is important for predicting the fate of contaminants discharged in the past (e.g., polychlorinated biphenyls (PCBs)), present (e.g., pathogens from combined sewer overflows (CSOs)) and future (e.g., accidental spills). Estuarine transport can be studied by observation as well as analytical and numerical modeling. Whereas either of these approaches can be used alone, the combination of data and model is the most effective approach because observational and modeling strategies complement each other. Data can be used to calibrate and validate a model and, at the same time, models help understand the physics governing natural systems and extrapolate data to areas and times with little or no coverage.

Continued improvements in analytical techniques provide us with the capability to observe tracers released into a water body at much higher temporal and spatial resolution. This allows for a much more sophisticated model calibration. At the same time computational power increases, and with it the spatial resolution of numerical estuarine models. The result is greater realism, but also increased complexity, which makes models more difficult to understand. High-
resolution models of complex natural systems, such as the Hudson Estuary, frequently produce features that are intuitively difficult to explain, and diagnosing such features is important for understanding the model and the real system. Advanced model diagnostic tools that allow for the visualization of computed parameters (e.g., animations of surface currents) are crucial for understanding the behavior of models. They are, in essence, tools for observing the model system, as data collection is a tool for observing the natural system. Another diagnostic strategy, which is typically not possible with the natural system, is to modify the model forcing functions and coefficients systematically and observe the effect on the simulated variables. Freshwater flow, for example, can be reduced to understand its effect on the transport of constituents dissolved in the water. This technique is commonly used to understand the sensitivity of model results to the values of various input parameters (e.g., uncertainty analysis). However, it can also be used to identify and understand the mechanisms controlling the behavior of the model. Here, a sensitivity analysis is used to understand the behavior of a model and the physical processes operating in the Hudson Estuary.

Here a numerical simulation of a tracer release into the Hudson Estuary is presented. The study combines high-resolution tracer sampling (over 2,000 samples, 400 m resolution) and modeling (over 10,000 mass balance segments; 600 m horizontal, 1 m vertical resolution in the study area). An existing model (Li et al. 2002) is used to simulate the fate and transport of SF₆ released in a field study presented by Ho et al. (2002).
Study Area

The Hudson River starts at Lake Tear of the Clouds in the Adirondack Mountains and ends in New York City. The 248 km stretch below Troy, NY is commonly referred to as the Hudson Estuary. Freshwater inflow into the estuary occurs predominantly from the Upper Hudson River at Troy, NY, but smaller tributaries also discharge downstream of that point. The flow of the Upper Hudson River is seasonal, highest during spring snowmelt and lower in the summer. As a result the salinity intrusion is also seasonal. In the spring the salt front is located near Yonkers, NY and in the summer it is located by Newburgh, NY. The hydrodynamics of the Hudson Estuary have been studied by Steward (1958), Busby and Darmer (1970), Abood (1974), Posmentier and Rachlin (1976), Hunkins (1981) and Geyer et al. (2000).

Data

In the summer of 2001 a large-scale SF$_6$ tracer release experiment was conducted in the Hudson Estuary (Ho et al. 2002). On 7-25-01, roughly 4.3 moles of SF$_6$ gas were injected at 5 m depth near Newburgh, NY (Fig. 1; KMP 98; distances are referenced to the Battery at the southern tip of Manhattan) from a boat while twice traversing the estuary laterally over a period of 28 min. The release time (12:14-12:42) approximately corresponds to slack water before flood (SBF) at Newburgh, NY. Based on subsequent concentration measurements Ho et al. estimated that of the 4.3 moles injected ca. 1.1 moles dissolved in the water, whereas the remainder escaped to the atmosphere in the form of bubbles. SF$_6$ is an inert gas and
consequently is lost from the water column only by gas exchange across the air-water interface. On the basis of a mass balance, Ho et al. estimated an average gas transfer velocity of 1.4 m d$^{-1}$ for SF$_6$ for the duration of the experiment.

SF$_6$ concentrations were measured over a period of two weeks following the release. Measurements were taken daily at 2 m depth with a fully-automated continuous analysis system from a boat while traversing the plume longitudinally. The typical sample interval was 2 min in time and 400 m in space. The 12 longitudinal profiles contain an average of 172 measurements for a total of 2,060 data points. On certain days SF$_6$ concentrations were measured at several depths at various locations (Fig. 2).

Model

The model, described in detail by Li et al. (2002), is based on the three-dimensional, time-variable, estuarine and coastal circulation modeling framework (ECOM). It is a modified version of the Princeton Ocean Model (POM; Blumberg and Mellor 1987), incorporating the Mellor-Yamada 2.5 level turbulent closure model that provides a realistic parameterization of vertical mixing processes. A curvilinear horizontal segmentation allows for smooth and accurate representation of shoreline geometry, and a sigma-level vertical coordinate system permits better representation of bottom topography. The model solves a coupled system of differential, prognostic equations describing the conservation of mass, momentum, salinity, temperature, turbulent energy, and turbulence macro scale. Recent applications of the model to St. Andrew...
Bay, FL and Pensacola Bay, FL are presented by Blumberg and Kim (2000) and Ahsan et al. (2001), respectively. A detailed description of the model’s governing equations can be found in Blumberg et al. (1999) and HydroQual (2001).

The model covers 209 km of the Hudson Estuary from Hastings-on-Hudson, NY, to Troy, NY (Fig. 1). It consists of 1,191 horizontal grid boxes, each with 10 layers in the vertical, for a total of 11,910 mass balance segments. The model is forced with discharge from five rivers (Upper Hudson River, Esopus Creek, Rondout Creek, Wappinger Creek and Croton River), atmospheric heat flux and wind stress (based on data at Albany and New York City) and water surface elevation, salinity and temperature at the downstream boundary (Hastings-on-Hudson, NY). In addition, withdrawal rate and discharge rate and temperature rise of five power plants (Danskammer Point, Roseton, Indian Point, Lovett and Bowline Point) are specified as input. The model was originally set up to simulate the periods 3-11-98 to 4-9-98 (high flow) and 8-1-97 to 8-30-97 (low flow) and validated extensively against field data including water surface elevation, salinity and temperature at various locations, shipboard acoustic Doppler current profile (ADCP) velocity, salinity and temperature measurements and fixed-site ADCP velocity, salinity and temperature measurements as described by Li et al. (2002).
Tracer Simulation

MODEL SET-UP

For the tracer simulation the model forcing functions were updated for the period 7-10-01 to 8-9-01 allowing for 15 days of “spin-up” before the tracer release on 7-25-01. The model boundary conditions (freshwater flow rate, wind speed, wind direction and downstream boundary water surface elevation) were assigned based on data. The mean flow rate for the model period of the Hudson River at Troy was 140 m$^3$ s$^{-1}$. Salinity and temperature initial conditions were not available. However, limited salinity measurements performed by Ho et al. (2002) indicate that the salinity regime was similar to that in the original low flow period (1997). Salinity initial conditions and boundary values were therefore taken from the original low flow period. Power plant intake and outfall data for the new period were not available and were kept the same as for the original low flow period.

$\text{SF}_6$ was added to the model at a constant loading rate (mol s$^{-1}$) over a period of 28 min at KMP 98, distributed equally over the 10 lateral grid boxes (Fig. 2) and top 5 vertical layers (corresponding to approx. 5 m). The release time is consistent with the actual release and the ability of the model to predict the tidal condition observed during the field experiment (SBF at Newburgh, NY) was verified. Ho et al. (2002) injected 4.3 moles, of which they estimated 1.1 moles dissolved. Their estimate was based on subsequent $\text{SF}_6$ inventory estimates, and in a
similar manner the total mass added to the model was adjusted here to match the SF$_6$ concentration profiles, resulting in an addition of 1.6 moles to the model.

To simulate SF$_6$ gas exchange a constant gas transfer velocity ($K_L$, m d$^{-1}$) was specified. This velocity was divided by the depth of the top layer, to yield a first-order decay rate, which was applied to the top layer. The approach is relatively crude, in that it neglects the effect of varying wind speed on the gas transfer velocity, assumes the tracer is vertically uniformly mixed over the top layer and assumes the atmospheric gas concentration is negligible. A constant gas transfer velocity of 1.4 m d$^{-1}$ as estimated by Ho et al. (2002) was used.

The horizontal dispersion determined by Li et al. (2002) was based on calibration to relatively small horizontal gradients in temperature and salinity. Initial simulations of the SF$_6$ tracer release using the same coefficient of dispersion ($C_S = 0.10$; $C_S$ is the constant in the dispersion formulation by Smagorinsky 1963) as Li et al. (2002) resulted in an underestimation of dispersion of SF$_6$. The $C_S$ coefficient was recalibrated to match observed tracer concentrations. The resulting value was 0.01, which is within the range of other applications (HydroQual 2001; Ezer and Mellor 2000).

**MODEL-DATA COMPARISON**

**General Considerations**
In the study area, tide can cause an injected tracer to travel upstream and downstream within the tidal cycle (Fig. 3). The distance traveled by a water parcel between low and high water (tidal excursion) is typically about 8 km. As a result the tracer concentrations at a given location can vary significantly in time. The model-data comparison is therefore a very stringent test, because it does not only test the ability of the model to reproduce the general shape of the plume but also tests the timing. In this contribution, tracer concentrations will be presented on a logarithmic scale for two reasons. First, the concentrations vary over four orders of magnitude and a logarithmic scale allows for the visualization over a large range. Second, as described in the next paragraph, the logarithmic scale is most appropriate for skill assessment of fate and transport models, especially for conservative tracers.

Quantitative Model Skill Assessment

To quantitatively describe the skill of the model, a (statistical) measure is needed. Often the root mean square error (RMSE) is used for this purpose, because it is simple to compute and easy to understand (i.e., on average the model is ‘wrong’ by a certain degree quantified by the RMSE). However, the RMSE is a poor descriptor of the skill of fate and transport models, especially for conservative tracers. This is related to the way in which errors are generated in these types of models. For conservative substances, the mass balance equation is linear. For non-conservative substances, reactions can introduce non-linearities. However, often reaction equations are also linear (e.g., first-order decay), resulting in a linear mass balance equation for non-conservative substances as well. For linear models, errors in the transport or reaction terms
will cause errors in concentration proportional to the absolute magnitude of the concentration. A model error that causes a concentration error of 50 fmol L\(^{-1}\) for a concentration of 100 fmol L\(^{-1}\) will cause an error of 5 fmol L\(^{-1}\) for a concentration of 10 fmol L\(^{-1}\). The absolute error varies with concentration (i.e., 150-100 ≠ 15-10), which makes it an unsuitable measure of model skill.

Consider a slug release of a tracer into a model with a spatially and temporally uniform error (e.g., dispersion coefficients are too high by a factor of 2). Since the error is constant, so is the skill of the model. However, the absolute error would vary spatially and temporally with the concentration. A better measure of skill is the ratio of model-predicted to measured (true) values. In the above example this quantity is constant (i.e., 150/100 = 15/10 = 1.5) and therefore the preferred statistic. Therefore, for assessment of model skill the relative agreement and not the absolute error is of interest.

Quantitative calculations are simplest when the data and model are first transferred to logarithmic space, because absolute difference in logarithmic space corresponds to relative difference in arithmetic space (i.e., log(150)-log(100) = log(15)-log(10) = log(1.5)). In this manner the relative agreement (RA) is defined as:

\[
RA = 10^{d-m}
\]

where \(d\) and \(m\) are the logarithms of the data and model, respectively. The RA is the absolute value of the difference between data and model in logarithmic space transferred back to
arithmetic space. To summarize multiple observations a new statistical measure, called mean relative agreement (MRA), is defined:

\[
MRA = 10^{\sqrt{-\frac{\sum (d-m)^2}{n}}} = 10^{\text{RMSE}}
\]  

(2)

The MRA is the root mean square error (RMSE) in logarithmic space transformed back to arithmetic space. The interpretation of the MRA statistic is discussed further below. The MRA should be evaluated with respect to the spread in the data. A model that reproduces data varying over four orders of magnitude with an MRA of 2 is better than a model that reproduces data varying over one order of magnitude with an MRA of 1.5. To quantify model skill in this manner the model skill score (MSS) is defined as:

\[
\text{MSS} = 1 - \frac{\text{RMSE}}{\sigma_d}
\]

(3)

where \(\sigma_d\) is the standard deviation of the logarithms of the data. An MSS of 1.0 indicates perfect agreement. When the MSS is 0.0 the deviation between the model and data is as large as the deviation in the data.

The same argument against using absolute error speaks against presenting model-data comparisons on an arithmetic scale. The logarithmic scale is best suited to visualize relative agreement, because a constant relative agreement corresponds to a constant distance on a
logarithmic scale, regardless of the magnitude of concentration. To perform the model-data comparison, the model computed concentration corresponding to each of the 2,060 data points was extracted. This involved finding the model computed value corresponding most closely in three dimensional space (grid box) and time (1-h “print” interval) to the data value. This real-time comparison shows that the model can predict the observed SF₆ concentration over four orders of magnitude (Fig. 4). For this application the MRA is 2.0, indicating that on average the relative agreement between the model and data is a factor of 2 (i.e., 50 vs. 100 fmol L⁻¹).

Graphically, the MRA is the mean vertical distance between the points and the 1:1 line in Fig. 4 (transformed back to arithmetic space; \(10^{0.3} = 2.0\)). Although the agreement between model and data is generally good, a bias is evident with the model generally over-predicting higher concentrations and under-predicting lower concentrations. The distribution of modeled concentrations is less dispersed indicating that the model under-predicts dispersion.

**Longitudinal Profiles**

Longitudinal profiles of surface SF₆ concentration from data and model simulations are compared for the 12 days for which data are available (Fig. 5). A comparison of spatial profiles is only useful if it shows a “snapshot” of values at one point in time. Also, to evaluate the day-to-day progression of the tracer plume it is desirable to eliminate the variability introduced by tidal movement. This is done by plotting each subsequent day at the same time in the tidal cycle (SBF at Newburgh, NY). For model results this is not a problem, because a virtually continuous representation of concentrations is available for each grid box. However, for the data, which
were collected at different times over the course of a sampling cruise and at a different time in
the tidal cycle at subsequent cruises, a correction has to be applied. Here the data were made
synoptic and corrected to the same time in the tidal cycle as described by Ho et al. (2002) and
any errors in this transformation are therefore reflected in this model-data comparison.

Figure 5 shows that the SF$_6$ concentrations decreased with time due to gas exchange and
dispersion. At the same time dispersion increased the length scale over which the tracer was
spread out. The peak tracer concentrations decreased from more than 10,000 to less than 1,000
fmol L$^{-1}$ during the 14 days following the release. After 4-5 days the concentration at KMP 115
reached 10 fmol L$^{-1}$ and remained at approximately that value for the remainder of the study
period. The tracer continuously spreads in the downstream direction. The model reproduces
these features. Downstream of KMP 70 the model under-predicts the tracer concentration by up
to about a factor of two. The model boundary is located far enough downstream (KMP 36; tidal
excursion ~ 8 km), for this not to be a boundary effect.

On the large scale, the data and model both show an asymmetric longitudinal
concentration profile. Downstream of KMP 80 the tracer spreads out faster. Since the
asymmetry starts at about KMP 80, this feature is most evident at later times when the tracer has
reached that location. The data and model show small-scale features (peaks) on the upstream
and downstream sides of the plume. These features are most pronounced early in the experiment
(e.g., 7-27-01) when the longitudinal concentration gradient is high, but they are present
throughout the simulation. The spatial scale of these features is as low as 1-2 km and they are
resolved because of the high resolution of the data and the model. The profiles at various times in the tidal cycle (Fig. 3) and at different days (Fig. 5) show that the location of these features is fixed in space. The cause of these large- and small-scale features will be discussed in the next section.

**Location of Peak Concentration and Center of Mass**

The location of the peak concentration and the center of mass as a function of time for model and data are compared (Fig. 6). The trajectory of the peak concentration is highly variable, because it is defined by a single point. The trajectory of the center of mass is a more robust measure, because it is based on all points. It moves downstream at a velocity corresponding to approximately the net estuarine flow, but the peak concentration travels downstream at a significantly lower velocity. This is evident in the data and model, and the cause of this behavior will be discussed below.

**Vertical Profiles**

Vertical profiles of SF$_6$ concentration were measured on several days (Fig. 7). The model reproduces the vertically averaged concentration at Storm King, but underestimates the concentrations at World’s End and Iona Island. At Iona Island the model under-predicts the concentration by about a factor of two, consistent with the longitudinal profiles. Although SF$_6$ mixes to great depths, a weak concentration gradient remains with concentrations generally
higher at the surface than at the bottom. The average ratio of surface to bottom concentration is 1.7 for data and model, indicating that the model reproduces the vertical mixing.

**Horizontal Distribution**

Most of the data were collected along one-dimensional longitudinal transects and therefore cannot resolve any two-dimensional features of the tracer plume. However, limited lateral surveys performed by Ho et al. (2002) did show significant lateral structure with concentrations on the banks as low as half of those in the channel. The model also predicts significant two-dimensional structure in the plume (Fig. 8). The modeled concentrations in the channel, which approximately corresponds to the sample locations, can be higher (KMP 107) or lower (KMP 102) than on the banks. This pattern is variable in time, depending on the tidal condition (i.e., flooding or ebbing).

**Discussion**

**Analysis Strategy**

The model-data comparison illustrates that the model can reproduce many features of the observed SF$_6$ fate and transport in the Hudson Estuary. In this section the model is analyzed with the objective to learn how different features of the system (e.g., freshwater flow) affect the fate and transport of dissolved constituents. Also, the cause(s) of (a) the large-scale asymmetry,
(b) the small-scale secondary features in the longitudinal concentration profile, and (c) the
difference in downstream velocity of the peak concentration and center of mass are investigated.
To answer these questions a sensitivity analysis was performed. Rather than visualizing
parameters computed by the model (e.g., plot surface velocities) the model forcing functions
(e.g., reduce freshwater flow) and parameterizations of processes (e.g., double gas transfer
velocity) are modified and the effect on the simulated concentration is examined. The
concentrations computed by the modified model are compared to that of the unmodified model
(base case). The longitudinal profile ten days after the release (8-4-01) is used for comparison.

EFFECT OF AIR-WATER GAS EXCHANGE

Air-water gas exchange is the only sink of SF₆ from the water column and it is of interest
how much of the magnitude and shape of the longitudinal concentration profile can be attributed
to it. This allows for the results to be related to spills of more or less conservative substances.
Further, it is possible that gas exchange is responsible for the asymmetric concentration profile,
because gas exchange is a function of the surface area. The width of the estuary significantly
decreases downstream of Storm King (KMP 88; Fig. 2) causing a decrease in surface area (on a
per unit length basis), which could be responsible for the asymmetric concentration profile.

Two simulations were performed with the gas transfer velocity ($K_L$) modified from the
base case (1.4 m d⁻¹) to zero and twice the base case (2.8 m d⁻¹). The results illustrate that gas
exchange is responsible for about half of the decrease in peak SF₆ concentrations over the ten
days following the release (Fig. 9a). Gas exchange affects mainly the overall magnitude of tracer concentration. The general shape of the longitudinal concentration profile, including the asymmetry and secondary peaks, is not affected. Those features are therefore not related to gas exchange.

**EFFECT OF FRESHWATER FLOW**

Freshwater inflow to the estuary affects the transport of constituents in mainly two ways. First, on the time scale of days to weeks, it causes a net downstream movement of water that contributes to the flushing of the estuary. Second, on the time scale of weeks to several months (e.g., seasonal), it affects the salinity stratification that influences much of the estuarine circulation. Here the short-term effect of freshwater flow is examined. For this purpose the tributary inflows are modified and the initial and downstream boundary salinity concentrations were assigned as in the base case. Several simulations were performed with the Hudson River flow rate at Troy being modified from the base case (140 m$^3$ s$^{-1}$) to zero, mean flow (400 m$^3$ s$^{-1}$), typical spring flow (1,000 m$^3$ s$^{-1}$) and the 10-year flood (3,400 m$^3$ s$^{-1}$).

The results illustrate how freshwater inflow causes a net downstream movement of tracer (Fig. 9b). The modeled concentrations for the 10-year flood simulation are not visible at that scale, because the tracer is flushed out of the estuary by 8-04-01. The no-flow case shows that after 10 days the peak concentration is located upstream of the release point. This is an effect of the different dispersion characteristics in the upstream and downstream direction, to be discussed
subsequently. The center of mass shows no temporal trend and after 10 days it is located at the release point (KMP 98). As for the base case, the longitudinal concentration profiles for various flow regimes have secondary peaks and are asymmetric, illustrating that neither of these features are related to the short-term effects of freshwater flow.

**Effect of Salinity**

The presence of salt in the water column has a pronounced effect on the circulation of estuaries and on the transport of a tracer. Freshwater inflow maintains a salinity (and hence density) variation that increases seaward due to increasing salinity (Pritchard 1954). The horizontal salinity gradient is mixed upwards by the tidal action resulting in a gravitational circulation with the salty water moving upstream in the lower layer and right-bank side (looking upstream) of the estuary and freshwater moving downstream in the surface layer and left-bank side. There is also a small net vertical motion directed from the bottom to the surface layer (Pritchard 1969). The vertical and lateral shear was recognized by Pritchard (1954) and Fischer (1972) as the main contributor to longitudinal dispersion. A tracer released in the upper portion of the water column tends to move downstream, continuously mixing with salty water being entrained from below, the upstream moving lower layer water.

To investigate the effect of salinity, the initial and open boundary salinity concentrations were set to zero and twice the base case. At the downstream boundary the salinity was thus increased from 15 to 30, which represents extremely saline conditions. The tracer concentrations
for the zero salinity simulation are similar to the base case at the upstream end of the plume (Fig. 9c). This is plausible, because at that location the salinity is close to zero for the base case as well. However, the downstream end of the plume has changed significantly. Most interestingly, the new profile is symmetric, which shows that the asymmetry is related to salinity. For the high salinity simulation the point where the asymmetry starts (80 km in the base case) is further upstream. This shows that the location where the asymmetry starts is determined by dynamics, depending on the salinity and not tied to fixed physical features (e.g., bathymetry). The effect of salt is to stratify the water column vertically and set up an estuarine circulation. The estuarine circulation acts on the downstream part of the plume by rapidly diluting the tracer. Both simulations exhibit secondary peaks, illustrating that they are not related to salinity. It is interesting to note that although salinity has a pronounced effect on the longitudinal transport of tracer, it does not prevent the vertical mixing of tracer to significant depths (Fig. 7).

**Effect of Geometry**

The geometry of the Hudson Estuary is highly variable containing deep narrow channels (e.g., World’s End), wide shallow bays (e.g., Newburgh Bay) and many smaller scale indentations that occur in the form of coves and inlets. The geometry affects the fate and transport of a tracer directly, by trapping water parcels as the tracer plume passes and allows them to be released later in the tidal cycle. The phase lag between the currents in the nearshore embayments and main channel acts to form “dead zones” that trap and release tracer into the main flow. The effect is to increase longitudinal dispersion of the tracer (Okubo 1973). Besides
this “tidal trapping”, the overall dynamics of the circulation are also affected by the geometry, which can have indirect effects on tracer transport.

To investigate the effect of geometry on tracer transport the model grid was modified to a straight rectangular channel with dimensions based on those of the Hudson Estuary covered by the model grid (width = 1.3 km, depth = 9 m). Other factors that introduce two-dimensional effects (tributary freshwater flow, wind, coriolis force and power plants) were kept as in the base case. The model predicts less overall spreading of the tracer plume illustrating that geometry irregularities contribute to the longitudinal dispersion (Fig. 9d). The profile is symmetric, which is a reflection of a reduced salinity intrusion, consistent with the decreased longitudinal dispersion. For that reason it might be more appropriate to compare the straight channel case to the no salinity case (Fig. 9c). The peak concentration travels downstream at a higher velocity than in the base case, because now the dispersion is similar in the upstream and downstream directions (see subsequent discussion). The location of the peak concentration coincides with that of the center of mass. Although the profile is not perfectly smooth, there are no pronounced secondary peaks, which illustrates that those features are related to geometry irregularities. Small-scale embayments, like that near Wappinger Creek (KMP 106; Fig. 8) trap tracer mass leading to the secondary peaks in the longitudinal concentration profile. The effective longitudinal dispersion is two orders of magnitude greater than that calculated via the Smagorinsky (1963) formulation built into ECOM.
In the model-data comparison it was observed that the center of mass moves downstream at a faster velocity than the peak concentration. Also, for the no freshwater flow the peak concentration moved upstream, consistent with the base case considering the center of mass remained stationary. In the straight channel case the peak concentrations and center of mass coincided, illustrating that the difference in velocities is related to the geometry. The cause for this phenomenon is the difference in the dispersion characteristics in the upstream and downstream directions. In the downstream direction mass continues to spread by dispersion. In the upstream direction dispersion through the northern end of Newburgh Bay is limited (KMP 115; see Fig. 5). Over time this causes the peak to shift upstream from the center of mass. If there were absolutely no dispersion across KMP 115 and the only loss process was dispersion in the downstream direction, the peak concentration, after a long time, would actually be located at KMP 115.

Summary and Conclusions

A numerical model was used to simulate a large-scale SF$_6$ tracer release experiment in the Hudson Estuary. In general, the model reproduces the observed fate and transport of the tracer. The model underpredicts concentrations at the downstream end of the plume, which points to possible areas for improvement. Also, instead of specifying a constant gas transfer velocity it would be desirable to calculate it dynamically based on the wind (Wanninkhof 1992) and/or current speed (O’Connor and Dobbins 1958).
The data show a large-scale asymmetry in the longitudinal concentration profile (plume), small-scale secondary features at the upstream and downstream sides of the plume, and a difference in the velocity of the peak concentration and center of mass. The model reproduces these features. To understand the underlying mechanism responsible for these features, the model forcing functions and coefficients were systematically varied. This leads to the following general conclusions about the fate and transport of a tracer in the Hudson Estuary:

1. Salinity leads to an estuarine circulation with downstream surface currents and upstream bottom currents, which leads to increased dispersion of the tracer. A constituent released in the freshwater part of the Hudson Estuary will spread out faster over the saltier water leading to an asymmetric concentration profile.

2. Geometry irregularities significantly increase longitudinal mixing by tidal trapping. Kilometer scale embayments, like those by Wappinger Creek, temporarily trap water masses. This causes entrainment of water with higher tracer concentrations into water with lower concentrations, and vice versa. Over time this contributes to longitudinal dispersion.

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FIGURE LEGENDS

Fig. 1. Hudson Estuary from Troy to Hastings-on-Hudson.

Fig. 2. Model grid in the study area. The grid extends from Troy to Hastings-on-Hudson (see Fig. 1) and consists 1,191 horizontal boxes with 10 vertical layers each. The data consist of 12 longitudinal transects of surface (2 m) concentrations with a total of 2,060 data points (small points) and 4 vertical profiles each at 3 stations (large points). Grid boxes corresponding to tracer release are rendered solid.

Fig. 3. Longitudinal profiles of modeled surface (2 m) SF$_6$ concentration on 7-27-01 at three different times. Dashed line corresponds to release location.

Fig. 4. Modeled vs. measured SF$_6$ concentration (fmol L$^{-1}$). Solid line is 1:1 and dashed lines are +/- 1 order of magnitude. Data below KMP 60 are omitted due to proximity to the model boundary at KMP 36. Statistics are for model and data in logarithmic space (N = number of data points, ME = mean error (model bias), RMSE = root mean square error, R = cross correlation (correlation coefficient), SS = skill score; Kara et al. 2002; MRA = mean relative agreement, MSS = model skill score; see text).

Fig. 5. Longitudinal profiles of modeled (solid lines) and measured (points) surface (2 m) SF$_6$ concentration. Concentrations correspond to the same time in the tidal cycle (slack before flood
at Newburgh, NY). Data from ship cruises were made synoptic as described by Ho et al. (2002).
Model concentrations correspond to horizontal location of data (i.e., ship track, see Fig. 2).
Dashed line corresponds to release location.

Fig. 6. Location of data and model SF₆ (a) peak concentration and (b) center of mass vs. time.
Center of mass for model and data were calculated from one-dimensional longitudinal profiles of
surface concentration (2 m; Fig. 5) applied to model geometry. Points are data. Heavy line is
model. Dashed line corresponds to the release location. Light line corresponds to the net
freshwater flow during model period (150 m³ s⁻¹ upstream of Newburgh, NY) and average
geometry (depth = 9 m, width = 1.36 km)

Fig. 7. Vertical profiles of modeled (solid lines) and measured (points) SF₆ concentrations at
three stations (Storm King, World’s End, and Iona Island). See Fig. 2 for station locations.

Fig. 8. Horizontal distribution of modeled surface (2 m) SF₆ concentration (fmol L⁻¹) in
Newburgh Bay on 7-27-01 14:28. Points are the sample locations for that date.

Fig. 9. Longitudinal profiles of modeled surface SF₆ concentration on 8-4-01. Thin lines are for
the base case and heavy lines are for various modifications (see text). Dashed lines correspond to
the release location.
FIGURE 3
FIGURE 6

(a) PEAK CONCENTRATION

(b) CENTER OF MASS
FIGURE 7