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Farfield Tracing of a Point Source Discharge Plume in the Coastal Ocean Using Sulfur Hexafluoride

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Pathways and dilution of a point source ocean discharge in the farfield (≈10−66 km) were measured using the deliberate tracer sulfur hexafluoride (SF_6). The injection of SF_6 was performed by bubbling the gas over a period of 6 days into an ocean outfall pipe discharging into the southeast Florida coastal ocean. The surface SF_6 concentrations show that the discharged water flowed northward parallel to the coast with a broadening of the width of the plume to about 3 km at the farthest point sampled, 66 km from the outfall. The discharge was fully mixed throughout the water column within 13 km of the outfall terminus. In the first 20 km from the outfall, SF_6 surface concentrations were highly variable, while beyond this the SF_6 concentrations decreased monotonically going northward. The currents were measured during the study with a bottom-mounted acoustic Doppler current profiler (ADCP) located 5.5 km from the outfall. Velocities were variable in magnitude and direction but showed a net northward flow during the 6-day study. Maximum concentrations decreased by about 200-fold per kilometer from the outfall to the northern end of the study area. The study shows that SF_6 is an effective method to trace point source releases far from their origin.

Introduction

The Florida Area Coastal Environment (FACE) program is an effort of state and federal agencies and water utilities to study the sources of nutrients and pollutants appearing in the coastal ocean of southeast Florida. To achieve FACE goals, it is necessary to determine the relative contributions of potential terrestrial and oceanic sources to the nutrients and pollutants at given coastal ocean locations. Among the several natural and anthropogenic sources of nutrients are ocean outfalls. In southeast Florida coastal waters, outfall discharges occur using piping systems that extend 3−6 km into the coastal ocean. The discharges are believed to be rapidly diluted with surrounding water. However, no direct observations of flow paths and dilution in the farfield, defined as the region beyond 400 m of the outfall, have been obtained to date.

The coastal regime in which the outfall terminus is located is strongly influenced by the Florida Current. Several studies have shown that numerous current features present at the outfall site are unique to this environment (*1, 2*). The ambient current conditions during the present study appeared to be a combination of Florida Current-related flows, such as eddies, and wind-dominated flows. Variations in the location of the Florida Current are common and were observed during the southeast Florida ocean outfall experiments conducted from 1986 to 1993 (*3*). Periodically, the outfalls discharge shoreward of the Florida Current. This study was performed under these conditions.

Initial dilutions, defined as dilutions that occur during the vertical rise of the positively buoyant discharge, from the terminus of the outfall pipe to the surface equal to 20:1 or greater were determined during the Southeast Florida ocean outfalls experiment (SEFLOE II) (*4*). Dilutions of approximately 100:1 were measured at a distance of 800 m from the outfalls (*5*). Little is known about the farfield dilutions and pathways of discharges into the ocean. Direct tracing of the farfield discharge has not been possible to date. As stated in the SEFLOE II report, "measurements of farfield dilutions are the most difficult field measurements to obtain" (*3*).

The present effort pioneers the application of sulfur hexafluoride (SF_6) for the determination of pathways and dilution at great distances from the source of discharge. By injection of SF_6 into the source water, it can be a clear marker of this discharge in the coastal ocean and provide reliable and attributable dilution estimates in the farfield. These farfield dilution estimates are of interest because of uncertainties in regard to the potential effects of low levels of pollutants. SF_6 is a good tracer to study point source releases as it has low background levels in the environment. It is nontoxic, stable, and measurable at low concentrations.

Fluorescent dyes, with their ease of injection, the ability to measure their concentrations in situ, high sampling frequency, reasonable short-term stability in natural water, and low toxicity at dilute concentrations, have been used extensively for this purpose and are approved by EPA protocols to quantify nearfield dilutions (*6*). For farfield studies, however, the limitations of dyes with respect to longterm stability and relatively high detection limits, which requires large dosages, become apparent (*7*). SF_6 can augment fluorescent dyes for farfield studies. However, there are some limitations in its use. It is poorly soluble in water (*8*) which makes injection of quantifiable amounts of SF_6 into the water difficult. The gas escapes from the water column at the air−water interface, ultimately limiting the extent and duration of surface water studies. Detection cannot be done in situ but, rather, the water must be brought onboard, and the gas must be extracted from the water sample onboard or at a shore-based laboratory prior to analysis.

The low detection limit of SF_6 of less than 40 fM (1 fM = 10^{-15} mol L^{-1}) using static headspace analysis or continuous gas strippers, and 2 orders of magnitude lower than this with trap and purge techniques (*9*), has made SF_6 tracer studies possible over large space scales and long time scales. In the outfall study described here, the outfall water was traced 66

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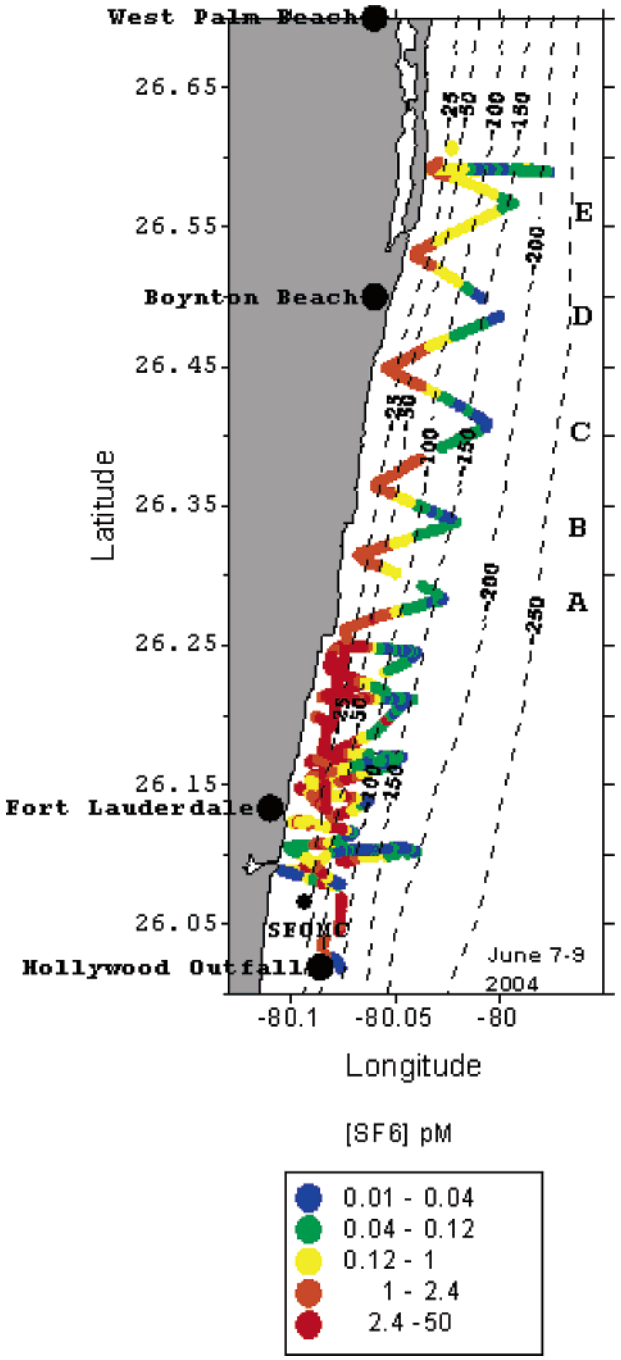

FIGURE 1. Ship track of the SF_6 survey on June 7−9, 2004. The concentration ranges are color-coded with concentrations expressed in picomolar (pM). The outfall terminus labeled as Hollywood Outfall is located at the southern end of the map. The bottom-mounted ADCP labeled as SFOMC is located about 5.5 km northwest of the outfall. The bathymetry is shown as dashed lines with contours at 25, 50, 100, 150, and 250 m. The letters on the right side of the panel show the locations of the shoreward transects referenced in the text.

km north of the release site (Figure 1) by performing a continuous injection of SF_6 over 6 days into the main discharge pipe. The continuous release was performed to create a quasi-stationary tracer field in the ocean. This type of release, along with successful detection of the tracer at 3 orders of magnitude above background concentrations 66 km from the source, makes this proof-of-concept study unique and clearly shows the potential utility of SF_6 for following point-source releases in the aquatic environment. This application adds to the utility of SF_6 previously used as a tracer of gas exchange processes in the ocean (*10*−*12*) and lakes (*13*−*15*); as a surface water dispersion tracer (*16*−*19*); as a tag for surface water in Lagrangian studies (*17*−*18*); and to determine mixing in the deep ocean (*20, 21*).

The present study provides pathways and dilution estimates of the predominant northward motion of the discharge. The movement of a discharge plume in the coastal ocean of southeast Florida is complex. The Gulf Stream in this region is called the Florida Current and flows northward along the coast. The western (shoreward) edge of the Florida Current meanders such that on some occasions the outfall site is directly beneath it and at other times the outfall site is effected by western boundary eddies and secondary current systems (*1, 5*). Particularly during the latter situations there is significant variability in magnitude and direction of current flow. Although not conclusive, the sampling suggests that during the time of the field measurements the major discharge pathway was generally along the coast. This work provides unique new information on the farfield dilution of a discharge plume in proximity to the coast of southeast Florida.

Experimental Section

Injection. SF_6 was injected into a 150-cm i.d. outfall pipe at a capped-off shunt. A $^1/_8$-in. o.d. stainless steel tube with a small stainless steel diffuser at its end was snaked through the 10-cm i.d. shunt into the main outfall pipe, and SF_6 was injected in gaseous form into the discharge stream at a rate of 0.5−1 L min^{-1} (STP). The dissolution process is inefficient because SF_6 is an insoluble gas with a solubility coefficient of 2.5×10^{-4} mol SF_6 L^{-1} water (at 25 °C). We expect that a portion of the SF_6 was dissolved during the injection process while the remainder of the gas was swept along above the flow and concentrated in various air pockets in the pipe. Some of the excess SF_6 gas was possibly released through static air release valves beyond the location where the SF_6 was injected.

The length of the pipe from the SF_6 injection point to outfall is about 3.5 km. The outfall is located about 3.2 km offshore at a water depth of about 27 m (*4*). The outfall terminus is located about 1 m from the bottom and has a single release point without dispersers. The injection of SF_6 began on June 4, 2004 (10 a.m. EDT) and ended on June 9, 2004 (3 p.m. EDT). The daily freshwater flow in the outfall ranged from 95×10^6 to 190×10^6 L day^{-1} with low flows in the early morning and maxima in the early evening. Under these conditions, the transit time of effluent in the pipe was 50−100 minutes before reaching the outfall terminus.

The SF_6 gas injection into the discharge was monitored with a ball flow meter. Quantitative SF_6 injection estimates were obtained from the change in weight of the liquefied SF_6 in the gas tanks over time. Two 17-L tanks that each contained about 18 kg of SF_6 were used. The first tank was used from June 4−6, 2004 with an average flow of 0.9 L min^{-1}. The flow was higher than planned due to a bias in the ball flow meter probably caused by backpressure in the injection line and diffuser. The first tank was replaced by a second tank 18 h before the survey, resulting in a 3-minute interruption in flow. The SF_6 flow from the second tank was decreased to 0.5 L min^{-1}. During the June 7−9, 2004 survey period, the SF_6 flow was steady at the lower rate. SF_6 concentrations were not monitored in the pipe or right at the outfall, as the concentrations were too high to measure with the available analytical equipment without jeopardizing the lower concentration measurements in the farfield.

Sampling. The sampling survey of the coastal ocean waters began on June 7, 2004 at 11 a.m. EDT and ended on June 9, 2004 at 11 a.m. EDT. Sampling was performed in a continuous mode using a towed "fish" containing a Seabird MicroCat

CT (conductivity−temperature) sensor and a submersible water pump. The submersible pump pushed water into a second pump on the deck of the 24-m-long research ship R/V *Coral Reef II* to provide sufficient inlet pressure for the permeable membrane extractor (PME) used to extract the SF_6 from the water. About half of the water was diverted and drained before reaching the PME to decrease the residence time of water in the tubing. The internal volume of the 40-m-long 1.25-cm o.d. nylon tubing was about 5 L, and the flow through the PME averaged 2.1 L min^{-1}.

During survey operations, the "fish" was towed at approximately 2-m depth over the starboard side of the ship. Ship speed during surveying was about 3 knots. The survey track shown in Figure 1 started near the outfall. After an irregular course within 17 km of the outfall terminus, the track proceeded in a systematic zigzag pattern northward, crossing the eastern (seaward) boundary of the tracer patch before returning shoreward. The distance between sample points was about 250 m based on a sample throughput of 20 samples per hour at the survey speed of 3 knots.

On three occasions the ship dropped anchor and the tow fish was lowered to the bottom to obtain vertical profiles of SF_6 in the water column. The water depths at the stations were 12, 20, and 20 m at a range of 13 km, 17 km, and 66 km, respectively. The vertical sampling was performed by lowering the "fish" to mid-depth and then to the bottom. After remaining at the bottom for 0.5 h or more, it was raised to mid-depth and back to the surface. The mid-depth location was sampled for at least 15 min at the 13- and 17-km sites to ensure full flushing of the lines.

Analysis. SF_6 was analyzed by extracting it from seawater with a stream of nitrogen using a PME cartridge (Celgard LiquiCel). The SF_6 in the nitrogen stream was then analyzed with a gas chromatograph equipped with an electron capture detector (ECD). The analytical instrumentation and procedures are described in Wanninkhof et al. (*9*), and the application of a LiquiCel for SF_6 analyses is detailed in Ho et al. (*19*) and Caplow et al. (*16*). In short, water pumped from the towed "fish" was first passed through a 40-μm filter and then through the PME. The PME consisted of a bundle of gas permeable microtubes (lumen). SF_6 in the water stream diffused through the walls of these tubes into a nitrogen stream that was diverted to a 1.5-mL sample loop. The loop was injected into a gas chromatograph at 3-minute intervals, after which the gases were swept onto a 1.5-m, $^1/_8$-in. o.d. molecular sieve 5A column. The SF_6 was separated on the column from oxygen and other gases and measured with the ECD.

A linear calibration of the detector response was performed with two SF_6 standards with concentrations of 55.1 parts per trillion by volume (pptv) and 1109 pptv using the gas sample loop. Thirty of each standard were analyzed during the survey with standard deviation of the SF_6 standards being less than 1%, indicating that the ECD response was stable during the study. The gas transfer efficiency of the PME was quantified on the first day of the survey by sampling aliquots of water before and after the LiquiCel and analyzing their SF_6 content. The efficiency of extraction was calculated to be 50%, and results were corrected by this factor. Pump failure prevented a redetermination of the efficiency at the end of the study, but previous work has shown minimal changes (<5%) in extraction efficiency over several days (*22*).

The range of SF_6 encountered during the June 7−9 survey was 13 fM to about 90 pM (1 pM = 10^{-12} mol L^{-1}). The aqueous SF_6 concentrations, SF_{6aq}, below 8 pM were precise to within 5%. The precision of the SF_{6aq} measurements between 8 and 24 pM determined with the automated system was believed to be within 30%. The greater uncertainty was caused by a lack of calibration gases in this range. The response of the detector was off-scale for SF_{6aq} greater than 25 pM using the PME, and none of the SF_{6aq} measurements made with the PME greater than 25 pM were used in the calculations. All of the observations beyond 27 km from the outfall were below 8 pM. Concentrations up to 550 pM were measured in spot samples near the outfall terminus on June 6, the day before the survey began (Figure 2). These samples were diluted with SF_6-free water to bring the concentration into range of the standards. They were measured by headspace analysis in a glass syringe. The precision of these samples, accounting for uncertainty in dilutions, was within 10%.

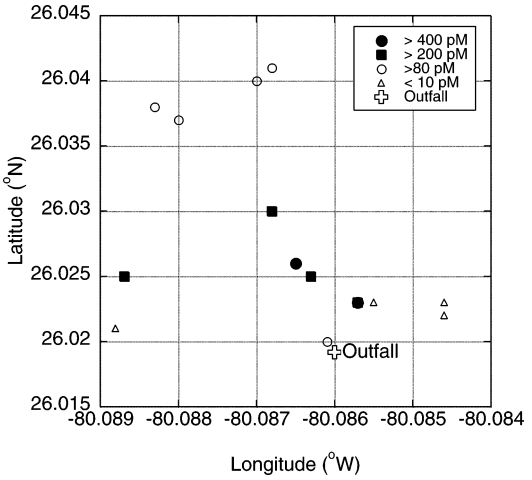

FIGURE 2. Sampling locations and concentrations for the samples taken during the pre-survey near the outfall terminus on June 6, 2004. Concentration ranges (in pM) are marked with different symbols as indicated in the legend. The grid boxes are approximately 100-m wide (longitude) and 550-m long (latitude).

Currents. Two sources of current information were available for this study. An acoustic Doppler current profiler (ADCP) mounted in 11-m water depth at the South Florida Ocean Measurement Center (SFOMC) at Dania Beach, FL (26.075°N, 80.094°W), 1.6 km offshore and 5.5 km from the outfall terminus, provided a continuous record of near-shore currents near the bottom, at mid-depth, and near the surface shoreward of the release site. Current and temperature measurements were also obtained from dropsondes at 27°N, 79.93°W, about 12 km from the coast and 30 km beyond the northernmost point of the survey area, on June 7 and June 9, 2004.

Results

The continuous injection of SF_6 into the outfall pipe was performed to facilitate tracking of the farfield SF_6 levels by creating an environment of elevated SF_6 concentrations along the flow path of the plume. A few spot samples were taken near the outfall on June 6, the day before the survey began, with the locations of the sampling shown in Figure 2. The maximum observed concentration near the outfall was 550 pM a day after the injection commenced. The survey tracks close to the outfall are shown in Figure 3 with concentration levels coded by different symbols. The measurements within the first 20 km of the outfall showed large variability in concentrations on a sub-kilometer scale and a poorly defined tracer field. The variable concentrations near the outfall terminus shown in Figures 2 and 3 suggest predominantly advective transport after the initial dilutions and variability in discharge concentration. The tracer appears to advect from the outfall in filaments and/or as boluses but full determination of pathways of the discharge immediately after nearfield dilution requires further study.

The tracer field between 27 and 66 km from the outfall terminus is more coherent. The concentrations increased systematically going shoreward, and the highest concentra-

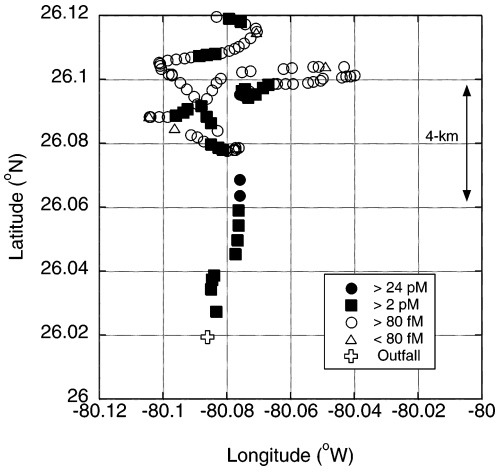

FIGURE 3. Concentrations of SF_6 in the region near the outfall measured at the start of the survey. Concentration ranges (in pM and fM) are marked with different symbols as indicated in the legend. The grid boxes are approximately 2 km × 2.2 km.

tions were measured near shore (Figure 1), sometimes increasing to the point that the ship turned seaward to avoid shallow depths and other navigation hazards. Concentrations decreased northward. SF_6 concentrations along the entire cruise track are provided in Figure 1 using a color-coding scheme for different concentration ranges.

One objective of the study was to determine at what point the discharge was mixed vertically in the water column and reached the bottom to assess its possible effect on the benthos. Since the outfall discharge is positively buoyant, it will rise to the surface at the terminus and form a seawater−effluent surface layer about one-third of the water depth (*3*). It is transported as a near surface plume until the density contrast is eroded by dilution with surrounding water. Three depth profiles of SF_6 measured nominally at 13, 17, and 66 km from the terminus in the projected centerline of the plume were taken to determine the vertical distribution of the tracer plume. High levels of SF_6 were observed to the bottom at each location sampled, indicating that vertical mixing of the discharged waters with surrounding waters occurred within 13 km of the outfall (Figure 4).

During sampling at the 17-km location, a 4-fold concentration increase was observed while the intake was at mid-depth. The surface samples showed an 8-fold increase when the "fish" was raised back to the surface as compared to the start of the depth sampling. This is another indication of significant meandering of the tagged water with time. Alternatively, this could be caused by the pulsating nature of the discharge and transport in boluses. The study of the actual causes of variability and characterization of the buoyant spreading and vertical diffusion of the plume close to the outfall were beyond the scope of the study.

A contour plot of surface water SF_6 concentrations is shown in Figure 5. A kriging interpolation scheme with a 5:1 aspect ratio in search radius oriented to the north was used. These plots clearly show the narrow swath where SF_6 was detected. The slight oscillating pattern at the offshore boundary was caused by a memory effect of the sampling equipment. When the ship left the patch, SF_6 concentrations decreased more slowly than when the ship re-entered the patch. This condition was likely caused by a combination of incomplete flushing of the tubing and SF_6 adsorption/desorption processes in the tubing and instrumentation.

Cross-sectional surface concentration profiles plotted versus longitude are shown in Figure 6 for the shore-bound legs. The outbound transects (not shown) show higher concentrations and more gradual decreases offshore due to

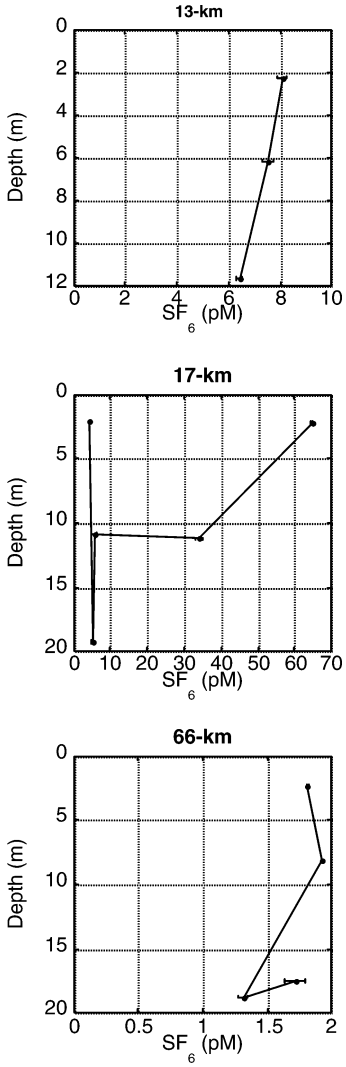

FIGURE 4. SF_6 concentrations (in pM) at the surface, mid-depth, and bottom measured at 13, 17, and 66 km from the outfall. Every point is an average of at least three samples with error bars indicated. When no error bar is apparent, the standard deviation is less than the size of the symbol. At the 17-km sampling site, a large concentration increase was observed at mid-depth and the surface while sampling during the upcast.

memory effects of the sampling equipment. The inbound transects were used to estimate the total mass of SF_6 transported along the coast.

The near-shore ADCP current record, obtained from the bottom-mounted ADCP, is shown in Figure 7. In general, there is alongshore northward flow during the injection punctuated by an occasional southward reversal. The record provides a qualitative explanation of the observed variability in tracer concentration near the outfalll. At the start of the injection, flow was predominantly northward but with variability of a factor of 4 in flow over the first day. Such variability was observed throughout the study with reversals from northward to southward flow occurring on a frequency of 1−2 days. The east−west component of the record showed an average westward (= shoreward) flow but with rapid changes in magnitude and direction. The pattern is caused by a complex interplay of tidal motions, wind drift, and interactions of the near-shore boundary currents with the Florida Current (*1*). In particular, some of the translations can be attributed to eddies passing through the study area. The combination of the variable discharge and the near-shore current variability are the likely causes of the observed

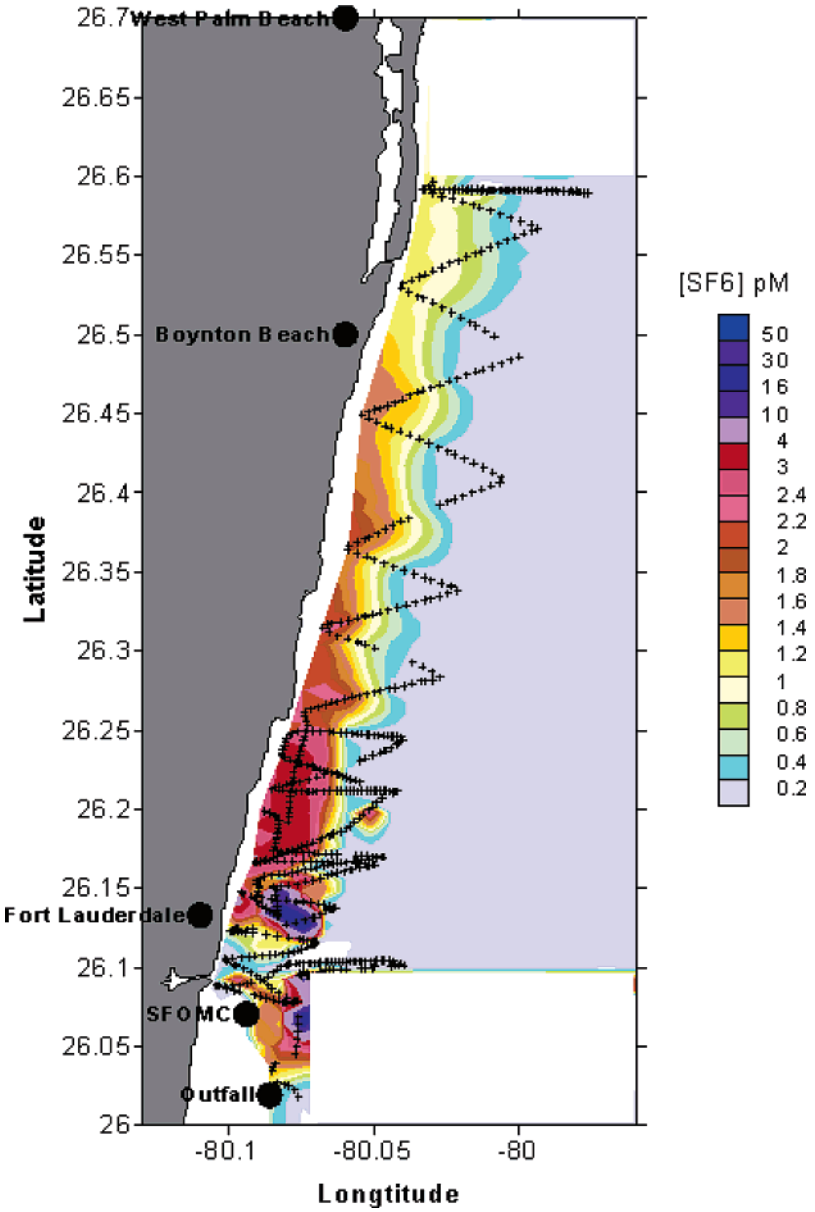

FIGURE 5. Contour plot of SF_6 concentrations encountered during the survey on June 7−9, 2004. The sampling locations along the cruise track are indicated by the + symbols. Concentrations are listed in pM.

concentration variability within the first 20-km from the outfall. On longer time and space scales the current fluctuations facilitate mixing of the plume.

The currents were also variable during the survey with a strong flow reversal to southward flow during the first day of the survey and smaller reversals thereafter. The average flow from the ADCP record at 1.5 km from shore was about 20 cm s^{-1}. The flow offshore was higher with dropsonde profiles 12-km from shore showing currents of 80 cm s^{-1} for the mean water column and 200 cm s^{-1} at the surface. While there was significant variability in vertical flow as determined from the 16 vertical bins of the ADCP, there was no systematic shear in the water column over time. The standard deviation of the flow in the 16 depth bins is on the same order of magnitude as the mean flow in the water column. Despite considerable variation in horizontal and vertical flow, the SF_6 concentrations observed beyond 27 km from the terminus vary systematically. This suggests that far away from the outfall the current variability can be considered a stochastic mixing mechanism that homogenizes the tracer field.

For the water column SF_6 integrals, the cross sectional areas perpendicular to the coast were determined along with the SF_6 concentrations along the transect. The surveys stopped about 0.5−0.8 km from the beach, and the concentration data were extrapolated to the shoreline assuming the same concentration as the last measured point. This assumption is based on the flattening of the cross sectional profiles for most of the transects (Figure 6). It was assumed that SF_6 concentrations were homogeneous to the bottom, or to the bottom of the mixed layer at 25 m, whichever was shallower. Gridded bottom topography and shoreline data were obtained from NOAA's National Geophysical Data Center. The estimated mass flow of SF_6 for each transect is given in Table 1. The cross sectional SF_6 mass integrals at four positions gave similar values ranging from 4.4 to 5.1 mol day^{-1}. The cause of the smaller integral of 2.8 mol day^{-1} for section D is unclear. The similarity of mass flow for the other transects suggest that no significant SF_6 losses occurred by advective features such as eddies or jets along the flow path.

Since SF_6 is a gas, it escapes into the atmosphere through the air-sea gas transfer. A rough estimate of the loss of SF_6 was obtained using an average current speed of 50 cm s^{-1}, a mixed layer depth of 25 m, and a wind speed of 6 m s^{-1} based on wind speed records from NOAA's National Data

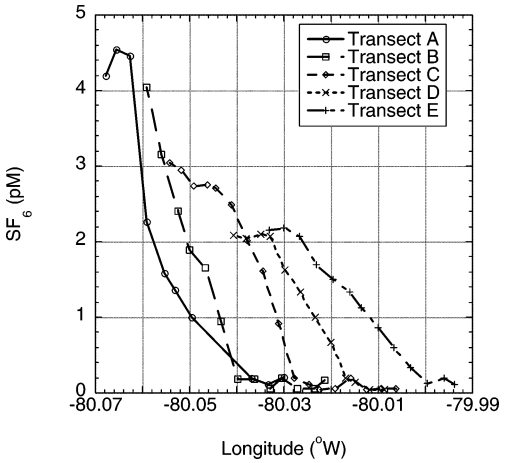

FIGURE 6. Surface SF_6 concentrations (in pM) for the shorebound legs of the survey. The locations of these transects are shown in Figure 1.

Buoy Center weather station LKWF1 located on an ocean pier in the town of Lake Worth, FL, just north of our study area. A quadratic relationship between the gas transfer and wind speed, $k = 0.31\ U^2\ (\mathrm{Sc}/660)^{-1/2}$, was used to estimate the gas loss, where U is the wind speed and Sc is the Schmidt number of SF_6 of 650 at 28 °C (*23*). The SF_6 concentrations would be expected to decrease by about 2.5% per 10 km due to gas exchange based on this parametrization or about 16% from the outfall terminus to the end of the observation area 66 km to the north. Using lower/higher current speeds or shallower/deeper mixed layer depths would make the SF_6 loss over distance due to air−sea gas exchange proportionally greater/less.

Discussion

Due to the exploratory nature of this study, not all relevant physical parameters were measured to fully characterize the discharge plume. The results are, therefore, semiquantitative at best. Nonetheless, the work provides important information of the flow path and farfield dilution of a point source discharge. While the discussion is cast in a framework of a quasi-steady-state tracer field, based on the systematic decrease of the SF_6 concentrations north of 27 km from the release point, the flow reversals in Figure 7 are indicative of near-shore eddies and other modes of flow variability. A possible scenario for the observed uniformity of concentrations is that the survey proceeded in the same direction as the flow at about one-third the speed as the inferred flow. Therefore it is possible that, for instance, a northward-translating eddy containing SF_6 was sampled over and over again, rather than that the tracer field was homogeneous. While this alternative would cast our results in a different light, the pathway of transport and dilution estimates are valid under either scenario.

The discharge plume rises to the ocean surface upon exiting the outfall pipe terminus at 26-m depth and occupies the upper few meters of the oceanic water column (*3*). Data shown in Figures 2 and 3 suggest that the discharge plume material was transported in a meandering but generally northerly direction from the outfall site. Samples were not gathered south of the outfall, nor were transects made in a direction perpendicular to the northerly plume sampling track for the first 6 km. No vertical casts were made near the outfall because of the high and variable concentrations encountered making sampling problematic.

Tracks with east−west lengths of approximately 7 km were carried out at the general latitude of Port Everglades Inlet (26.092°N). Peak SF_6 concentrations were observed approximately 3 km from the entrance to Port Everglades Inlet and about 1 km west of the ocean outfall site. Decreasing SF_6 concentrations were measured irrespective of whether the sampling vessel proceeded shoreward or seaward from the peak value measurement location. North of Port Everglades Inlet, peak SF_6 concentrations occurred at distances closer to shore, typically less than 1.5 km. The motion of the diluting, tagged discharge plume was generally toward the coast under the meteorological and physical oceanographic regimes present during the study. The shoreward migration with distance from the outfall of the peak SF_6 concentration appears to be the result of wind-driven flow with winds from the southeast at 6 m s^{-1}. The flow field associated with Port Everglades Inlet may have also influenced the movement of the location of the SF_6 concentration peak and facilitated the homogenization of the SF_6 field. Since very long range tracer

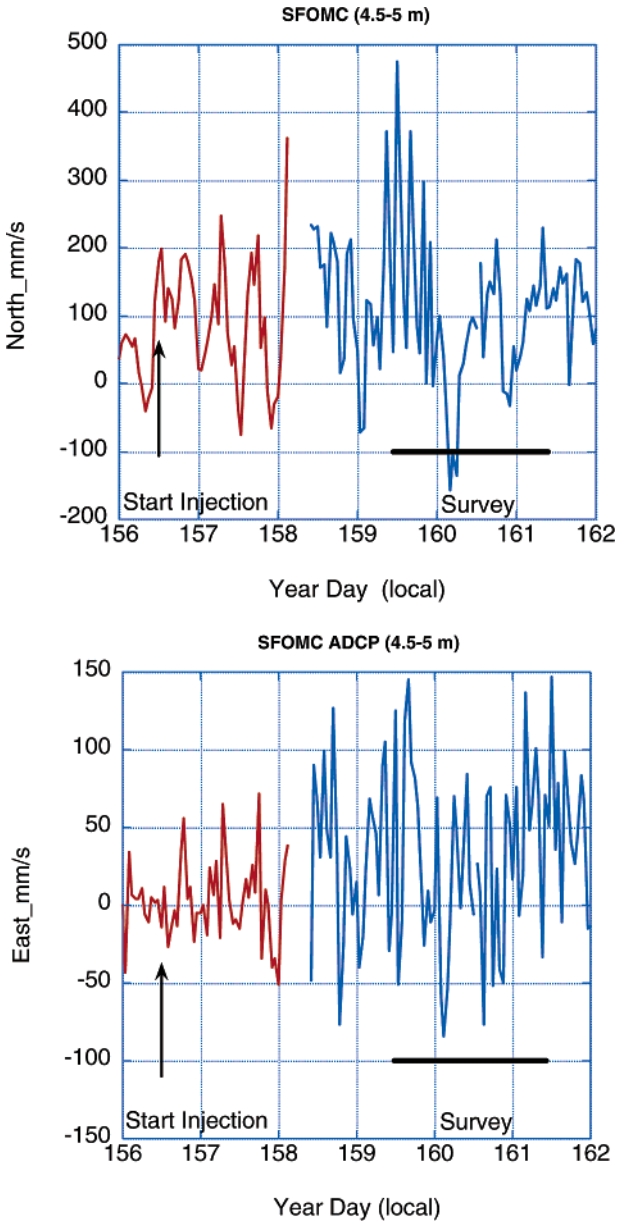

FIGURE 7. ADCP velocity records at about 4.5-m depth from the South Florida Ocean Measurement Center (SFOMC) located at the 11-m isobath 5.5 km north of the outfall (26.07°N, 80.09°W): (a) v-component (north−south); (b) u-component (east−west). The first part of the record (JD 156−158) shows 6-minute averages taken each hour; the second part shows hourly averages. Velocities are in mm s^{-1}. The start of the injection and survey period are marked.

TABLE 1. Cross Sectional Area Integral for SF_6 Cross-Sections and Width of Tracer Streak

transect[a]	distance from outfall[b] (km)	farthest sample from shore[c] (km)	nearest sample to shore[d] (km)	SF_6 integral[e] (mol day^{-1})	width streak[f] (km)
A	29	4.1	0.7	4.9	1.0
B	35	4.2	0.8	4.4	1.5
C	43	4.9	0.6	5.0	0.9
D	51	3.3	0.5	2.8	1.3
E	61	4.9	1.3	5.1	2.3

[a] Inbound legs of the survey from south to north with letters referring to the transects shown in Figure 1. [b] Distance of transect from the outfall. [c] Distance from the coast to where the outer edge of the tracer patch was encountered. [d] Nearest sample taken to shore. It is assumed that the concentration is constant from this point to the beach for calculation of the SF_6 inventory. [e] Cross sectional integration for the transect using the SF_6 concentrations measured (Figure 6) along the transect and using a bathymetry from www.ngdc.noaa.gov/mgg/bathymetry.relief.html. An average current velocity of 50 cm s^{-1} is used for these calculations. [f] Distance from peak concentrations to e^{-1} (37%) peak concentration.

studies have heretofore not been conducted in southeast Florida coastal ocean waters, mixing effects for discharge plumes, not previously recognized, may have been observed. On the basis of previous studies, the environmental conditions encountered during this study with northward coastal flow and southeasterly winds prevail about 40% of the time (*3*).

North of Port Everglades Inlet, the tracer field followed the coast. Peak concentrations were observed near the coast with a gradual decrease northward. The width of the tracer field generally increased with distance from the release point. Using the distance between peak concentration and a concentration of e^{-1} (= 37%) of peak levels as the characteristic width of the tracer streak, the width increases from 1.0 to 2.3 km between 29 and 61 km from the outfall. As shown in Table 1, the widths at intermediate points vary from 0.9 to 1.5 km in a nonsystematic fashion, suggesting undulations in the currents and/or variability in the tracer field. The shapes of the surface concentration curves for the five shoreward transects in Figure 6 show the general broadening and corresponding decrease in peak concentration with increasing distance.

Injection Efficiency and Dilutions. The injection efficiency of SF_6 into the outfall pipe was estimated by using the SF_6 mass flow along the coast (Table 1) and SF_6 injection rate into the pipe. The SF_6 injection rate into the outfall pipe in the latter part of the study of 0.5 L min^{-1} yields 29 mol of gaseous SF_6 bubbled into the discharge per day. For cross section B (Figure 1), the SF_6 area integral and flow of 50 cm s^{-1} translated into a mass flow of SF_6 through the section of about 4.4 mol SF_6 per day. This translates into an injection efficiency of 15%. There is a large and unquantifiable uncertainty associated with this estimate because of variations in coastal water flow. The injection efficiency is within the range of efficiencies for gaseous SF_6 injections in lake studies (*14, 24*).

Figure 8 gives the estimated minimum dilutions at increasing distance from the outfall. The estimates are based on the maximum concentrations encountered during the surveys. The estimates also assume SF_6 injection of 0.5 L min^{-1} with an efficiency of 15% into an average discharge flow of 140 $\times$ 10^6 L day^{-1}. This yields a calculated SF_6 concentration at the outfall terminus of 3.1 $\times$ 10^{-8} mol L^{-1}. The highest concentration measured in the ocean corresponds to a 60-fold dilution compared to the calculated value at the terminus, and concentrations decreased in a systematic pattern to a dilution of 14 000 at 66 km from the outfall. The

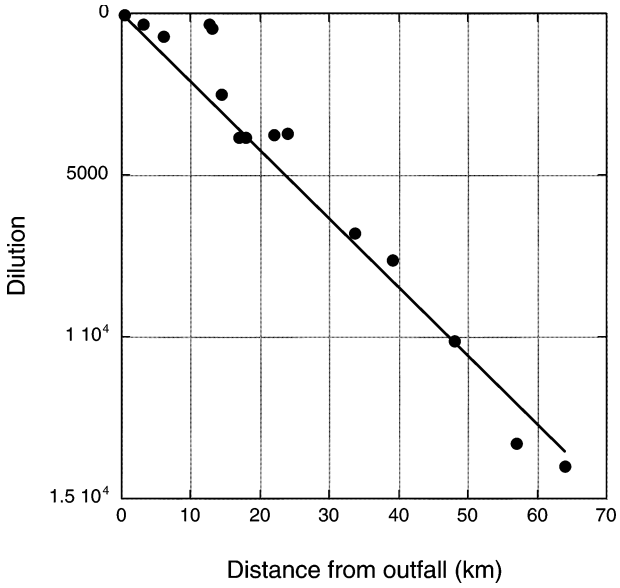

FIGURE 8. Dilution estimates based on maximum SF_6 concentrations measured at different distances downstream from the outfall. The line is a best-fit linear relationship forced through the origin excluding the points at 13 km.

absolute dilution values depend on the assumptions about the SF_6 concentrations at the outfall terminus, but the relative dilutions in the coastal waters are observation-based. The dilution can be well approximated as a linear trend with distance (Figure 8). Excluding the low dilutions at 13−14 km that coincidentally were encountered twice on surveys almost a day apart, the relation forced through zero at the outfall terminus yields:

$$\text{Dilution} = 212 \times \text{distance} \quad r^2 = 0.98 \qquad (1)$$

where distance is in kilometers. The uncertainty in the slope of the linear regression is ± 6 (≈3%). Including all points and not forcing the relationship through zero at the outfall increases the slope to 230 and the uncertainty in the slope to ± 11 (≈5%). The good fit to this relationship (Figure 8) suggests that the dilution occurs in a systematic fashion and can be well represented by a strong linear decrease with distance. Equation 1 will, of course, only be applicable for the conditions encountered but illustrates the rapid dilution with distance from the source.

The dilution equation determined in this study is in accord with SEFLOE II data (*3*) near the terminus that suggest that at a distance of 0.8 km from the outfall a dilution on the order of 100:1 is attained while eq 1 would suggest a dilution of 160:1. More importantly, this study indicates that dilution mechanisms, while complex, result in a linear decrease in SF_6 concentrations over the entire reach of the study, suggesting continued rapid dispersion of the discharge.

While the feasibility study fulfilled its objectives of tracing the discharge plume in the farfield, it lacked supporting measurements for full quantification of the observations. Future studies would benefit from better quantification of the amount of tracer injected into the effluent and denser spatial and temporal sampling. Continuous monitoring of SF_6 concentrations at the terminus would be desirable to determine the variability of the input levels. Ideally, an injection procedure could be devised that assured constant levels of tracer into the discharge. Continuous observations throughout the study region starting before and ending after the injection would help to estimate the flushing rate. This would be particularly useful for estimating the effect of catastrophic releases of undesirable compounds. More

current information would be desirable as well from a combination of fixed observations in the study region and from deployment of drifters. This study has provided important groundwork and background information to successfully execute a more quantitative study of the fate of a multitude of continuous point source discharge releases in the coastal environment of southeast Florida.

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