Pure appl. geophys. 162 (2005) 2005–2028
0033–4553/05/102005–24
DOI 10.1007/s00024-005-2702-y

Pure and Applied Geophysics

Metropolitan-scale Transport and Dispersion from the New York World Trade Center Following September 11, 2001. Part II: An Application of the CALPUFF Plume Model

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Abstract—Following the collapse of the New York World Trade Center (WTC) towers on September 11, 2001, Local, State, and Federal agencies initiated numerous air monitoring activities to better understand the ongoing impacts of emissions from the disaster. The collapse of the World Trade Center towers and associated fires that lasted for several weeks resulted at times in a noticeable plume of material that was dispersed around the Metropolitan New York City (NYC) area. In general, the plume was only noticeable for a short period of time following September 11, and only apparent close to the World Trade Center site. A study of the estimated pathway which the plume of WTC material would likely follow was completed to support the United States Environmental Protection Agency's 2002 initial exposure assessments. In this study, the WTC emissions were simulated using the CALMET-CALPUFF model in order to examine the general spatial and temporal dispersion patterns over NYC. This paper presents the results of the CALPUFF plume model in terms of plume dilution and location, since the exact source strength remains unknown. Independent observations of $PM_{2.5}$ are used to support the general dispersion features calculated by the model. Results indicate that the simulated plume matched well with an abnormal increase (600–1000% of normal) in $PM_{2.5}$ two nights after the WTC collapse as the plume rotated north to southeast, towards parts of NYC. Very little if any evidence of the plume signature was noted during a similar flow scenario a week after September 11. This leads to the conclusion that other than areas within a few kilometers from the WTC site, the $PM_{2.5}$ plume was not observable over NYC's background concentration after the first few days.

Key words: Dispersion modeling, CALPUFF, CALMET, plume modeling, sea breeze, particulate matter.

1. Introduction

In response to the events on September 11, 2001 at the New York World Trade Center (WTC), a study utilizing the CALMET-CALPUFF (Scire *et al.*, 2000) dispersion modeling system was conducted for the three-month period following the

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events. Prior efforts were already underway to use a similar modeling system for real-time support of local air pollution studies in the Raleigh-Durham area of North Carolina. After the events at the New York WTC, all efforts were redirected toward the WTC impact on the New York City (NYC) region. The results of the study as a whole were used to support the U.S. Environmental Protection Agency's (EPA) preliminary assessments of the WTC emissions impact on the surrounding New York City region.

The purpose of the research reported herein (Part II) is to examine the metropolitan-scale pathway and dilution of airborne emissions from the WTC recovery site after September 11. We examine the first few weeks after the attack using $PM_{2.5}$ observations and the air-dispersion simulation of the WTC plume. Additionally, longer temporal averages of the modeled plume are analyzed to elucidate areas that may have been influenced more regularly because of seasonal flow patterns.

Part I of the study presents an evaluation of the CALMET model results and a summary of the synoptic conditions during the study period. Part I highlighted biases and uncertainties in the meteorological fields derived by CALMET. CALMET has a bias to calculate stronger winds and greater mixing heights over land. Another bias that was observed in the CALMET model was a consistent clockwise wind direction downwind of Manhattan relative to observations. The biases in wind speed and daytime mixing height might lead to less actual plume dilution. There may also be a more northerly (inland) transport of WTC material because of the wind direction bias. The paper also indicated that CALMET tended to poorly define the properties of the sea-breeze circulation, specifically the rapid wind shift along the front and thermal stratification of the marine boundary layer.

More refined studies of the meteorology and plume pathways of the WTC plume are ongoing by several groups, including the US EPA, NC State University, and the Environmental and Occupational Sciences Institute of Rutgers University (EOHSI). The US EPA and EOHSI have an ongoing project to study potential human exposures within lower Manhattan by using models (Computational Fluid Dynamics and Wind Tunnel models) of the detailed flow about urban buildings and detailed environmental concentrations observed near the WTC site. While these detailed refined modeling methods may be critical near the WTC site, application of a CALMET-CALPUFF type system may be useful for human exposure and epidemiological studies over the larger metropolitan region.

CALMET-CALPUFF was used in part because the system is openly available, widely used (GODFREY, 1998; HONAGANAHALLI *et al.*, 2000; LEVY, *et al.*, 2002; BARNA and GIMSON, 2002; ZHOU *et al.*, 2003), and has performed well compared to similar models (U.S. EPA, 1998) and observations (IRWIN *et al.*, 1996, 1998). It is believed the system is adequate to support this application to generally characterize the temporal and spatial area of impact by potential emissions from the collapse of the World Trade Center and associated fires. The model was reviewed (ALLWINE *et al.*, 1998) and recommended by the U.S. EPA, Appendix A of the Guideline on Air Quality by the U.S. EPA (U.S. EPA, 2004), in both near- and long-range transport applications.

2. Methology

2.1. CALPUFF

A CALMET-CALPUFF model domain was designed to cover the central portion of the New York City (NYC) metropolitan area. The domain encompasses a 50×50 km area centered over lower Manhattan which has a horizontal grid spacing of 500 m. Figure 1 shows the area covered by the model domain along with

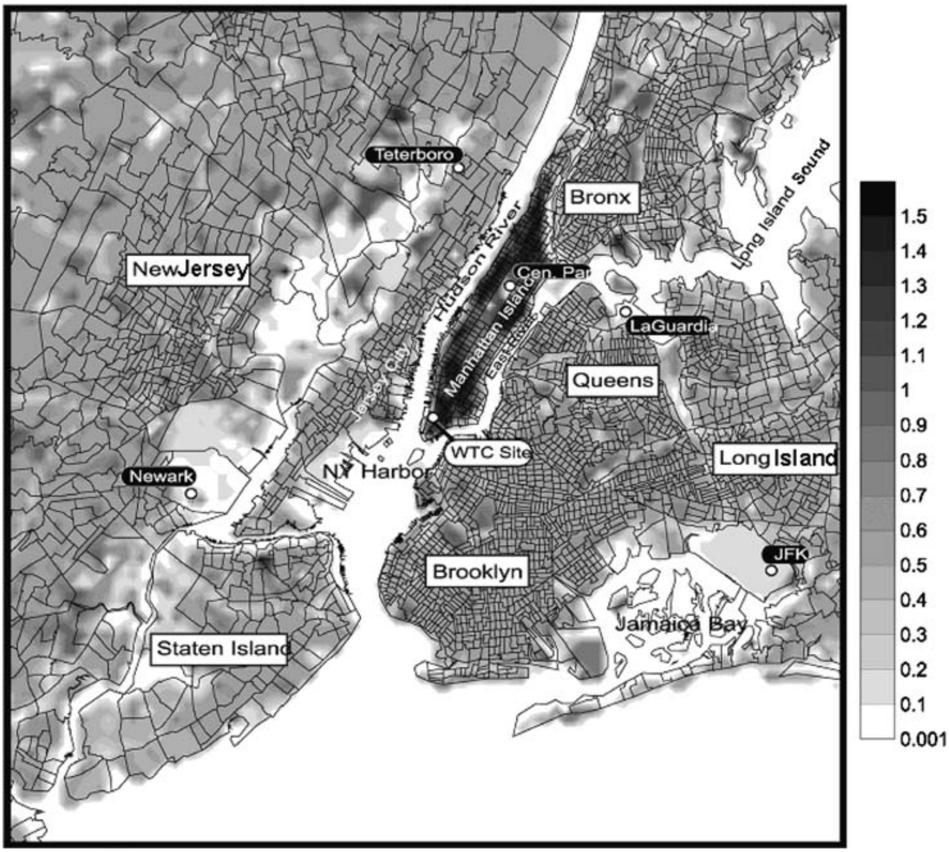


Figure 1
Plan view of the CALMET-CALPUFF model domain. Gray shading represents the parameterized surface roughness length (m). Meteorological observation sites are indicated by the black ovals. Other locations, which are used as reference points in the analysis, are labeled.

prominent Municipalities and bodies of water that will be used as reference points in the analysis. CALPUFF is a Lagrangian puff model that uses the hourly meteorological fields calculated by CALMET (refer to Part I of the study for CALMET configuration) to estimate the growth and transport of released puffs. Transport of the modeled material is governed by the wind diagnosed by CALMET, while the growth or diffusion is determined by turbulence-related boundary layer variables. These variables include the friction velocity (u^*), convective velocity scale (w^*), Monin-Obukhow length (L) and boundary layer height (h). CALPUFF also has algorithms that estimate processes such as dry deposition, wet deposition and various chemical transformations. CALPUFF includes methods to account for influences such as plume rise, stack/building downwash (not used), wind shear and plume penetration of the inversion layer.

Emission at the World Trade center recovery site was specified as a volume source with dimensions of 500 by 500 meters in the horizontal and 50 meters (V_s) in the vertical. The main rationale behind this configuration was to simulate a well-mixed initial volume source consistent with aerial photographs of the void left after the terrorist attack. The hourly emission rate (s_{1hr}) was set to 100 kg of $PM_{2.5}$ for model operational purposes only, since reliable estimates were not known. Hourly averaged ground-level concentrations (c_{1hr}) from the model simulation were normalized by the concentration of $PM_{2.5}$ within the assumed uniformly mixed volume source (8000 μg m^{-3}) to derive a dilution factor (d, see Equation 1). In the future, this dilution factor can be applied to estimate ground-level concentrations when the source emission rate is determined.

$$d = \frac{c_{1\mathrm{hr}}}{s_{1\mathrm{hr}}} * V_s. \tag{1}$$

In order to calculate the spatial variation of $PM_{2.5}$ dilution at the ground level, a set of gridded receptors was prescribed with a spatial resolution of 500 meters. The wet and dry deposition options were considered in the simulations. A sensitivity analysis indicated the deposition removed at most 1–2% of the simulated $PM_{2.5}$ thus this was considered to have a negligible effect on the simulated air concentration presented herein. The potential temperature profile provided by the Advanced Regional Prediction System, Data Assimilation System (ADAS) (ZHANG *et al.*, 1998), is taken into account when the vertical distribution of mass is calculated. Additionally, the wind variation with height is considered as a puff splitting algorithm was activated. The dispersion coefficients, which influence the simulated puff growth, were calculated using the micrometeorological variables from CALMET.

CALPUFF does have an option to model the material release as a slug or tight series of overlapping puffs. This formulation, in theory, yields a more exact near-source concentration distribution but requires significant computational time. Test examples showed little difference between the puff and slug options beyond a distance of a few kilometers. For this reason, the puff formulation was prescribed with an average puff release rate of one per minute. The spatial and temporal dependent dispersion coefficients were calculated, using the CALMET estimated scaling parameters u^*, w^*, L and h, based on similarity theory. All other parameters were assigned using the recommended defaults, including the deposition and scavenging rate for $PM_{2.5}$. For complete documentation on the model formulation refer to A Users Guide for the CALPUFF Dispersion Model (SCIRE *et al.*, 2000).

2.2. Advantages and Limitations

The NYC CALMET-CALPUFF modeling system has several known limitations that must be considered. Primarily, this approach is not able to resolve the near-source concentration distribution accurately in lower Manhattan. The 3-km area surrounding the World Trade Center site is an extremely non-homogeneous surface consequently similarity relations do not apply well. A complex urban canopy flow is the dominant factor in pollution dispersion within the city and can only be modeled explicitly with a suitable computational fluid dynamic model that can explicitly resolve the relevant turbulent processes. CALMET uses a surface roughness length to describe the surface of the urban canopy. This lower boundary parameterization does not apply well in this situation, as the plume height might be lower than the roughness elements in lower Manhattan. In spite of this, it is believed that the simulated concentration distribution further away from the source (i.e., beyond distances where the plume dimension is considerably larger than the building scale) can provide useful information.

An additional limitation is the relatively coarse time step (1-hour) in both model input and output. Over such a complex region, the time scale of significant variations in the boundary layer structure is in many circumstances considerably less than one hour. Additionally, the NWS ASOS surface observations used by CALMET are only representative of a brief period ($\sim$2 min) before the top of each hour. It was illustrated in Part I of this study that during certain synoptic flow regimes, changes in wind speed and direction can dramatically shift over time periods of less than 1 hour. Other drawbacks with regards to the meteorology are errors in handling certain mesoscale phenomena like sea-breeze fronts and urban heat island effects. Part I of the study also found that the near-surface wind speeds and mixing heights were overestimated by CALMET. These biases are likely to lead to an underestimation of the concentration by CALPUFF. CALMET also tended to poorly define the properties of the sea-breeze circulation, namely the rapid wind shift and thermal stratification.

Advantages of a CALMET-CALPUFF type modeling system are that a complete simulation over a seasonal period may be completed in less than twelve hours using a standard PC. The long study periods that are feasible with this type of model allow for a large pool of modeled concentrations which can be used to derive statistically significant results. This procedure provides a decisive advantage over the application of a model with full physics, which for many applications are only practical for short simulations. Additionally, by incorporating ADAS model analysis profiles in CALMET rather than 12-hourly soundings, we gain better temporal resolution of the meteorology as indicated by LEVY *et al*., (2002). Also, many other types of observations are injected via the assimilated data (i.e., Doppler radar, satellite and aircraft observations).

3. Results

A series of CALPUFF plume plots is used in the following WTC $PM_{2.5}$ dispersion analysis. As highlighted in the methodology section, the absolute concentrations are not examined, but rather a normalized concentration in the form of a dilution factor which is defined as the plume concentration at any location divided by the concentration of the well-mixed volume source. The plume dilution shading is partitioned quasi-logarithmically with a separate color for each of the following dilution amounts: 10^2, 500, 10^3, 10^4, 10^5 and 10^6. $PM_{2.5}$ observations (New York State Department of Environmental Conservation and New Jersey Department of Environmental Protection) are compared with the simulated plume dilution to ascertain if abnormally high $PM_{2.5}$ is correlated in space and time with the simulated location of the plume. There were a total of 17 permanent sites that were operational on September 11, 2001 and 5 sites that were deployed several weeks after the event. Figure 2 displays the locations of each site. The dense arrays of sites in lower Manhattan, with the exception of *ps64* that was already operational, were deployed in response to September 11. Figure 3 presents the measured concentration averaged over the September 11 through December 8, 2001 period as a function of time of day. A separate average was calculated for the $PM_{2.5}$ sites in lower Manhattan. It is evident in Figure 3 that higher concentrations are measured in lower Manhattan at all times during the day. In both time series, the diurnal component of commuter traffic is the dominant mode. These mean concentrations over the entire study period will be used in the following analysis to sense if the concentrations observed during each case are abnormally high.

3.1. Average Wind Flow and Plume Dilution

Following the dramatic dust cloud generated by the building collapse, widespread fires of burning debris continued for a prolonged period, and a visible smoke plume was dispersed around the New York City area. The following figures provide summary information of the simulated WTC wind and dilution patterns for the three-week period following September 11th. This information is presented using a wind rose plot overlaid on the averaged plume dilution. Contours are plotted for the 10^2, 500, 10^3, 10^4, 10^5 and 10^6 dilution zones relative to the source at ground zero.

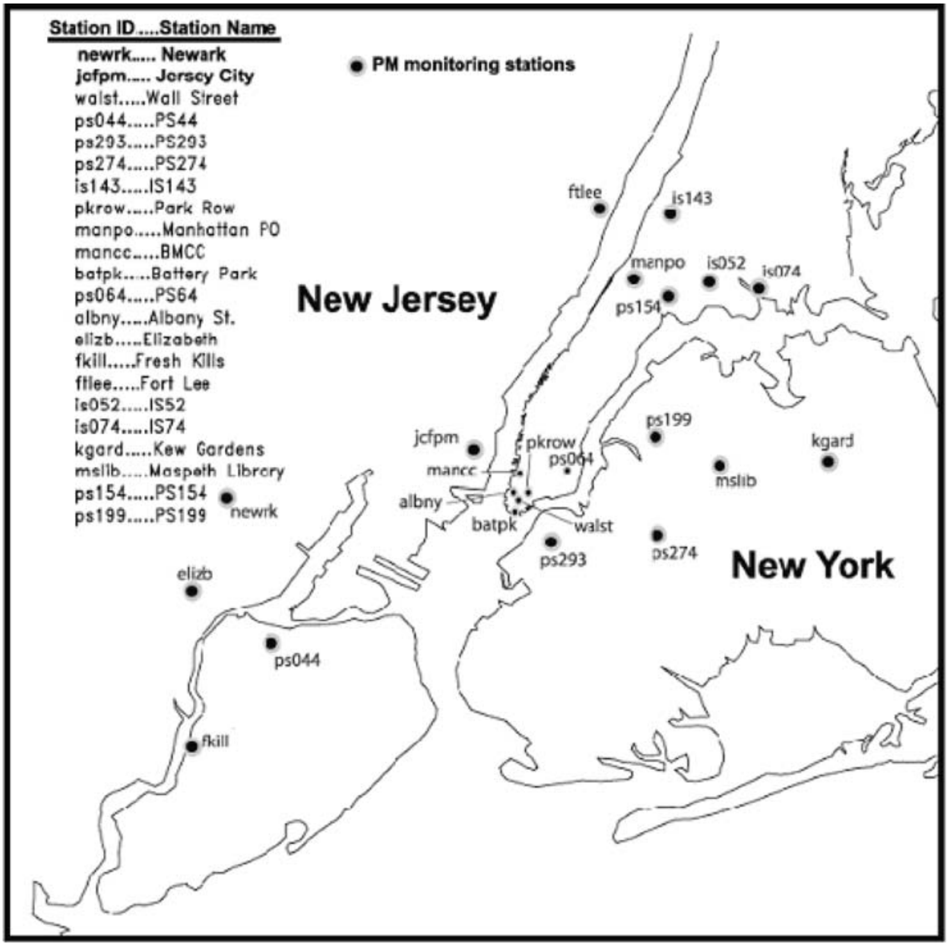


Figure 2
Map showing the name and location of $PM_{2.5}$ monitoring sites in the New York City area. The New York State Ambient Air Monitoring System and New Jersey Department of Environmental Protection manage most of the monitoring sites. Sites in lower Manhattan, marked with small dots (except *ps64*), are temporary monitoring stations deployed after September 11, 2001.

The wind rose shows the direction and speed distribution of hourly wind estimates at lower Manhattan from the CALMET simulation.

The simulated flow strength and direction distribution and average plume dilution for the period from September 11–13, 2001 is shown in Figure 4. During the initial 12–18 hours the wind was a moderate 4–6 m s^{-1} from a northerly direction as shown on the wind rose. Northwest to northeasterly wind was simulated for about 45 percent of this three-day period. Because of this flow direction, the WTC plume was directed over the far western tip of Long Island, specifically the Brooklyn borough of NYC. The CALPUFF simulation estimates that on average the particulate

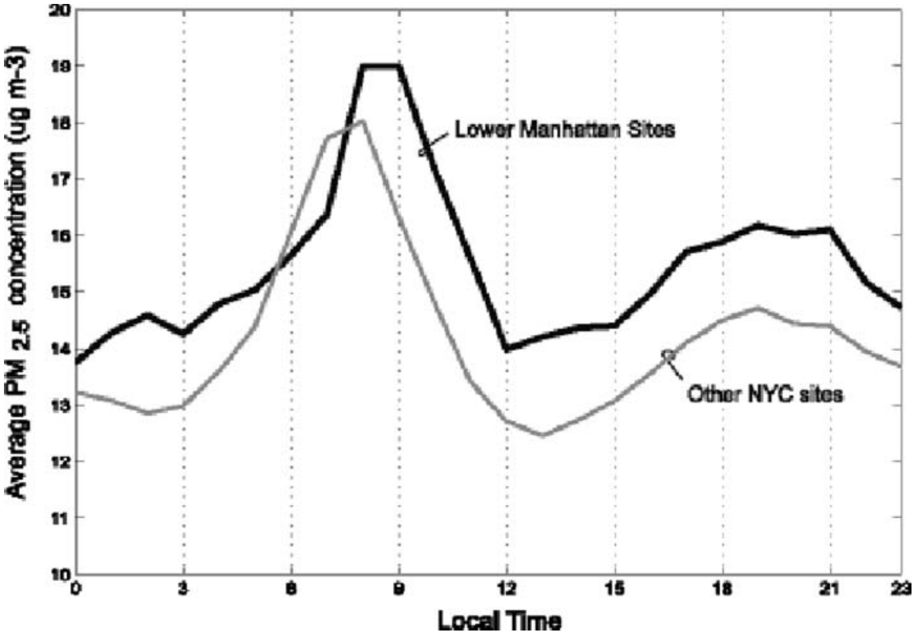


Figure 3
Average $PM_{2.5}$ ($\mu g\ m^{-3}$) concentrations from September 01, 2001 to January 31, 2002 as a function of time of day (LST). The average is partitioned between sites located in lower Manhattan and those farther away. Considered in the calculations are hourly averaged data from 25 combined monitoring stations managed by the New York State Ambient Air Monitoring System and New Jersey Department of Environmental Protection.

concentration from the WTC plume was diluted 1000 to 10000 times before it was advected over this region. The other preferred wind direction over this period was southwesterly, which accounts for more than 50 percent of the wind direction distribution. It is noticed that the winds were lighter on average from this direction (2–4 m s^{-1}). Lower wind speeds are normally linked to less dispersion and higher concentrations. This is seen in the average dilution pattern. Both the 1000 and 10000 dilution contours extend out further from the source as compared to the northerly flow regime. Also plotted are the average concentration measurements at all available $PM_{2.5}$ sites. Most values are in the 10–15 $\mu g\ m^{-3}$ range with the exception of *ps64* in lower Manhattan, which reported a three-day averaged concentration of 22 $\mu g\ m^{-3}$. The elevated $PM_{2.5}$ concentration at *ps64* is likely a result of the WTC plume being directed towards the northeast by southwest winds on September 12–13, 2001 as indicated by the CALPUFF simulation.

Several other periods in the weeks following September 11 were examined in a similar manner, although the figures are not shown. Here is a brief summary. During the September 14–16 period the dominant wind direction (~85%) for the period was from the north to northeast. As a result, the plume dilution pattern was biased to the

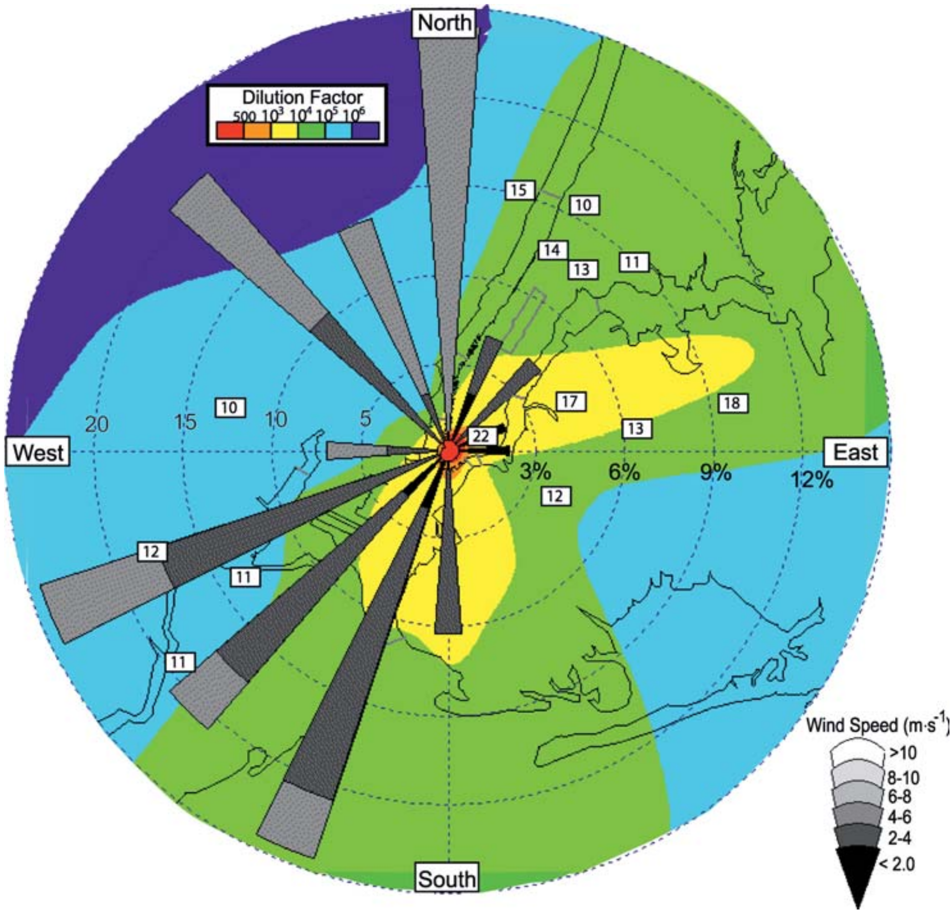


Figure 4
Wind rose of simulated wind at the grid point closest to the World Trade Center (September 11–13, 2001). Also, plotted in the background are the dilution contours of $PM_{2.5}$ from the CALPUFF simulation, averaged over the same period as the wind rose. The distance between concentric percentage rings is approximately 5 km as noted by the numbers left of the center. The plotted numbers (black outlined, white rectangles) represent the average observed $PM_{2.5}$ (μg m^{-3}) concentrations for the active monitoring stations.

southwest of lower Manhattan, specifically over New York Harbor and eastern Staten Island. The 1000-times dilution contour actually extended away from the source considerably farther than the previous three-day period. One factor that reduces the modeled dispersion is the lower mixing depth and increased stability over water. During the September 17–23, 2001 period, the principal wind component was southerly approximately 75% of the period, and generally less than 5 m s^{-1}. Over this time span, the diluted plume influenced the areas north and east of lower Manhattan. The flow direction during the third week after September 11 (September

24–30, 2001) was mostly west-southwest to westerly as well as a brief period of northeasterly winds. Consequently, the dilution contours indicate that the areas to the north and east of lower Manhattan are influenced by higher concentrations as compared to the areas to the west.

Overall, the preceding series of plots provide insight into the dispersion patterns over the New York City Metropolitan area during the most critical period, from an air quality standpoint, after the terrorist strikes on the WTC. Noticeable but diminishing fires and particulate emissions continued until mid-December. This study developed hourly estimates of the plume dilution factor for the period from September 11 through December 8. Figure 5 presents a similar plot as the previous, but for the entire three-month simulation period. More conspicuous in the long-term wind rose is the climatological signature of southwesterly to northwesterly winds. These flow regimes account for two-thirds of the simulated wind directions over this three-month period. Consequently, it is noticed that the average plume position over the three months is more biased towards the east and northeast of lower Manhattan. For example, the 10^4-dilution contour extends out nearly 17 km from the WTC to western Long Island and the Queens Borough. Another potential reason for the higher average concentration over this area is the marine boundary layer. This region is frequently affected by a stable marine layer which restricts horizontal and vertical dispersion. A similar effect is observed to the southwest of the WTC site where the 10^4-dilution pattern seems to follow the coastline of the New York Harbor. This is likely a direct consequence of the lower boundary layer height and limited diffusion of the plume over the water. Over inland New Jersey where the marine layer less frequently resides, the average dilution over the period is an order of magnitude greater. The lowest dilution contours very near the source are more concentric, although slightly biased to the northeast, which is consistent with the climatological wind direction preference.

Overall, it seems that a landuse influence lower on average mixing heights and dilution over the water bodies and a large-scale climatological influence (predominant southwest to northwest flow) can be discerned from the data. Average observed $PM_{2.5}$ concentrations from all available stations are plotted in Figure 5. Over the period, the average concentration at all sites is nearly identical, even sites located in lower Manhattan. This suggests that the longer-term observation records do not distinguish a signature of the WTC plume. Further evidence to support this thinking is presented in the following section through a more rigorous inspection of the data.

3.2. Case Studies

In the following, we present the results of the modeled WTC plume and observed $PM_{2.5}$ concentrations for three of the same cases presented in GILLIAM *et al.*, (2004). Each of the cases was a period highlighted by the US EPA where measured $PM_{2.5}$ concentrations were well above normal. The first case spans several days immediately after the WTC incident (September 11–12, 2001). The second case looks at another

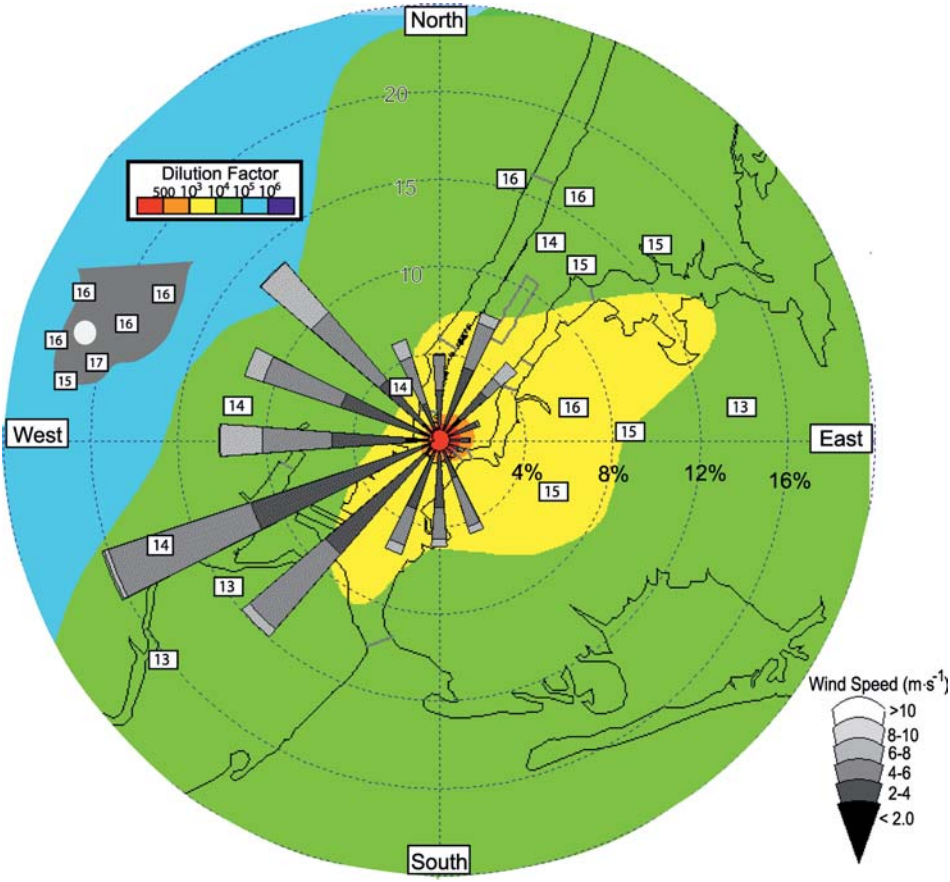


Figure 5
Wind rose of simulated wind at the grid point closest to the World Trade Center (September 11 to December 8, 2001). Also, plotted in the background are the dilution contours of $PM_{2.5}$ from the CALPUFF simulation, averaged over the same period as the wind rose. The distance between concentric percentage rings is approximately 5 km, as noted by the numbers left of the center. The plotted numbers (black outlined, white rectangles) represent the average observed $PM_{2.5}$ (μg m^{-3}) concentrations for the active monitoring stations.

similar flow event about one week after the disaster, September 17–18, 2001. The final case is another period (October 3–5, 2001) during which widespread concentrations measured around the city were abnormally high.

September 11–12, 2001 (Strong northwest to light southerly flow case)

Immediately after the WTC collapse, the emission of dust, smoke and toxic gases into the atmosphere was greatest. A surface high-pressure system was building into the area from the west on September 11. This resulted in moderate to strong northerly winds through the early morning of September 12. During the daytime hours of the 12th, high pressure settled over the region, at which point the winds decreased. High pressure remained in control through the following day (September 13). The northerly flow on September 11 was favorable for efficient mixing and rapid southerly transport of the airborne WTC debris away from the NYC area.

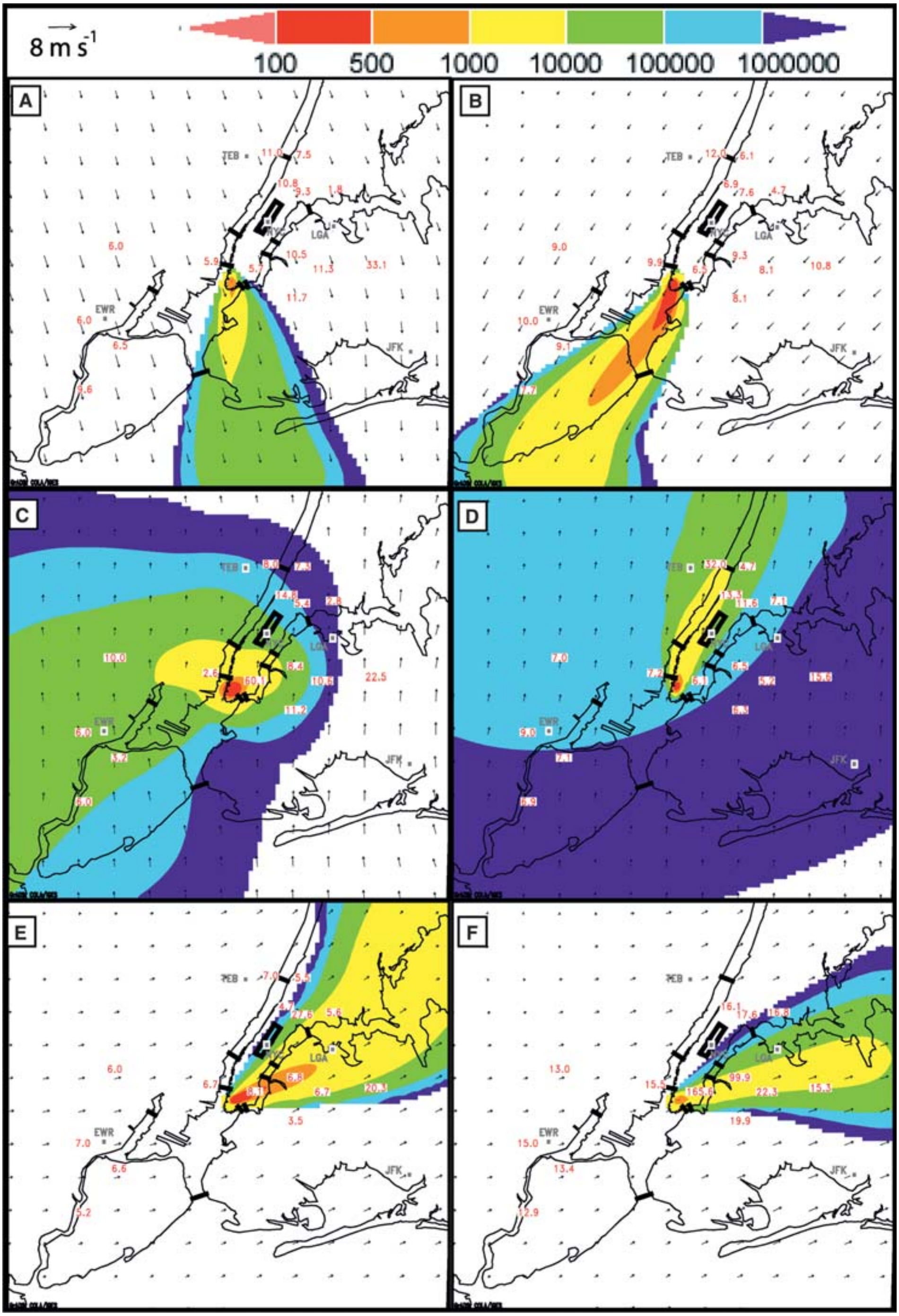
Shown in Figure 6a is the simulated plume dilution from the WTC volume source at 1100 LST on September 11. Also plotted are the $PM_{2.5}$ observations around the region. Figure 3 suggests that a typical concentration of $PM_{2.5}$ around the city at this time of day is 13–14 μg m^{-3}. The sampled concentrations indicate that $PM_{2.5}$ levels are well below the average for this time of day, as observed concentrations range from 50 to 75% of normal. Moderate northwest winds and the fact that a ''fresh'' air mass was being advected into the region from the northwest are likely reasons for the low pollution levels. The WTC plume spreads across the far western tip of Long Island with ground–level concentrations quickly dropping to 10^3–10^4 times less than that of the specified volume source, within 3 km downwind of the source. The modeled WTC plume is rapidly dispersed because CALMET mixing heights over western Long Island rise from 100–200 m in the early morning to 600–800 m by noon. Another noted characteristic is that the plume is not symmetrical about the centerline. The mixing height varied (not shown) substantially across the plume path, about 400 m over water to 800 m overland. This results in a broader eastward mixing of the plume while the west side remains more compact. None of the $PM_{2.5}$ sampling sites is in the path of the estimated plume, but aerial and satellite images agree well with the simulated CALPUFF plume position. Overall, the moderate wind, convective mixing and plume-path over water help to effectively transport airborne WTC material away from the recovery area.

On September 12, high pressure settled over the region and the winds lightened. In the morning at 0700 LST (Fig. 6b), observed concentrations across the area remained well below normal levels (normal: 16–17 μg m^{-3}) with most values below 75% of average. The simulated WTC plume is advecting material south and west of lower Manhattan over New York Harbor, towards Staten Island. Plume dilution is much less during this time with the 10^2 to 10^3 contours extending farther ($\sim$15 km) from lower Manhattan than the previous mid-day case. The mixing height calculated by CALMET was about 300–400 m over the plume path. The lower mixing height estimate is responsible for the compact, higher concentrated plume. Satellite images on this morning appear to be in good agreement with the plume position.

▶

Figure 6

Simulated CALPUFF dilution (100–10^6 dilution) of a volume source located at the World Trade Center recovery site. The plotted numbers indicate the hourly-averaged $PM_{2.5}$ (μg m^{-3}) concentrations for the active monitoring stations. Also shown is the estimated 10 m wind from the CALMET diagnostic model. Time periods shown are: (**A**) September 11, 2001 at 1100 LST, (**B**) September 12, 2001 at 0700 LST, (**C**) September 12, 2001 at 1500 LST, (**D**) September 12, 2001 at 1800 LST, (**E**) September 13, 2001 at 0100 LST, and (**F**) September 13, 2001 at 0900 LST.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During the afternoon (1500 LST, Fig. 6c) of the same day, a weak sea-breeze boundary developed and moved inland. As a result, the flow becomes southerly and the simulated WTC plume rotated clockwise, passing over areas of New Jersey and Manhattan. Figure 6c shows the simulated plume when the abrupt south to north shift occurred. CALPUFF estimates that the plume is diluted by no less than 10^3 times outside of lower Manhattan. The reason for this dilution, even though winds are light, is the deep convective boundary layer, estimated by CALMET to be in the 1300–1500 m range. The shift in wind transports material over a large portion of New Jersey. However, in this figure the observed concentrations do not reflect a measurable component of $PM_{2.5}$ that can be directly attributed to the WTC plume outside of lower Manhattan. The only available observation in lower Manhattan (*ps64*) does increase to 480% ($\sim$60 μg m^{-3}) of normal. The concentration of $PM_{2.5}$ at (*ps64*) in lower Manhattan jumped from below normal to well above the average in temporal agreement with the simulated plume's northward shift. This may imply that the simulated WTC plume shift is reasonable. Additionally, there is a satellite image showing a similar plume shift on this afternoon.

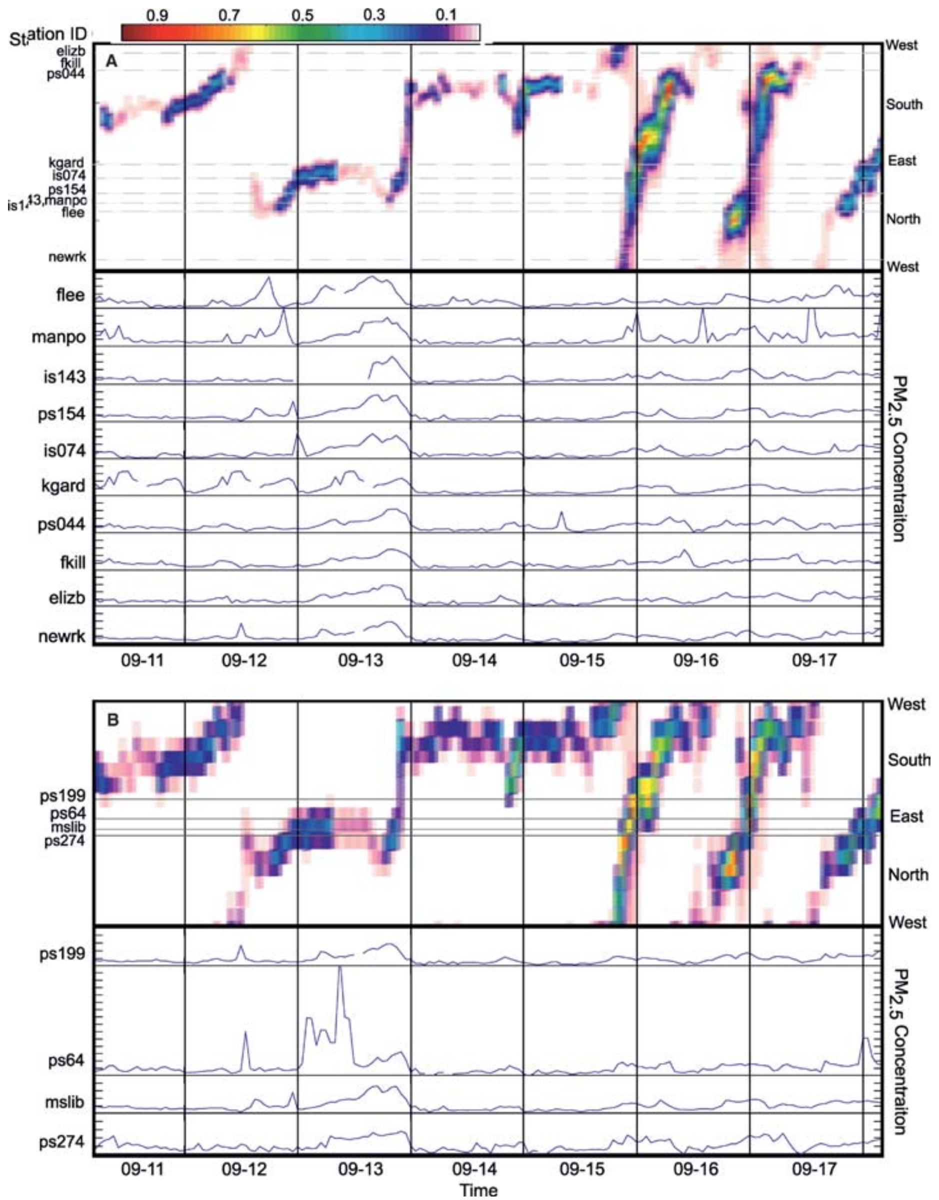
Several hours later, in the early evening (1800 LST), the simulated plume was directed up the Hudson River on the east side of Manhattan as shown in Figure 6d. Plume dilution was generally above 10^3 within a few kilometers of the source. The plotted $PM_{2.5}$ observations, with the exception of one, do not show a signature of the WTC plume as all values are below the normal level. The Fort Lee observation was actually 213% (32 μg m^{-3}) above the normal average measurement (normal: 15 μg m^{-3}) for this time of day. Subsequent times (0100 and 0900 LST, September 13, 2001) that evening and through the following morning the simulated WTC plume rotated from north to east (Figs. 6e and 6f). A pattern was noticed between the hourly-simulated plume position and the hourly observations. One to two hours after the simulated plume rotates and passes over the observation site, the measured concentration increases to 200–350% of the normal values while those to the west and east remain in the normal or below normal range. It is believed that the more stable conditions allow the plume to remain more concentrated over a greater distance, and therefore is easier to identify by the more distant $PM_{2.5}$ samplers. It is also noted that the simulated plume remains relatively more concentrated farther away from the source when the estimated mixing height and turbulence are low. This agrees with the observations indicating a general increase in $PM_{2.5}$ concentrations around the city.

The next morning (0900 LST on September 13, 2001), the WTC plume in Figure 6f is positioned towards the east-northeast of lower Manhattan. Observations indicate that most sites are reporting near-normal $PM_{2.5}$ values, except for the well-above normal concentrations along the simulated plume centerline, specifically the two observations (*ps64* and *ps199*) that are 600–1000% above normal (normal: 15–19 μg m^{-3}). This indicates that the plume position is well simulated by the dispersion model. The *ps199* observation, in fact, remained well above normal through the entire morning of September 13, 2001 while surrounding stations were at normal levels, in agreement with the simulated plume position. This is evidence that at least initially there was some signature of the WTC plume in the concentration measurements outside of lower Manhattan.

Another more detailed look at the time variation of the modeled CALPUFF plume and the $PM_{2.5}$ observations around the area is presented in Figures 7a and 7b. These figures provide a unique view of the spatial and temporal modeled WTC plume together with the observed $PM_{2.5}$ time series. The shaded values in the upper panel correspond to the plume concentration normalized by the maximum value over the period at a distance of 13 km surrounding the WTC site. The observation sites are noted on the y–axis corresponding to the angle from the WTC (direction from the site is noted on the right y-axis). Below the CALPUFF plume plot are the time series of $PM_{2.5}$ observations from all the stations that are approximately 13 km away from the WTC. Also designated are horizontal lines on the CALPUFF plume variation portion of the plot, which correspond to the direction of the observation station from the WTC site as labeled.

Of particular interest is the period from noon on September 12 through the following day. The CALPUFF plume as shown before and in Figure 7a is directed towards the south at the beginning of the day on September 12. Around mid-day, the shift to west and then north is noticed. Furthermore, the shift corresponds to a decrease in the simulated concentration during the day as the mixing depth increases. In the late day and evening hours of September 12 and early hours of September 13, the plume shifted from north to east-northeast. The observed concentrations indicate an abrupt increase in $PM_{2.5}$ over this exact time span. Additionally, the increase occurs first at Forth Lee (*tlee*), then Manhattan PO (*manpo*), then Public School 154 (*ps154*) and then at Independent School 74 (*is074*). Preceding this, the Newark airport observation actually indicates an increase that is correlated with the simulated WTC plume earlier in the day. However, later that week, from September 14–17, there is little evidence that the WTC plume was observed in the area except possibly at the Manhattan PO (*manpo*) station. There are several spikes in the reported concentration time-series that have some correlation to the simulated emissions from the WTC rubble. The most notable is midnight on September 16. The CALPUFF plume is directed towards the north towards the *manpo* site. However, none of the other stations in the vicinity indicates an increase in the $PM_{2.5}$ so it cannot be conclusively stated that this signature is related to the WTC plume.

A similar look at the simulated WTC plume and observations is provided in Figure 7b. The simulated plume plotted for a ring 3 km from the WTC and the observation time series are from stations in the 3–7 km range. The CALPUFF concentration is of similar variation to the previous figure. The reported observation time series show similar peaks, which correspond well with the simulation. The first peak noted in both the Public School 64 and 199 (*ps64* and *ps199*) time series occurred in the afternoon of September 12 as the sea breeze rotated the plume from



south to north. The second and more dramatic signature occurred the morning of September 13 when the *ps64* observation reported extremely high $PM_{2.5}$ levels over a span of 6–12 hours as discussed in prior results. The simulated plume is in agreement with this incident. The stations that were farther away like *mslib* and *ps274* did not indicate a defined signature; however, *ps199* does show a minor increase. In

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Figure 7
The upper portion of the figure panels is the patterns of the CALPUFF simulated World Trade Center (WTC) plume at a distance of 13 km (Panel A), and 3 km (Panel B) from the WTC site (September 11–17, 2001). The shaded values correspond to the simulated $PM_{2.5}$ normalized by the maximum value over the time series. The normalized concentration plume pattern is plotted with respect to the time and direction from the WTC as indicated by the right y-axis label. The stations are labeled on the left y-axis according to the direction from the WTC site (e.g., *flee* is approximately north of the WTC, *kgard* is east of the WTC site). The lower panels are the observed $PM_{2.5}$ ($\mu g\ m^{-3}$) time series for each of the monitoring sites. The station id is located on the y-axis of each time series. Each tick mark on the y-axis represents 10 $\mu g\ m^{-3}$ above a zero baseline.

agreement with the previous analysis, there is little indication that the WTC plume influenced the $PM_{2.5}$ observations after this initial period.

September 17–18, 2001 (light and variable flow case)

The next case occurred almost 1 week after the WTC collapse, during a synoptic pattern similar the September 11–13 case. High pressure was positioned over the area on September 17th and remained in control of the weather for several days. During this time the winds were light and variable so local effects dominated the flow patterns. Most noticeable is a diurnal rotation of the winds. During the day the wind turned southerly in response to an inland propagating sea breeze boundary, and then turned northerly at night in response to a weak land breeze. Starting at noon on September 17th, Figure 8a shows the simulated plume dilution/location. The plume is estimated to be diluted 10^3 over the harbor to 10^4 over land areas. The influence of a spatially variable mixing height is observed as the 10^3 contours follow the land-water interface where the mixing height and stability are drastically different. The mixing height over New York Harbor was in the 300–400 m range while increasing to 1200–1400 m over the adjacent landmass. The observed concentrations across the NYC area were all well below normal (normal: 13–14 $\mu g\ m^{-3}$) except at Fort Lee which was slightly above the normal levels. There is no apparent signature in the observations that the WTC plume is significantly increasing $PM_{2.5}$ observations in the surrounding areas.

Several hours later in the afternoon (1800 LST) the plume redirected northward as a sea-breeze front passed over the region. Figure 8b depicts the simulated plume in a similar position as the previous case. Mixing heights are lower in this case compared with the prior, thus the dilution of the plume decreases. CALMET estimated mixing heights across the plume path are in the 800 m (Hudson River) to 1100 m (over New Jersey) range. The 100–500 dilution contours extend up the east side of lower and midtown Manhattan, some 10–12 km away from the source. The 10^3 contour extends even further (20 km) from the source. As for the previous time period, the concentration observations do not show a noticeable signature of the WTC plume as values are mostly in the normal to slightly above normal range (normal: 15 $\mu g\ m^{-3}$). An exception is Fort Lee, which is about 200% of normal.

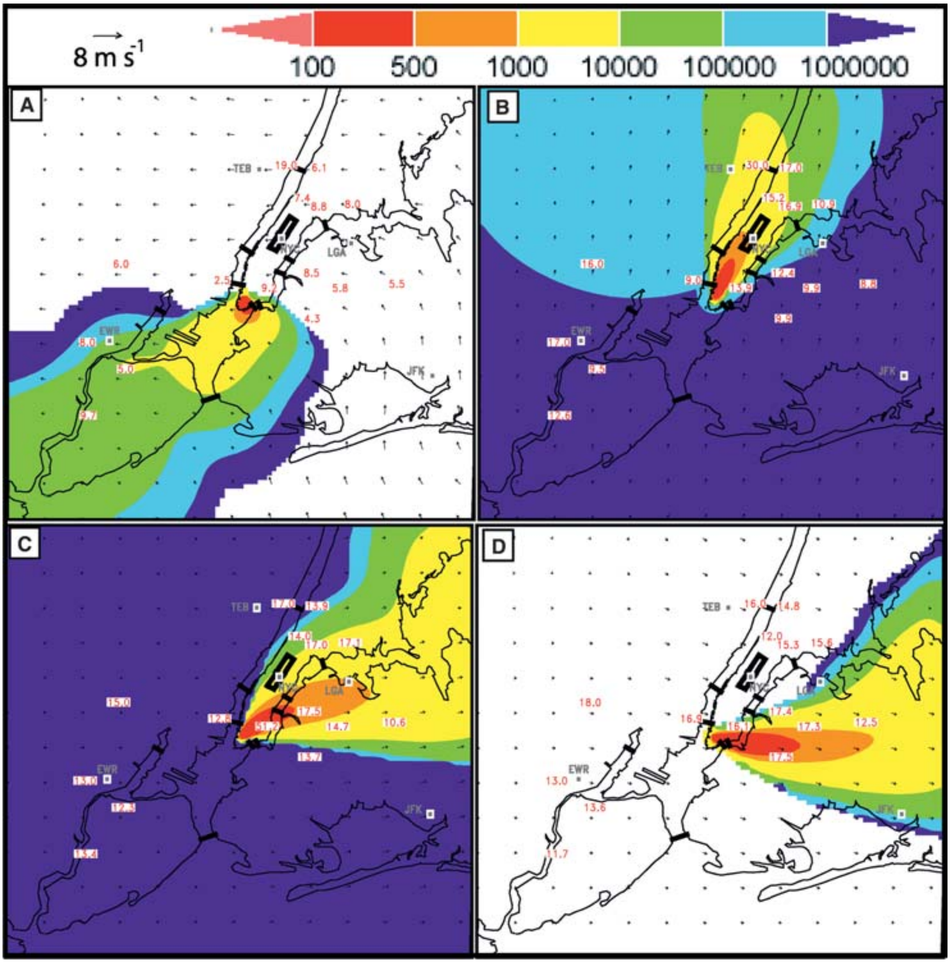

Figure 8
Simulated CALPUFF dilution (100–10^6 dilution) of a volume source located at the World Trade Center recovery site. The plotted numbers indicate the hourly-averaged $PM_{2.5}$ (μg m^{-3}) concentrations for the active monitoring stations. Also shown is the estimated 10 m wind from the CALMET diagnostic model. Time periods shown are: (**A**) September 17, 2001 at 1200 LST, (**B**) September 17, 2001 at 1800 LST, (**C**) September 18, 2001 at 0100 LST, and (**D**) September 18, 2001 at 0300 LST.

Figures 8c and 8d show the same type of plots at 0100 and 0300 LST the following morning. The modeled plume rotated as winds turn from southerly to northerly. The mixing heights decreased overnight to 150–200 m, as a response the simulated dilution value decreases significantly. Most of the $PM_{2.5}$ observations, opposite from the previous case (September 11–12), do not manitest a clear signature of the WTC plume away from lower Manhattan as the reported values are similar over the entire area. The observations do indicate slightly above normal (normal: 12–13 μg m^{-3})

concentrations, which may only be a result of the stable atmospheric conditions. Figure 8c does show that as the plume turned to the northeast, the reported concentration at the *ps64* in lower Manhattan increased to 445% of normal. Several hours later Figure 8d indicates that as the plume turned clockwise, the reported concentration at *ps64* significantly decreased back to near normal (normal: 14 μg m^{-3}). This is certainly evidence that the WTC plume did influence the *ps64* observation and that the turning/placement of the simulated plume is a fair representation of what actually took place. The fact that the meteorological conditions are almost identical between this case and the overnight period of September 12, 2001, and the signature of the WTC plume beyond lower Manhattan is not defined in the observations, would lead one to believe that there was a considerable decrease in the source strength between September 12–13 and September 17–18. Hence there was slight impact from $PM_{2.5}$ emissions on areas outside of lower Manhattan after the first week post September 11, 2001.

October 3–6, 2001 (southwest flow case)

In the early part of October (2–6) attention was placed on an extended period of high $PM_{2.5}$ concentration measurements around the NYC area. A strong surface high-pressure system was anchored off the eastern U.S. for the period; this resulted in a wind flow from the southeast region of the U.S to the northeastern U.S. In this case study the simulated WTC plume and observations are examined during the morning and afternoon of October 3–4.

Figure 9a shows the simulated WTC plume and $PM_{2.5}$ observations on October 3, 2001 at 0500 LST. The plume is directed towards the east-northeast of lower Manhattan. Dilution of the simulated plume material is low with the 100–500 diluted zone extending 15–20 km away from the WTC site. The plume width, loosely defined by the 10^4 dilution contour, is greater relative to other times, spreading out as much as 5 km from the centerline. The very low mixing heights (100 m) and low simulated wind speeds (1–2 m s^{-1}) are the main reason for the relatively high plume concentration away from the source. An animation of the plume over several hours indicates that the wind oscillated from southwest to west, resulting in the wide plume coverage. Observations plotted with the WTC simulated plume demonstrate that the reported concentrations across the entire area are well above normal by 200–300% (normal: 14–15 μg m^{-3}). Even those concentrations upwind of the simulated WTC are well above normal ($\sim$300%). $PM_{2.5}$ measurements closest to the WTC site are all slightly higher than the other surrounding sites. Hence it is reasonable to infer that the augmented concentrations during this period are a result of a regional increase in pollution levels and not the WTC site.

Later this day at 1500 LST (Fig. 9b) the simulated plume becomes considerably less concentrated because mixing heights rise to nearly 1500 m. The dilution contour less than 1000 is limited to the area directly over the WTC volume source. Another factor that contributes to the rapid dilution is the

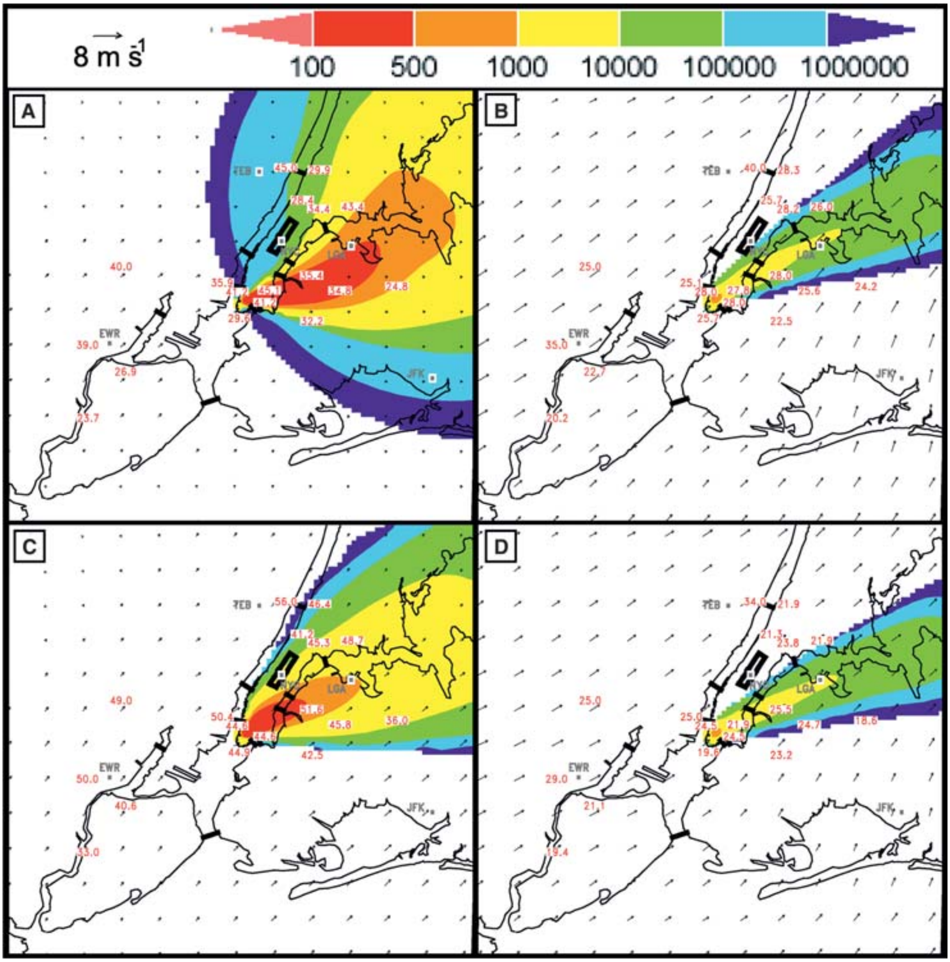

Figure 9
Simulated CALPUFF dilution (100–10^6 dilution) of a volume source located at the World Trade Center recovery site. The plotted numbers indicate the hourly-averaged $PM_{2.5}$ (μg m^{-3}) concentrations for the active monitoring stations. Also shown is the estimated 10 m wind from the CALMET diagnostic model. Time periods shown are: (**A**) October 3, 2001 at 0500 LST, (**B**) October 3, 2001 at October 4, 2001 at 0500 LST, and (**D**) October 4, 2001 at 1500 LST.

stronger southwest wind, which increases mechanical mixing near the surface and quickly disperses the material and transports it away from the source. Several $PM_{2.5}$ observations near the WTC recovery site are noticeably greater (360% of normal) than those more distant. All observed $PM_{2.5}$ values well away from the WTC site remain above 200% of normal.

The following morning at 0500 LST (Fig. 9c) the simulated plume becomes more concentrated again as the mixing heights lower to less than 200 m, similar to the previous night. The winds also lighten as a result of the more stable boundary layer.

The dispersion pattern of the plume is similar to the previous night in that the overall plume widens because of the light winds that meander between southwest and west. The observed concentrations are very similar to the previous night, with consistent 300% above normal values across the region. Observed $PM_{2.5}$ air in and around the WTC site is negligibly different from other areas of NYC. The following afternoon Figure 9d shows that the near-surface winds, boundary layer heights and, hence, the simulated plume is almost a replica of the previous day at 1500 LST. Reported concentrations show $PM_{2.5}$ levels ~150–200% of normal, slightly lower than the previous day but not significantly different.

Although the early October period raised concerns among local officials, as stated above, we believed the synoptic conditions were the main cause, and not the still smoldering WTC rubble. This increase in measured $PM_{2.5}$ is typical of what occurs when upstream winds arrive from a path over areas with substantial $PM_{2.5}$ emissions. Once a front passed on October 6, the observed concentrations dropped to below normal levels as the air mass was replaced with "clean" air from the north.

4. *Summary*

In this study the dispersion patterns of a simulated WTC plume are analyzed for a three-month period post September 11, 2001. $PM_{2.5}$ measurements from a network of samplers located around the NYC metropolitan area were analyzed to evaluate the potential impact of the WTC plume. These data sets are examined for signatures of the WTC plume during several case studies and over averaged periods ranging from several days to months. A primary goal was to determine if a signature of the plume was evident in the observation records so a conclusion can be reached regarding the air quality impact of the WTC disaster on surrounding areas outside of lower Manhattan. The other objective is to find out how well the plume position and dilution variations are simulated by application of a CALMET-CALPUFF modeling system.

In general, the simulated WTC plume was diluted quicker as material traveled away from the source during the daytime. Estimates from CALPUFF indicated that the material was diluted more than 10^3 times once the plume of material moved out of lower Manhattan. At night the plume became less diluted with the 10^3-contour stretching away from lower Manhattan to areas of Long Island and the 10^4-contour more that 30 km from the source. The higher observed concentrations occurred at night, and are direct responses to the lowered mixing depth and increased atmospheric stability. Although validation of the simulated concentrations is not possible, the diurnal behavior of the simulated plume dilution followed trends similar to those of the $PM_{2.5}$ measurements.

Observations of $PM_{2.5}$ around the NYC region did show some signature of the WTC plume during the first few days after September 11, 2001. During the initial few hours the plume was simulated to travel towards the southeast and did not pass over any of the air monitoring stations, thus no signature was recorded. A plume signature was observed on the night/early morning of September 12–13, 2001 when the simulation showed a concentrated plume northward over several air monitoring stations. Additionally the simulated plume position matched up well with increases in observed concentrations both near and away from lower Manhattan. The simulated plume also matched up with photographs of the plume (not shown) over the metropolitan area that was visible during these first few days.

In the two other cases that were examined (September 17–18 and October 3–4), there was no clear signature of the particulate matter from the WTC site outside of lower Manhattan. The September 17–18 and September 11–13 cases had similar meteorological conditions, however no clear WTC plume signature was evident at the monitoring sites because the source strength at ground zero was substantially lower. The October 3–4 cases had substantially above average particle concentrations at all monitoring sites with no clear signature of the particle matter from ground zero. Overall, the hourly observations combined with the hourly plume modeling indicate it is likely that the plume did not substantially impact areas more than a few kilometers away from the WTC except possibly for the first few days. This is also supported by the uniformity in the 3-month averages of the $PM_{2.5}$ measurements among sites in lower Manhattan, including those sites within several kilometers of the WTC recovery site and those sites outside of lower Manhattan. A comparison of the diurnal variation of average concentrations between the distant and nearby station in lower Manhattan show that the lower Manhattan sites, on average, measure higher concentrations, nonetheless the difference was not very significant, only a few $\mu g\ m^{-3}$.

The main purpose of the plume simulations was to provide general guidance on the likely pathway for pollutant emissions from the WTC site, both temporally and spatially. These simulations are applicable to pollutant emissions near the ground that are well mixed by the buildings surrounding the WTC "ground zero" area. Except for periods during the first few days, particularly the first few hours, the ground-level emission assumption is valid. The plume before the building collapse and during the initial open fires immediately following the collapse was buoyed by the heat of the fire to elevations above the ground. The plume dilution values and locations presented in this paper are representative of the added dilution by atmospheric processes during transport away from the WTC site. It is important to note that the initial dilution from a point or small area source within the "ground zero" area is not being modeled. Also, local wind flow patterns caused by the influences of buildings of lower Manhattan are not being modeled. These limitations are most significant close to the WTC, especially during nighttime periods when the winds are light and the atmosphere is stable. During these periods, emissions from "ground zero" may not become well mixed before they are transported away. For some periods, emissions may even be caught in wind currents "snaking" through the area dominated by large buildings within lower Manhattan. Nevertheless, even for these situations, emissions would eventually be caught within the atmospheric transport that is being modeled by the methods used in this paper. For these reasons the plume simulations are only considered herein appropriate at distances beyond 2 km downwind from the WTC site. Applications such as the CALMET-CALPUFF system have their advantages and limitations because of their known simplifications in characterizing meteorology, and plume transport and dispersion processes. A CALMET-CALPUFF based modeling system, while probably not providing as precise an estimate of pollution levels as mesoscale models, might be adequate for many applications as has been demonstrated in this research. Knowing generally where the plume may have been while not knowing the concentrations precisely can still help determine where to conduct additional monitoring or more refined modeling of human exposures and where to study the population in epidemiological studies. Having such results rapidly as a forecast or screening tool could be valuable to groups that do not have access to sufficient computing resources to operationally run fuller physics models.

Acknowledgements

This work was supported by the United States Environmental Protection Agency, State Climate Office of North Carolina and the Department of Marine, Earth, and Atmospheric Sciences of North Carolina State University. It has been subjected to United States Environmental Protection Agency and National Oceanic and Atmospheric Administration review and approved for publication. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use. We thank Bob Kelly and Henry Feingersh (US EPA Region 2) for their support of the application of meteorological models and instrumentation following the events of September 11, 2001. Gratitude is expressed to the constructive peer review by John IRWIN (NOAA), Tom Coulter (EPA), and Joseph Pinto (EPA). Comments by John Irwin lead to substantial changes in the original draft, including the addition of the companion paper to provide an assessment of the CALMET modeled meteorology. Discussions with Haluk Ozkaynak (EPA) were helpful in guiding the potential applications and limitations of the methods used in this paper for supporting human exposure assessment studies. Dennis Atkinson (NOAA) and WILLIAM Brown (NOAA) were instrumental in the quick delivery of the quality assured ASOS data from the NOAA National Climatic Data Center. The CAPS group at the University of Oklahoma was instrumental in providing the hourly ADAS data set. Matt Darcangelo (NY State Department of Environmental Conservation) and James Oxley (NJ Department of Environmental Protection) were instrumental in providing the air monitoring data needed to support this modeling study.

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(Received August 11, 2004, accepted October 20, 2004)
Published Online First: June 21, 2005