Pure appl. geophys. 162 (2005) 1981–2003
0033 – 4553/05/101981 – 23
DOI 10.1007/s00024-005-2701-z

Pure and Applied Geophysics

Metropolitan-scale Transport and Dispersion from the New York World Trade Center Following September 11, 2001. Part I: An Evaluation of the CALMET Meteorological Model

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Abstract—Following the collapse of the New York City World Trade Center towers on September 11, 2001, Local, State and Federal agencies initiated numerous air monitoring activities to better understand the impact of emissions from the disaster. A study of the estimated pathway that a potential plume of emissions would likely track was completed to support the U.S. EPA's initial exposure assessments. The plume from the World Trade Center was estimated using the CALMET-CALPUFF dispersion modeling system. The following is the first of two reports that compares several meteorological models, including the CALMET diagnostic model, the Advanced Regional Prediction System (ARPS) and 5th Generation Mesoscale Model (MM5) in the complex marine-influenced urban setting of NYC. Results indicate wind speed, in most cases, is greater in CALMET than the two mesoscale models because the CALMET micrometeorological processor does not properly adjust the wind field for surface roughness variations that exits in a major built-up urban area. Small-scale circulations, which were resolved by the mesoscale models, were not well simulated by CALMET. Independent wind observations in Lower Manhattan suggest that the wind direction estimates of CALMET possess a high degree of error because of the urban influence. Wind speed is on average 1.5 ms^{-1} stronger in CALMET than what observations indicate. The wind direction downwind of the city is rotated 25–34 clockwise in CALMET, relative to what observations indicate.

Key words: Dispersion modeling, CALPUFF, CALMET, Plume modeling, Sea breeze, ARPS, MM5.

1. Introduction

In response to the events on September 11, 2001 at the New York World Trade Center (WTC), a study using the CALMET-CALPUFF (SCIRE *et al.*, 2000a) dispersion modeling system was conducted for a three-month period following the events. Prior to the WTC attack, efforts were already underway to use a similar modeling system for real-time support of air pollution studies in the Raleigh-Durham

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area of North Carolina. After the events at the New York WTC, all efforts were redirected toward the impact of the WTC event on the New York City (NYC) region. The CALMET-CALPUFF simulation was used as a support tool for the US EPA's preliminary assessment of the potential impact of emissions from the WTC site on New York City. In Part I of the study CALMET, the meteorological processor for the CALPUFF (SCIRE *et al.*, 2000b) dispersion model is examined to provide a better understanding of its strengths and weaknesses in representing the meteorology over a complex urban area such as NYC. Additionally, Part I of the study serves to better highlight the uncertainty of the meteorology and inherent limitations of the modeling system before the dependent dispersion results are analyzed in Part II. The study as a whole serves as a documented application for reference by the growing CALMET-CALPUFF user community.

It is well known that atmospheric boundary layer (ABL) heterogeneity is characteristic of a dense urban center like NYC that lies adjacent to an ocean or a large lake, especially when compared to the ABL over rural, inland areas. NYC's landuse is characterized as a highly developed urban core on Manhattan Island, and a sprawling dense suburban area that covers northeastern New Jersey and western Long Island. The NYC urban blocking effect and urban heat island phenomena have been examined in detail by BORNSTEIN and JOHNSON (1977) and BORNSTEIN *et al.* (1994).

Adding to this complex urban surface is a highly variable coastline consisting of many small bays, rivers and sounds (Jamaica Bay, New York Harbor, Hudson River, East River and Long Island Sound). A thermal internal boundary layer (TIBL) often develops along the coast, influencing the boundary layer structure over land. Its variation downwind depends on the surface roughness, upwind atmospheric stability and land-sea temperature contrast (RAYNOR *et al.*, 1979). TIBL exists to some extent during all conditions however is most pronounced during light to moderate synoptic flow cases in which the local temperature and wind variation can dominate the meteorology of the region. FRIZZOLA and FISHER (1963), BORNSTEIN *et al.* (1994), REISS *et al.* (1996) and MICHAEL *et al.* (1998) examine the sea breeze of NYC in detail using numerical models, surface and upper-air observations, and radar imagery. All of these features and their influence on the lower atmosphere make attempts at modeling the region difficult (MICHAEL *et al.*, 1998).

Considering all of these factors, the study first presents an overview of the general weather patterns that occurred during the study period. The synoptic conditions over the three-month study period (September 11, 2001–December 8, 2001) are classified into climatological flow regimes that normally exist during the fall season. Next, independent wind measurements are used for a quantitative evaluation of CALMET near the WTC site. Then, two prognostic models are used to examine the complexity of mesoscale and local scale variations over NYC. The prognostic models are compared and contrasted with the CALMET, as well as with observations, and the historical studies summarized above. It should be stated that the use of the prognostic models is strictly to illustrate that local features, which are important during certain synoptic flow patterns, are not as well represented by diagnostic models like CALMET. Also, observations are rather limited relative to the complexity of the flow patterns. This limitation makes an exact evaluation more difficult consequently some subjectivity is used in the analysis.

2. Methodology

2.1. Synoptic Flow Classification

Weather patterns affect the local meteorology and dispersion of pollutants over NYC. Climatologically, a weather system moves through the region every 4–6 days (Brown and Raman, 1981) during the fall season. This cycle, starting after a cold front passage, typically includes a day of moderate to strong (> 4–5 m/s) N-NW winds; followed by a transition day where the wind decreases as it veers from northerly to northeasterly. Next, the region experiences a day where high pressure is centered near or directly over the area and winds become light and variable. Following this, the high pressure system moves east and winds turn southerly but remain light for a day, then as another frontal boundary approaches from the west, southwest winds increase to moderate levels. Based upon this evolution, all days during the study period have been categorized as one of these flow regimes, except for a limited few that could not be justly grouped into the above classification. These "other" days were mostly conditions when either a strong low pressure system affected the area or frontal boundaries oscillated over the region, resulting in drastic wind shifts.

Table 1

Classification of the synoptic conditions during the September 11–December 8, 2001 study period. Synoptic conditions are classified according to the flow strength and direction observed over the NYC region. Light flow is considered to be less than 4–5 m s^{-1} and strong flow greater than 4–5 m s^{-1}. Percentage of the entire period is shown in parenthesis. Also cited are the modeling case study(s) presented in this research that correspond to the synoptic category.

Synoptic Classification	Number of days (Percentage)	Representative Modeling Case
Light Southerly	17 (19%)	Nov. 14
Strong Southerly	16 (18%)	Oct. 4
Light Westerly	08 (9%)	Sep. 17
Strong Westerly	15 (17%)	Oct. 4
Light Northerly	05 (6%)	N/A
Strong Northerly	06 (7%)	Sep. 11
Light and Variable (High)	14 (16%)	Nov. 13, Sep. 12
Other	08 (9%)	N/A

Table 1 shows the frequency of the various flow classifications that occurred during the study period. The categories are southerly, westerly and northerly with these further divided by the estimated flow strength (light or strong). The light and strong flow classification was determined by the critical wind speed of 4.0 m s^{-1} that has been linked to the urban heat island (BORNSTEIN and JOHNSON, 1977) and sea-breeze development (ARRITT, 1993). The flow strength and direction were subjectively determined by examining six-hourly synoptic charts and surface observations. A light and variable and an "other" classification were included to account for days when the wind was highly variable or a strong storm system affected the region. Four flow regimes dominated: light southerly (19%), strong southerly (18%), strong westerly flow (17%), and light and variable flow (16%). These regimes occurred on 70% of the days. The remaining periods were light westerly (9%), light northerly (6%), strong northerly (7%) and other (9%).

2.2. Calmet Description

To support the EPA's study of the potential impact of airborne pollutants from the WTC tragedy on the populous, a CALMET model domain was designed to cover the central portion of the New York City (NYC) metropolitan area. The grid was centered over lower Manhattan and covered a 50 × 50 km square area at a grid spacing of 0.5 km. Figure 1a shows the extent of the CALMET model domain in relation to the surrounding suburbs of NYC. The vertical grid was stretched in a terrain following a coordinate system with twelve vertical levels: 10, 27, 51, 90, 195, 350, 512, 700, 1000, 1350, 1650 and 2000 meters.

CALMET is a diagnostic, observation-based model that requires three key data sets to function: landuse information, surface observations and upper-air observations. The landuse for the New York City model domain is classified in CALMET according to the United States Geological Survey landuse land cover database. For residential (category #11) the default roughness value was lowered from 1.0 m to 0.75 m (WIERINGA, 1993). The surface properties for water were set to its default values. Built-up urban classification is another landuse that covers a considerable portion of the domain. Both lower and upper Manhattan Island is densely covered by some of the tallest buildings in the world. For this reason, several of the surface properties were changed from their default value to represent this urban anomaly. The surface roughness was increased from 1.0 to 1.5 meters to account for the extremely tall buildings. This follows the high range of aerodynamic roughness length for a "regularly built-up town" proposed by WIERINGA (1993). A roughness of 1.5 m may be too conservative for lower Manhattan, as more recent studies that examine the urban morphology (RATTI *et al.*, 2002) find that extremely built-up areas like Los Angeles or Manhattan are better described by aerodynamic roughness lengths of 5–7 m or more. However, the sensitivity of CALMET-CALPUFF to magnified roughness lengths will be investigated in a later study.

Hourly surface observations are the second required input of the CALMET model. In Figure 1a, the plan view of the model domain is shown along with the locations of the six National Weather Services Automated Surface Observing System (ASOS) stations used in the simulations. The stations are Newark Airport, Teterboro Airport, Central Park in Manhattan, LaGuardia Airport, John F. Kennedy Airport and Islip, located about 100 km to the east of the model domain's center. Quality assured, hourly ASOS data were acquired from the National Climatic Data Center (NCDC) for the study period. These data provide CALMET the near-surface wind speed and direction, temperature, cloud cover and precipitation.

CALMET uses upper-air profile data to estimate the above-surface flow and thermal stratification. Typically, upper-air observations are used from the National Weather Service rawinsonde sites. These observations are available twice daily, at approximately 0700 and 1900 LST (12 and 00 UTC, respectively). Between these morning and evening soundings, considerable boundary layer variation occurs. Additionally, the number of these stations (Islip and Albany) is relatively small in comparison to the region being modeled. For this reason hourly-assimilated model analysis profiles were used (temperature, winds and moisture) from the Advanced Regional Prediction System, Data Assimilation System (ADAS) (ZHANG *et al.*, 1998). Model data, including the ADAS data set, have been successfully utilized in at least one other CALMET-CALPUFF study (LEVY *et al.*, 2002) to provide more physically realistic meteorological fields. The ADAS data were interpolated to the four corners of the CALMET grid, shown as squares in Figure 1a.

After ingesting these data sources, CALMET uses several routines to estimate the winds and stability of the planetary boundary layer. The diagnostic wind field module of CALMET includes several steps. The first step is to apply diagnostic algorithms that account for terrain, kinematic effects, divergence minimization, Froude number adjustment and possible slope flows. In the second step observations are introduced through an objective analysis method based on the inverse distance (R^{-2}) method. A radius of influence (R) limit of 20 km was placed on the interpolation of observations to the CALMET grid. The final step utilizes the O'Brien procedure (O'BRIEN, 1970), which takes the wind field and adjusts the horizontal divergence so that the vertical velocity at the top level of the model is zero. During this procedure, the horizontal winds are adjusted iteratively so that the resulting divergence is lowered to a user-specified value, in this case the default (5×10^{-6} s^{-1}).

2.3. Instrumentation Description

An instrumentation cluster was deployed near the WTC recovery site in lower Manhattan. The cluster consisted of two Sound Detection and Ranging (SODAR) systems and a three-level micrometeorological tower. The instruments were activated on November 08, 2001 providing approximately one month of independent data during this study period. A plan view showing the location of the instrumentation cluster with respect to lower Manhattan and the WTC recovery site is provided in Figure 1b. The 10-meter wind from the tower and several levels of SODAR data from the Aerovironment Model 4000 miniSODAR are used to evaluate the CALMET-derived winds near the WTC site.

2.4. Dynamic Model Configuration

Two dynamic models, ARPS (XUE, 1998; XUE *et al.*, 2000, 2001) and the fifth generation PSU-NCAR Mesoscale Model (MM5) (GRELL *et al.*, 1995), were used in this investigation to examine the local variation in the meteorology during different synoptic flow scenarios. Of specific interests are the synoptic regimes where ASOS observations may not provide enough resolution to entirely capture the local-scale variations in the meteorology.

ARPS is a nonhydrostatic, fully compressible, primitive equation model, capable of resolving microscale meteorological variations. The turbulence closure scheme in the boundary layer utilizes a 1-1/2 TKE formulation after SUN and CHANG (1986). All moisture processes were activated, an advanced radiation scheme was used and the soil state was integrated using a soil-vegetation model designed according to NOILHAN and PLANTON (1989). A nested ARPS domain was designed to replicate the CALMET grid by centering over the same area and using identical landuse information. The grid spacing was 1.0 km in the ARPS simulation. Boundary conditions were provided by a similarly configured ARPS simulation with a horizontal grid spacing of 5 km. This grid was initialized and its boundary conditions were obtained from the hourly assimilated data of the 32 km ADAS system. Landuse properties of the CALMET domain such as surface roughness and leaf area index were regridded from 500 m to 1000 m for use by the ARPS simulations. Required surface specifications, such as vegetation fraction and soil type, were assigned in ARPS according to the 200 m USGS (United States Geological Survey) CTG (Composite Theme Grid) landuse data set.

The other dynamical model used in this study is the three-dimensional, nonhydrostatic version of the MM5. The mesoscale model incorporates the physics of the Oregon State University (OSU) land surface model (LSM). The OSU model is coupled with the ETA model planetary boundary layer (PBL) scheme. National Center for Environmental Prediction (NCEP) ETA model output was used in this study for initial and lateral boundary conditions. The MM5 default surface variables such as landuse, vegetation type, roughness and topography were acquired from a 900 m USGS database. Default surface roughness value used for the highly urbanized area of NYC in the MM5 model was 1.0 m versus 1.5 m in the ARPS model. For this study, a triple nested version (27, 9, 3 and 1 km) of the MM5 was utilized. The innermost, high-resolution grid was centered over the study area. All four domains had 36 vertical sigma levels (between 1000 hPa and 100 hPa).

3. Results

3.1. Comparison of calmet Winds with Independent 10 m Tower Observations

A statistical analysis is provided of the difference between the WTC tower wind speed and direction observations and the CALMET model simulation. It is realized that comparing point measurements to model output may raise questions. However, the fact that CALMET is a diagnostic model that essentially derives a wind field from observations, and that the WTC tower observations are independent of CALMET; we feel this analysis is a useful exercise. Figure 1b shows the plan view of the lower Manhattan area and the location of the WTC instrumentation cluster, which is important in the following analysis. The statistics are separated according to the observed flow direction at the WTC Tower site. Each of four flow classifications cover a 90° sector that is rotated −30° with respect to north as illustrated by Figure 1b. The flow classifications are northerly (330°−60°), easterly (60°−150°), southerly (150°−240°) and westerly (240°−330°), similar to the classification of the modeling case studies in Table 1. Flow regimes were derived from the plan view to isolate flow directions that are influenced by lower Manhattan (southerly and easterly) from those influenced by the Hudson River (westerly and northerly).

Descriptive statistics of wind speed differences between CALMET and the WTC Tower (CALMET-WTC Tower) in Table 2 are grouped according to the flow direction. The data are hourly wind speeds (m s^{-1}) over the period of November 11–27, 2001. The bias in wind speed is 1.46 m s^{-1} when the flow is from an easterly direction. It is illustrated in the plan view in Figure 1b, easterly flow results in a fetch of up to 8 km over the roughest surface in NYC, so weaker observed winds are not surprising, especially when the wind in CALMET is based on airport observations, taken over considerably smoother surfaces. When the flow is within the southerly quadrant the CALMET bias is 0.98 m s^{-1}, not as pronounced as for the easterly wind flow regime. Westerly flow also has a bias of nearly 1.0 m s^{-1} and the northerly flow was approximately 0.50 m s^{-1}. The average bias over all directions is about 1.0 m s^{-1}.

Wind direction differences between the simulated and observed data are summarized by the statistics in Table 3. A positive wind direction bias indicates that the CALMET wind direction is rotated clockwise relative to the observed wind. Analysis of the data (scatter plot not shown) and compiled statistics in Table 3 reveal

Table 2

Lower Manhattan Tower and CALMET wind speed (m·s^{-1}) comparison statistics grouped by observed wind speed (m·s^{-1}). Bias is calculated by standard (model-observation)

Wind Direction	Direction Criteria	Mean Bias	Mean Absolute Error
Northerly	330°– 60°	0.48	0.82
Easterly	60°−150°	1.46	1.52
Southerly	150°−240°	0.96	1.11
Westerly	240°−330°	0.98	1.15

Table 3

Lower Manhattan Tower and CALMET wind direction (degrees) comparison statistics grouped by observed wind direction. Bias is calculated by standard (model-observation)

Wind Direction	Direction Criteria	Mean Bias	Mean Absolute Error
Northerly	330°– 60°	−4	27
Easterly	60°–150°	34	48
Southerly	150°–240°	25	34
Westerly	240°–330°	−4	20

a few interesting characteristics. First, the mean absolute error (mae) and bias of the wind direction is greatest when the observed wind is from a northerly to southeasterly direction, with the peak differences associated with easterly flow (bias: 34°; mae: 48°). When the observed wind is between southwesterly, clockwise to northerly, the error is considerably less (bias: −4°; mae: 20–27°). The tower location (Fig. 1b) provides insight into these variations. When the flow is from an easterly to southerly direction the air travels over lower Manhattan before reaching the tower. The numerous tall buildings disrupt the flow pattern and increase the wind variability. When the flow is from a westerly to northerly direction, the scatter in the data is considerably less, as the air is traveling across the Hudson River. The lower friction over water and increased stability leads to a less turbulent flow.

A primary question is: How do these CALMET differences relative to a point observation relate to other areas in the model domain? There is at least some evidence from the statistics above that the urban area of lower Manhattan significantly influences the leeside flow in the city. The near-surface wind speed is reduced and the flow direction turns cyclonically as the flow decelerates. Since CALMET does not dynamically generate this general urban flow modification, there is a greater uncertainty in the model results within and directly downwind from the main urban center. This basic statistical analysis would suggest that the flow is lighter and curves cyclonically over the city. BORNSTEIN and JOHNSON (1977) showed similar results with a data set of surface observations. The magnitude of uncertainty may be related to cross-urban flow regimes examined above (i.e., an angle uncertainty of ± 50° in the wind direction and a little over ± 1.0 m s^{-1} in the wind speed). Areas upwind of Manhattan may have less bias in the wind direction, however the wind speed represented in CALMET is likely stronger than reality. Again, the wind speed differences may be related to the footprint of the ASOS stations not being representative of the urban environment. Although evidence of these urban effects is presented, more observations are needed to prove that these processes are occurring.

3.2. CALMET Versus Dynamical Model Simulations

Mesoscale model simulations, both ARPS and MM5 were conducted for a number of cases, each representing a different synoptic flow regime. Three of these

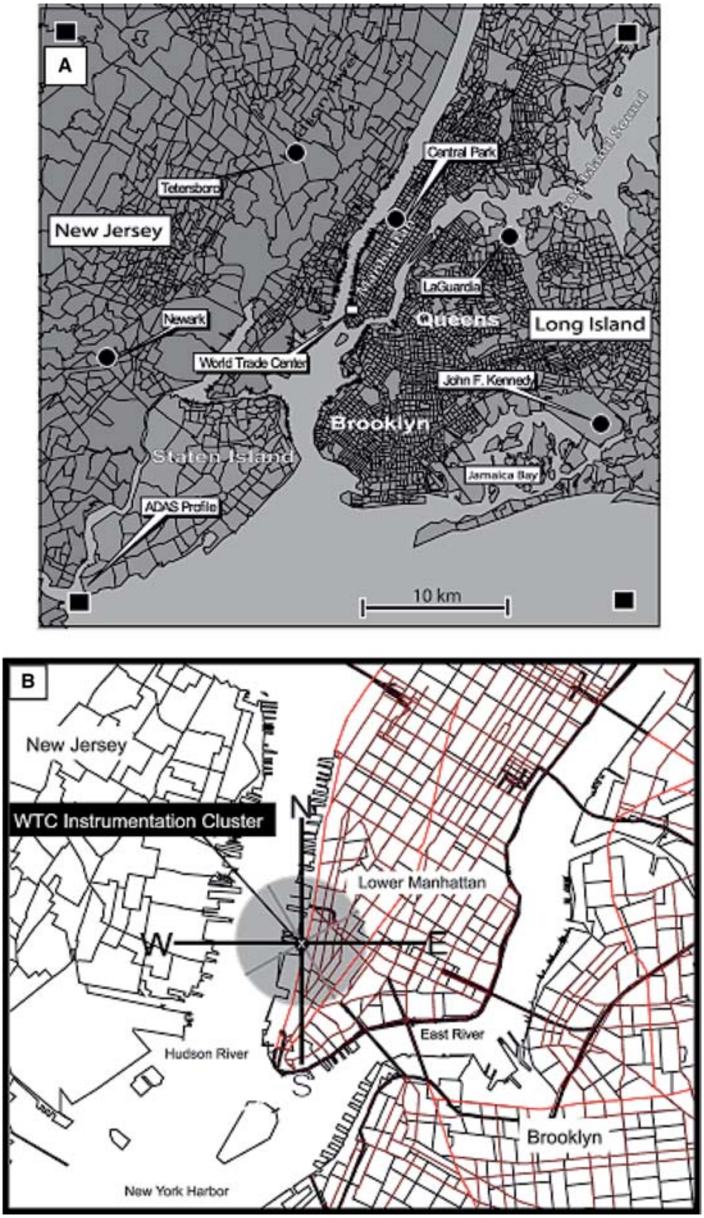

Figure 1
(**A**) A plan view of the CALMET-CALPUFF, ARPS and MM5 model domain over the New York City area. Surface meteorological observation sites are depicted by solid black circles with a white outline and the ADAS profile locations are shown by the squares. The WTC site as well as other NYC landmarks is labeled. (**B**) Plan view of the lower Manhattan area showing the location of 10 m tower and two SODAR's. The offset gray axis (-30°) represents the directional grouping (northerly, easterly, southerly, and westerly) of the CALMET-TOWER wind comparison statistics.

cases are presented in this paper. The first case, November 13–14, 2001 represents three of the synoptic classifications: A cool season light and variable case, a cool season light southerly nocturnal and light southerly daytime case. Unlike the other two cases, the WTC instrumentation cluster data were available. Following, a case will be examined in which the large-scale forcing is strong and the wind flow oscillates between a southerly and westerly direction (October 3–5, 2001), satisfying both the strong southerly and westerly flow classifications outlined in Table 1. The final simulation was conducted for September 11–13, 2001 exclusively using the MM5 model. ARPS was not applied because the assimilated data sets used to initialize and provide boundary conditions were not readily available. On September 11, 2001 the flow was brisk out of the north and on the following day, high pressure was centered over the region. This case represents a strong northerly condition and a light and variable warm season scenario. A more detailed description of the synoptic pattern precedes each of the following case studies.

Case I: November 13–14, 2001

High-pressure controlled the weather over much of the contiguous United States on November 13. Centered over West Virginia, the surface high pressure (1036 hPa) resulted in clear skies and calm winds over NYC. Given the light large-scale flow, local influences were more pronounced on November 13, 2001. The surface high pressure moved off the mid-Atlantic coast on November 14–15 resulting in a light to moderate southwesterly flow across NYC. Case I represents the synoptic classifications of a light and variable flow on November 13 and a light southerly flow on November 14.

Model estimated 10 m wind at 1400 LST is shown in Figures 2a (ARPS) and 2b (MM5). Also included are the NWS ASOS 10 m wind observations. The ASOS wind barbs are in knots, however the number to the right represents the wind speed in m s^{-1}. Sea-surface temperature (SST) measured from NOAA's AVHRR (Advanced Very High Resolution Radiometer) satellite was 282 K, while observed land temperatures rose to above 285 K, causing enough temperature differential to induce a weak TIBL at the land-water interface. The ARPS model was initialized with the AVHRR SST that averaged 282 K, but the MM5 used a climatological database that had a much lower SST of 278 K.

Noted in the ARPS wind field at 1400 LST on November 13 (Fig. 2a), there is a distinct shift from a southwesterly to southerly wind along Staten Island and northward along the New Jersey side of the Hudson River. Surface observations agree with this wind variation as the 10 m wind measurements in lower Manhattan display southerly winds while Newark was reporting a southwest wind. The 10 m averaged wind speed from the WTC Tower indicated that this southerly surge of wind simulated by ARPS over the NYC Harbor began at 1400 LST and lasted through the evening at which point the flow veered southwest. FRIZZOLA and FISHER

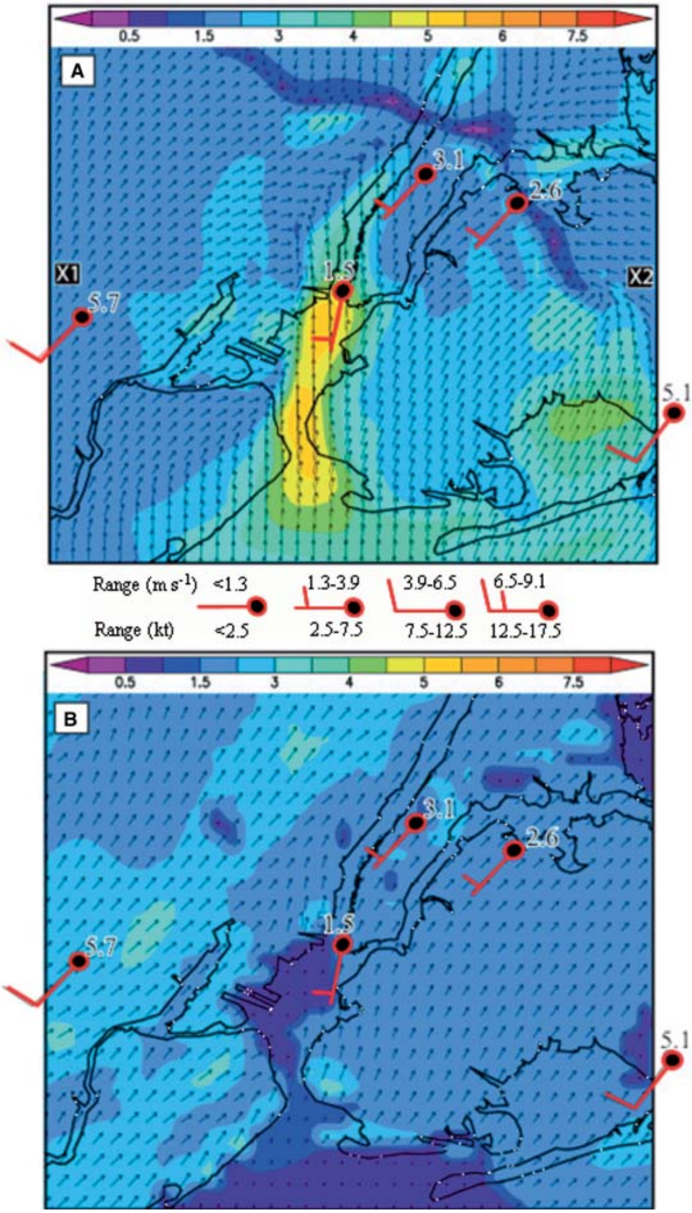

Figure 2
(**A**) ARPS simulated 10 m wind (m·s^{-1}) at 1400 LST on November 13, 2001. (**B**) MM5 simulated 10 m wind (m·s^{-1}) at the same time. Wind speed (m·s^{-1}) is shaded with a legend at the top of the plot. Wind vectors are scaled according to the wind speed. ASOS wind observations for the same time are plotted overtop of the simulated fields with the standard barb notation in knots (refer to legend). The observed wind speed values (m·s^{-1}) are shown next to the station plot.

(1963) plotted observations from the same ASOS sites during a similar light synoptic flow pattern that show a nearly identical wind direction variation at the same time of day (1300 LT). BORNSTEIN *et al.* (1994) performed numerical simulations over the same area that showed a similar frontal alignment that extended through Staten Island, across lower Manhattan and eastward through central Long Island. In Figure 2a, the ARPS simulated front extends further north in New Jersey, possibly because the large-scale flow was slightly stronger (4 m s^{-1}) and more northwest in BORNSTEIN *et al.* (1994). Northwest flow would limit the sea breeze from moving inland or northward.

Also of importance is an apparent ARPS simulated Long Island Sound breeze in the far northeastern part of the domain where an easterly flow exists across the northern part of Manhattan Island. Most sea-breeze studies in the area, specifically an observational report by MICHAEL *et al.* (1998) using WSR-88D Doppler imagery, show similar variation in both the radar data along the northern and western shores of Long Island Sound.

The MM5 simulation at the same time is shown in Figure 2b. The general wind flow pattern is similar between the MM5 and ARPS models for a majority of the domain. A comparable but less discrete front is indicated in the MM5 wind field on the west side of the Hudson River. The most noticeable difference between the MM5 and ARPS is the calm winds over water in the MM5, which could be a response to the 4 K cooler sea-surface temperature in the MM5 resulting in a more stable marine boundary layer.

An examination of the ARPS simulated vertical wind and turbulence (m^2 s^{-2}) cross section from X1 to X2 (Figure 2a) at 1400 LST was performed (Figure not shown). The TIBL on the west side of the Hudson River in New Jersey was distinguished in the cross section as a shift of westerly to southerly wind at the surface to approximately 300 m, representing a shallow 300 m TIBL associated with the weak sea breeze front. Ahead of the front were layers of enhanced TKE and deeper mixing, while the turbulence was suppressed behind the front, within the sea-breeze flow. On the same cross section the CALMET estimated mixing depth was plotted. Both models show lower mixing depths over water areas and greater mixing depths over land areas. However, there are substantial differences in the magnitude, with ARPS indicating a mixing layer of 200 m over water and 400 m to 700 m over land while CALMET estimates a depth ranging from 400 m over water to 1200 m over land. The daytime calculation of the mixing height in CALMET, based on the potential temperature lapse rate acquired from 32 km resolution assimilated data, may not accurately resolve the temperature structure of the coastal TIBL over NYC. The dynamical simulation of ARPS that considers the TKE budget, realistic sea-surface temperatures and temperature advection presumably better represents the boundary layer depth.

The CALMET wind field was examined at the same time. Figure 3 illustrates the 10 m wind field from the CALMET. Visual comparisons with the ARPS simulations

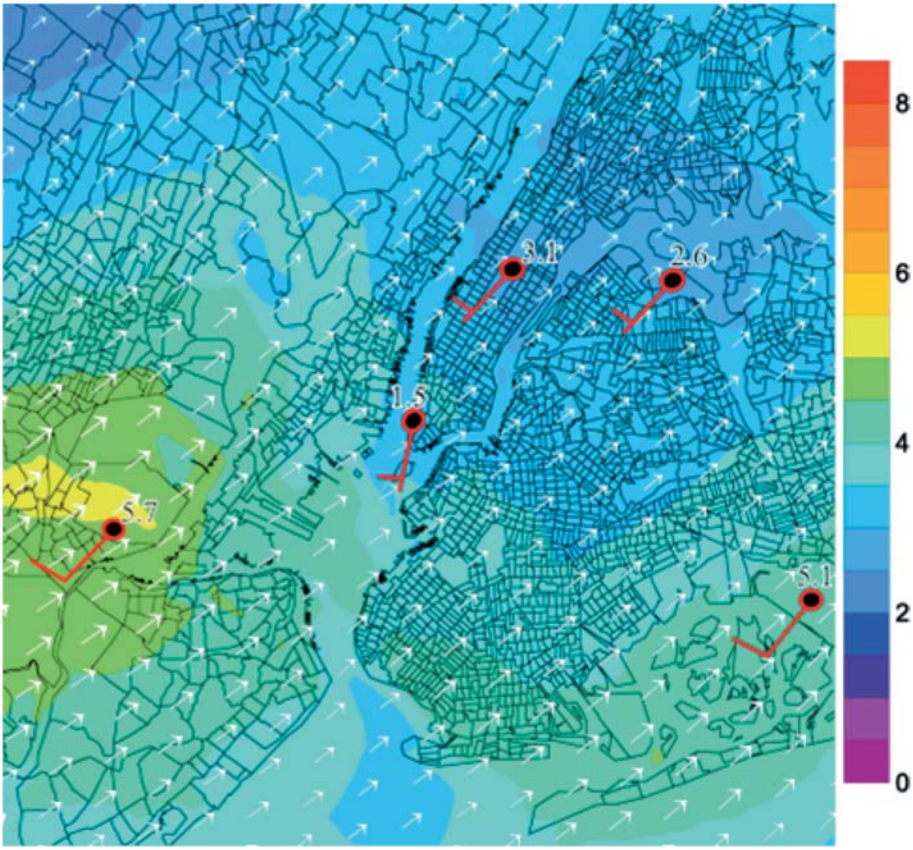

Figure 3
CALMET simulated 10 m wind ($m \cdot s^{-1}$) at 1400 LST on November 13, 2001. Wind speed ($m \cdot s^{-1}$) is shaded with a legend at the top of the plot. Wind vectors are scaled according to the wind speed. ASOS wind observations for the same time are plotted top of the simulated fields with the standard barb notation in knots (Refer to wind barb legend in Figure 2). The observed wind speed values ($m \cdot s^{-1}$) are shown next to the station plot.

in Figure 2a indicate several notable differences. First, the CALMET wind direction is nearly uniform, while the dynamical ARPS and MM5 simulations depict a discrete sea breeze front with an associated wind direction shift. Some may argue that because CALMET is using surface wind observations to derive the wind field, it has to be accurate. However, it was seen in Figures 2a and 2b that the observed ASOS wind directions are consistent with the ARPS and MM5 simulations, as was the wind observation in lower Manhattan. This observed southerly wind at the WTC tower indicates that an abrupt southerly wind shift was not depicted in the CALMET simulation, possibly because the density of surface observations was not great enough to capture smaller scale details in the wind field. This demonstrates an inherent shortcoming of the diagnostic, observation driven method in regions where complex meteorological variations exist (BAKLANOV *et al.*, 2002).

Another feature to note is the overall wind speed difference between the ARPS and MM5 models and the observation-driven CALMET. The wind speed variation generated by CALMET (Fig. 3) is strictly a function of the diagnostic method, which does not explicitly take into account variations in surface roughness. The wind speed simulated by the dynamical models is affected by the prescribed surface roughness. During flow regimes like this, CALMET does not seem to resolve the local-scale variations in the wind flow around Manhattan during the daytime. An evaluation of the prognostic capability of the STEM-FCM model (SILIBELLO *et al.*, 2001) to predict ozone concentrations similarly found that the dynamical model RAMS (PIELKE and COTTON, 1992) provided better meteorological input than the diagnostic CALMET model in coastal regions. The synoptic classification (Table 1) highlights that 16% of the days during the study period were similar to this case study.

Case II: October 2–5, 2001

During October 2–6, 2001 the NYC area experienced a lengthy period of moderate to strong southwesterly flow. This flow dominated a large portion of the eastern United states. A large high-pressure ridge controlled the weather over much of the eastern United States on October 2. The high-pressure system off the southeastern United States coastline intensified under strong upper-level (300 hPa) confluence and remained stationary on October 3. This led to the development of a warm southerly flow over the New York City metropolitan region through October 6. There was increasing concern about the elevated particulate matter concentrations around the city during this three-day period. This episode is examined for this reason and because it fits into the classifications of both strong southerly and westerly flow outlined in Table 1.

The wind field simulated by the high-resolution 1 km ARPS model at 0700 LST on October 4, 2001 indicated that the variation in the wind field was dominated by the surface roughness (figure not shown). The wind speed varied from 5.0 m s^{-1} over water to less than 2.0 m s^{-1} over the rougher urban areas. The simulated wind directions compare well with the ASOS observations, and the simulated wind speeds are about 1.0 m s^{-1} less than observed.

Another important characteristic of the wind field variation is a slight but noticeable cyclonic turning in the low level winds near lower Manhattan; this was also noted in a nocturnal analysis on November 14, 2001. As the simulated west-southwest flow over the open NY Harbor intercepts by the tip of Manhattan Island, the winds slow and become more southwesterly. This feature is in agreement with observational findings by BORNSTEIN and JOHNSON (1977) that showed nighttime events during stronger flow regimes were associated with distinctive roughness

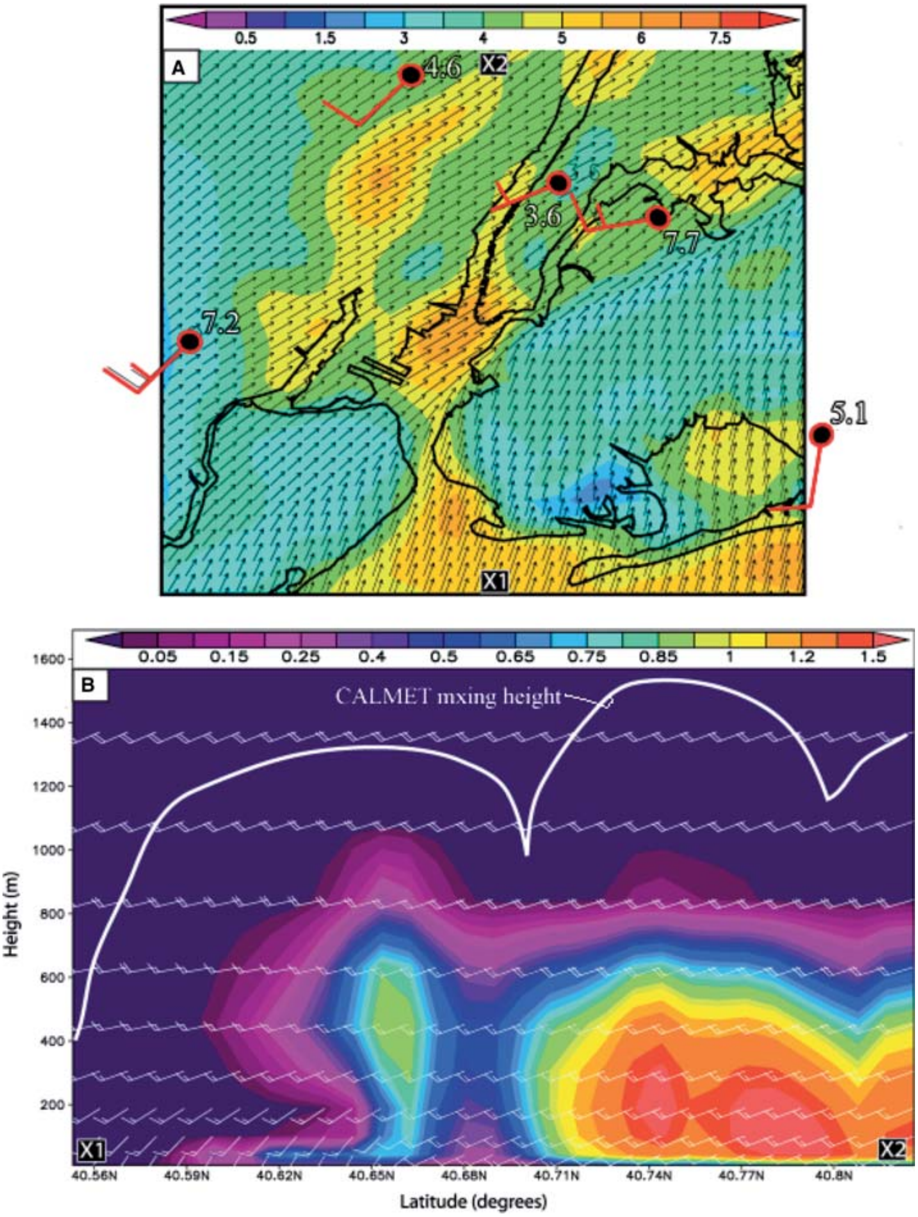

Figure 4

(**A**) ARPS simulated 10 m wind ($\mathrm{m{\cdot}s^{-1}}$) at 1500 LST on October 4, 2001. Wind speed is shaded with a legend at the top of the plot. Wind vectors are scaled according to the wind speed. ASOS wind observations for the same time are plotted overtop of the simulated fields with the standard barb notation in knots (Refer to wind barb legend in Figure 2). The observed wind speed values ($\mathrm{m{\cdot}s^{-1}}$) are shown next to the station plot. (**B**) North to south vertical cross-section of TKE ($\mathrm{m^2{\cdot}s^{-2}}$) and wind from the ARPS model across the model domain from point **X1** to **X2** in **Panel A**. TKE is shaded according to legend and wind is shown in standard barb format (kt). For comparison, the white line indicates the CALMET mixing height.

induced cyclonic turning in the winds over the main core of Manhattan. The CALMET wind direction for the same period was generally west-southwest as observed, however the CALMET wind speed was stronger over the land areas compared to the ARPS simulation. Over water, the ARPS simulation had stronger winds (4–6 m s^{-1}) compared to CALMET (2–4 m s^{-1}). The offshore buoy observation 35 km to the south-southeast of Manhattan reported southwest winds 6–8 m s^{-1} between 0630 and 0730 LST.

The second analysis used for evaluating this case occurs on the following afternoon. Temperatures were well above normal during the period with high temperatures reaching almost 300 K while sea-surface temperatures held around 290 K. Figure 4a shows the ARPS simulated 10 m wind field (speed in m s^{-1} shaded) along with the ASOS observations at 1500 LST on October 4, 2001. Evident in the wind field is a wind shift over Staten Island stretching over to the northern portion of Long Island. This is the sea-breeze front that has formed slightly inland. Surface observations agree with the existence of a sea-breeze front somewhere between JFK airport and LaGuardia airport, as the winds are south along the coast and more westerly inland. Other surface observations further inland indicate that the southerly wind associated with the sea breeze has not penetrated to Uptown Manhattan or westward into areas of New Jersey, as these observations show a west-southwest wind. With a stronger opposing wind, relative to the other cases, it is expected that the sea breeze will be held close to the coast along the New Jersey coastline, while the parallel flow to the Long Island coast will generally allow some inland penetration (SIMPSON *et al.*, 1977; ARRITT, 1993; ATKINS and WAKIMOTO, 1997). An examination of the CALMET wind field for the same time (not shown) does not reflect the sharp wind shift of the sea-breeze front, although the general wind direction is represented The interpolation scheme of CALMET allows only gradual changes in wind direction so frontal zones are not explicitly simulated.

The vertical distribution of wind and turbulence from south (X1) to north (X2) through this frontal feature is shown in Figure 4b. The frontal boundary is at 40.66 N as indicated by the south to west wind shift and elevated turbulence associated with an increase in upward motion along the sea-breeze front. The wide variation in boundary layer height determined from the turbulence profile is apparent as the sea-cooled air mass limits the vertical extent of mixing and the land-warmed airmass allows the boundary layer to grow to nearly 1 km. Similar to the previous case study, the CALMET-estimated mixing height (white line) seems to be overestimated when compared to ARPS. The synoptic review indicates that one-third (35%) of the days had strong southerly or strong westerly (Table 1) winds, and could be generally compared to this case.

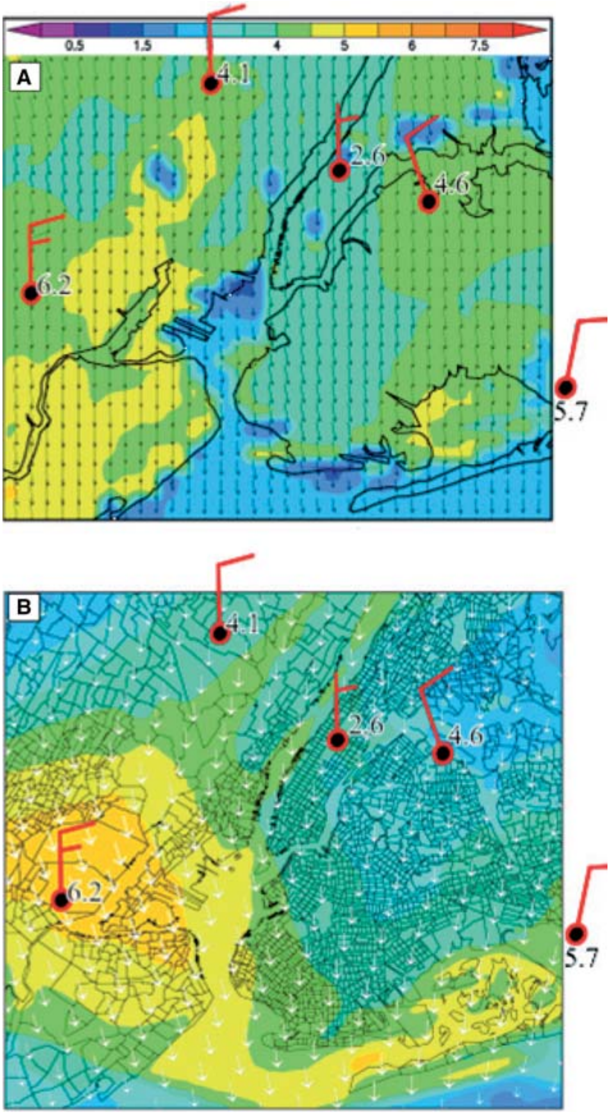

Figure 5
(**A**) MM5 simulated 10 m wind (m·s^{-1}) at 1400 LST on September 11, 2001. (**B**) CALMET simulated 10 m wind (m·s^{-1}) at 1400 LST on September 11, 2001. Wind speed is shaded (m·s^{-1}); legend is at the top of the plot. Wind vectors are scaled according to wind speed. ASOS wind observation from the same time period are plotted overtop of the simulated fields with the standard barb notation in knots (Refer to wind barb legend in Figure 2). The observed wind speed values (m·s^{-1}) are shown next to the station plot.

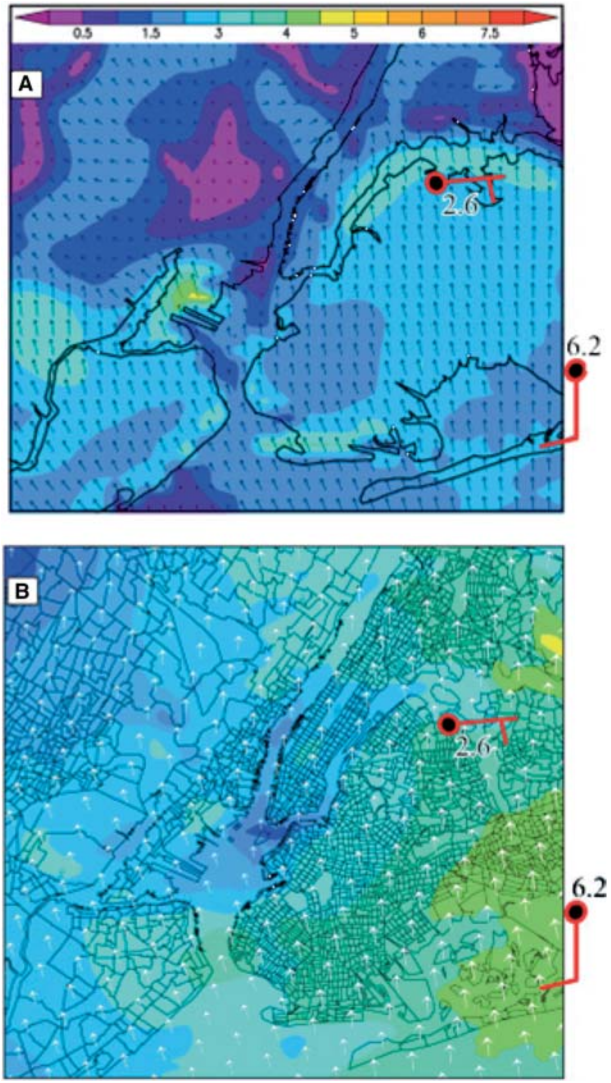

Figure 6
(**A**) MM5 simulated 10 m wind (m·s^{-1}) at 1400 LST on September 12, 2001. (**B**) CALMET simulated 10 m wind (m·s^{-1}) at 1400 LST on September 12, 2001. Wind speed is shaded (m·s^{-1}); legend is at the top of the plot. Wind vectors are scaled according to wind speed. ASOS wind observation from the same time period are plotted overtop of the simulated fields with the standard barb notation in knots (Refer to wind barb legend in Figure 2). The observed wind speed values (m·s^{-1}) are shown next to the station plot.

Case IV: September 11–12, 2001

Late on September 10, a surface cold front moved through New England, and out over the Atlantic Ocean. Behind this surface front, strong high-pressure (1027 hPa) ridged into New England and down through the Mid-Atlantic States. This led to subsidence throughout the atmosphere, which resulted in clear skies and brisk northwest winds over the NYC area on September 11. The strong high-pressure cell became situated directly over the Mid-Atlantic region on September 12. This period contains a case (September 11) that represents a strong northerly flow regime as outlined in Table 1 and also a light and variable, high pressure dominated case (September 12). A MM5-simulated 10 m wind field over the NYC region will be examined on the afternoon of each day.

Strong northerly flow existed on September 11, 2001. The simulated MM5 10 m wind field in Figure 5a shows a homogeneous distribution of the simulated mean wind direction at 1600 LST on the 11th. The simulated wind field over the region remained the same through the afternoon. The simulated wind speed ranges from 3.5 to 5.0 m s^{-1} across the region and seems to be correlated with the surface roughness variations specified by the MM5 landuse data set. The simulated winds are consistent with the overlaid ASOS observations in terms of wind direction, but the overall simulated wind speed is lighter than the observed values. The model simulation depicts an expected flow behavior for stronger northerly flow regimes. The CALMET simulation for the same time period is shown in Figure 5b. The CALMET wind field is similar with respect to wind direction, although the speed is greater. The overall wind speed is approximately 1–2 m s^{-1} stronger in the CALMET simulation.

Figure 6a shows the simulated 10 m wind field using the MM5 on the following day, September 12, 2001 at 1600 LST. High pressure dominated the area so the local effects became more apparent. The wind field manifests a sea-breeze front propagating through the domain. The sea breeze front can be detected as a southerly wind enhancement, inland over northeast New Jersey. The simulated front stretches across Manhattan and then along the East River. Several of the ASOS observations were missing during the afternoon nonetheless at this time the JKF airport ASOS observation agrees with the onset of a sea breeze as the winds have increased from a southerly direction. The LaGuardia airport observation is the only other wind measurement available at this time and it records an easterly wind. The LaGuardia wind observation did turn southerly the following hour, as did the wind at Newark and Teterboro, clearly indicating a sea breeze. The CALMET simulation shown in Figure 6b indicates a southerly wind over the entire area with stronger winds over the eastern domain. Lack of surface observations at this particular time resulted in a simplified CALMET wind field. In such cases the ADAS winds are used to aid in deriving a surface wind field. The 32 km ADAS data work well for upper-level winds that do not vary significantly over small areas, but it cannot resolve local effects closer to the surface.

This case demonstrates the ability of CALMET to represent the wind field over NYC reasonably well during stronger northerly flow regimes. In this case, the wind direction was well represented while the wind speed was overestimated by CALMET.

The synoptic review of the study period in Table 1 indicates that roughly 7% of the days during the study period were similar to the strong northerly flow exhibited in the September 11, 2001 case. Table 1 also indicates that about 16% of the days were similar to the light and variable flow that occurred on September 12, 2001. In these flow regimes, CALMET is less reliable as numerous local effects dominate the meteorology, and observations are not dense enough to provide CALMET an accurate wind field.

4. Conclusions

The goal of this investigation is to evaluate the meteorology of an observational-based CALMET model over the complex region of NYC. The CALMET meteorology is derived from a network of ASOS stations that have inherent bias since the wind observations are taken over open airfields, and are likely not representative of the wind in the built-up urban area. An independent data set taken from an observing system located in lower Manhattan was compared to the CALMET simulation to show any bias or uncertainty in the model. Also, dynamically driven numerical models were used to examine some of the local effects in the region that may not be correctly captured by the CALMET model. Simulations were performed after a careful evaluation of the synoptic weather over the study period, so that the simulations could be representative of not one, but a group of similar days. The following is a summary of conclusions of the results.

- CALMET meteorology is suitably representative of the NYC area during stronger wind flow scenarios, which occurred approximately 42 percent of the study period. We compared the CALMET wind field with several mesoscale model simulations, which showed fairly uniform wind distribution over NYC. The meteorology provided to CALPUFF by CALMET during such flow conditions will likely provide adequate WTC plume transport and dispersion. The CALMET mixing height algorithm may compute a deeper convective mixed layer in coastal areas than that which would be observed. The CALPUFF concentrations, which are influenced by the mixing depth, may therefore be underestimated during the daytime. However, more cases are needed to verify this claim.
- Numerical simulations showed that during light southerly flow regimes, sea-breeze fronts frequently passed over lower Manhattan. In many of these cases the CALMET model experienced problems resolving important details of the frontal evolution including the discrete wind shift, timing and location. A review of the weather patterns after September 11 revealed that during about 35 percent of the days the winds were light and from the south. Past research, observations and the numerical models (both ARPS and MM5) revealed that the wind flow and stability of the sea breeze resulted in complex flow patterns across lower

Manhattan and western Long Island. Typically with the sea breeze, the wind direction in CALMET could be off by as much as 45°. In all cases where CALMET resolves the sea breeze, the front is not discretely represented because of the interpolation method, and the timing is off because all but one ASOS station are located inland. As with strong flow cases, the CALMET mixing depth exceeds simulated by the mesoscale models. If the CALMET model overestimates the mixing height, it will lead to an underestimation of the CALPUFF concentrations. At night, the CALMET-estimated boundary layer depth is close to that from the mesoscale models. These events occurred during 25 percent of the simulation period.

- The observed wind direction downwind of the urban core of Manhattan backed or turned cyclonically 34° relative to the simulated CALMET wind. This wind direction bias in CALMET will influence the plume position estimated by the CALPUFF dispersion model around lower Manhattan.
- CALMET derived wind speeds have a bias as much as 1.5 m s^{-1} in wind speed when compared to observations in lower Manhattan. This bias in the meteorology will influence the dispersion calculation made by the CALPUFF dispersion model, presumably underestimating the concentration.

Overall, the CALMET model was found to provide meteorology that is adequate for driving a plume model most of the time. Naturally, the quality of CALMET is closely related to the quality and representativness of the input observations. For circumstances in which the meteorology is complicated by mesoscale features like the sea/land breeze circulation or a significant urban heat island, and computer resources are available, a full-physics model could be used to provide improved meteorological fields.

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. 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. We thank Bob Kelly and Henry Feingersch (US EPA Region 2) for their support of the application of meteorological models and instrumentation following the events of September 11, 2001. We also thank the North Carolina Supercomputing Center for use of computer resources for the ARPS and MM5 simulations. The CAPS group at the University of Oklahoma was instrumental in providing not only the source code of ARPS but also the assimilated data used to initialize the model. We would also like to thank Dr. Gary Lackmann, (associate Professor at North Carolina State University) and James Godowitch (NOAA), for their constructive review of the paper.

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(Received August 11, 2004, accepted October 20, 2004)