Meteorological Data for Atmospheric Dispersion Modeling in Urban Areas with Washington, DC Example

by Ronald L. Baskett

Certified Consulting Meteorologist

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Abstract

This paper discusses how meteorological measurements are used in modeling atmospheric releases in urban areas. For a background perspective, I briefly review urban meteorology with a focus on how cities affect wind flow and turbulence at the relevant scales of interest to plume dispersion. Next is an overview of the types and sources of surface and upper air meteorological observations typically available electronically in near real-time in cities. I show how these wind observations are used to initialize 3-dimensional dispersion models with an example application to the Washington, DC area.

Urban Meteorology

To understand the meteorological requirements for modeling atmospheric dispersion in cities, we address the relevant scales of motion. Figure 1 shows a simplified diagram of the vertical extent that cities can influence processes in the lower atmosphere. The extent of effects of urbanization on the atmosphere is known as the **Urban Boundary Layer (UBL)**. Meteorological processes relevant for modeling atmospheric releases in metropolitan areas vary in each of three sublayers layers within the UBL: The **Mixed** or **Mixing Layer,** the **Surface Layer** and the **Canopy Layer**.

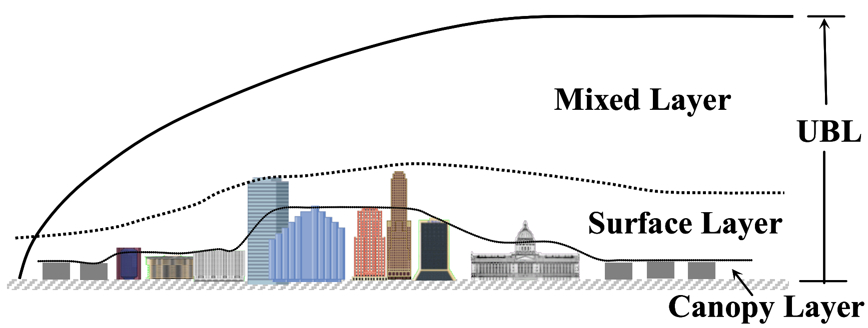


Figure 1. Structure of the urban boundary layer

Figure 2 illustrates the atmospheric scales of motion typically involved in modeling flow over a city. The largest scale shown is the **Mesoscale** which can extend from 20-200 km in range. The general term for the region of interest is called the **Planetary Boundary Layer (PBL)**. Over a city we call the PBL the **Urban Boundary Layer (UBL)** and over rural area, the **Rural Boundary Layer**. The PBL typically varies in height diurnally from 1 km or more during the daytime to a few hundred meters overnight. Due to the larger roughness elements, e.g., buildings, and warmer surfaces, Urban BLs are typically deeper than surrounding Rural BLs.

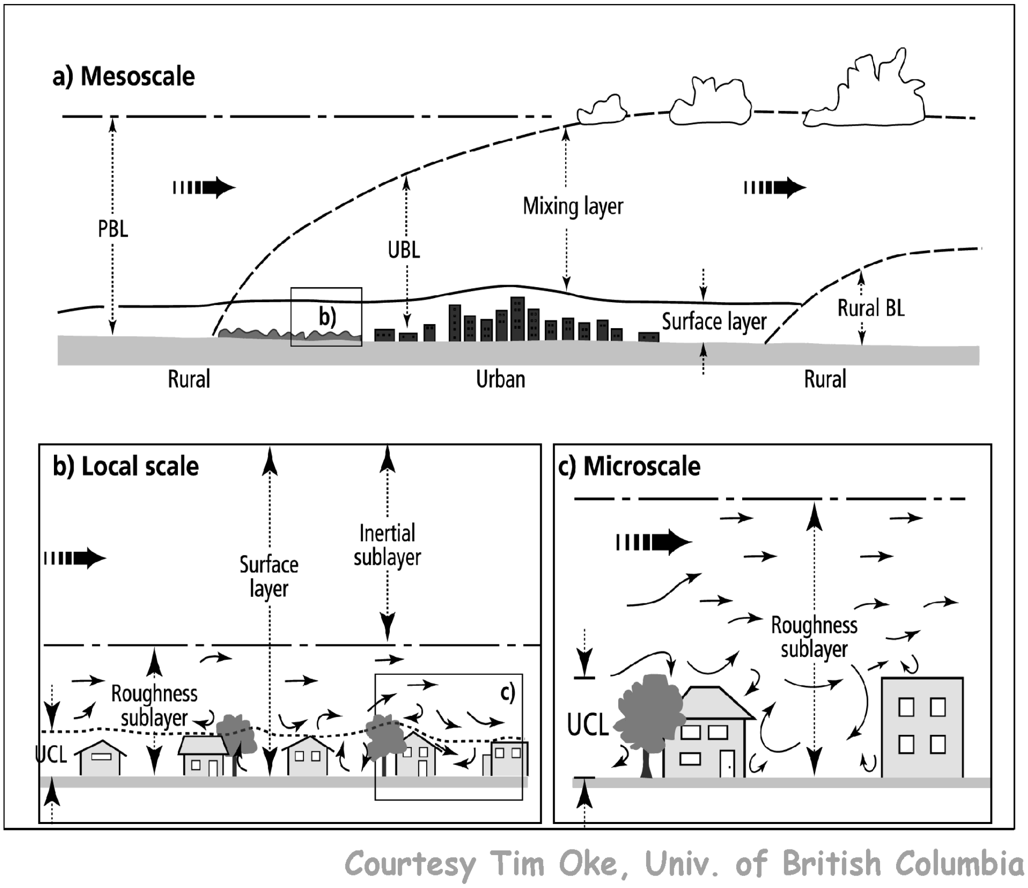


Figure 2. Urban influences on meteorological flows at three atmospheric scales

The **Mixing Layer** extends from the top of the **Surface Layer** to the top of the Urban Boundary Layer. Throughout this layer the wind speed and direction as a function of height, or wind profile, is driven by mesoscale and larger scale weather systems but may be significantly modified by terrain and city features as building complexes, trees, parks, water bodies. (See: [Boundary Layer Characterization – Air Resources Laboratory (noaa.gov)](https://www.arl.noaa.gov)).

On the 2 to 20 km **Local Scale** (Figure 2b) land use features, such as one-two story residential or multi-story commercial areas, high rise city centers, water bodies, or parks, influence the wind and turbulence in the **Surface Layer.** The surface layer typically extends up to roughly 10% of the height of the Urban Boundary Layer.

On the 20 m to 2 km **Microscale** (Figure 2c**,** individual buildings and other features on the surface determine wind and turbulence in the streets up to the top of the "**Roughness Sublayer**." Within this layer is the **Urban Canopy Layer (UCL)** where turbulent flows around buildings and through street canyons are at scales comparable to the width of a street canyon. The UCL height is roughly the mean height of the buildings in a local area and can vary significantly over the extent of a city that has a dense central business district with lower buildings in surrounding commercial and residential areas. Mechanical turbulence is generated by flow over roughness elements at the surface. Convective turbulence is created by daytime heating of urban surfaces, also referred to as the Urban Heat Island. Both mechanical and thermal turbulence are typically greater in cities than over rural areas.

Sources of Meteorological Data

Surface Measurements

Automated meteorological data in cities come from a variety of public and private sources with varying accuracy and quality. The National Weather Service and the Federal Aviation Administration provide hourly observations from 10 m towers at 1400 airports throughout the country. These standard federal observations are called Automated Surface Observation Stations (ASOS) and Automated Weather Observation Stations (AWOS). State and local air quality districts also collect reliable, high-quality data on 10 m towers in most major cities in the US. Many other federal, state, and local agencies (departments of transportation, water treatment, fire, emergency response) as well as private weather groups provide additional data with varying quality.

Each station represents an area of wind flow the size of which depends on the height of measurement, how openly exposed the station is sited, and what is upwind or fetch of the tower. If openly exposed such as at an airport, surface towers can represent several km in radius. Representativeness in residential areas may be only half a km. In commercial or downtown areas, towers must be sited on rooftops or above the urban canopy layer to be usable in modeling. Depending on the height of a rooftop tower, position of the tower on the roof relative to the wind direction, and height of the surrounding buildings, rooftop wind data may represent flow conditions up to 0.5 or 1 km radii.

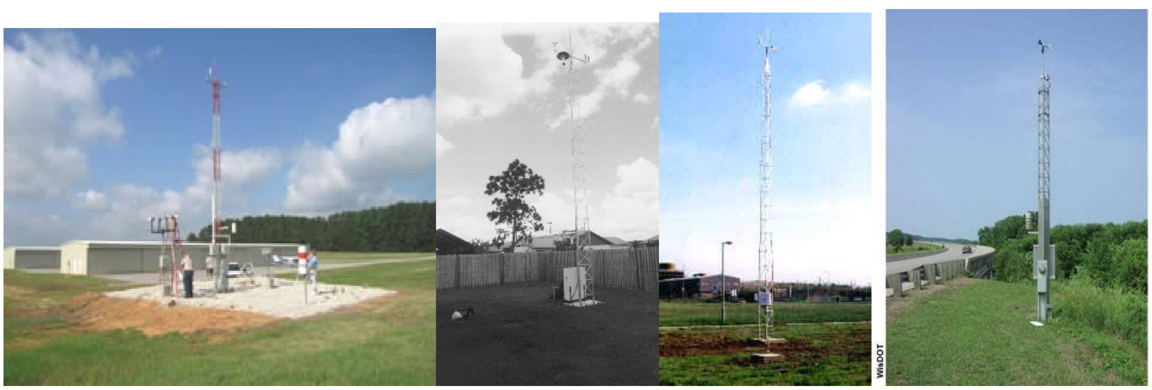


Figure 3. Example surface towers (airport, private backyard, open field, along highway)

Figure 4. Example rooftop towers

Coupled together an urban mesoscale network or "mesonet" of stations can number 50-100 in major US metropolitan areas. A network this size is sufficient to characterize flow at the local scale, but not at the microscale. It is not practical to make enough measurements to characterize microscale flows on every street, so estimating flow on this scale must be left to models.

Upper Air Measurements

Much more sparsely separated that surface measurements are those stations which collect data in the boundary layer and higher. The primary federal **upper air** network relies on twice-daily (0000 and 1200 UTC) weather balloons to transmit data from the surface to the top of the atmosphere at 92 locations across the US. That means that the typical separation between federal upper air stations in the US is 250 to 400 km, spacing designed for and appropriate to initialize the **Synoptic** or large-scale national weather forecast models (20,000 km domain).

Figure 5 shows an example output from a **rawinsonde observation (Raob)**. Note that these wind reports only provide a few data points in the PBL (the vertical scale on the left side of the line is pressure; the right side is height above ground in meters). Wind data are shown as wind barbs with wind direction from the direction of the barb and the length and number of barbs indicating the speed.

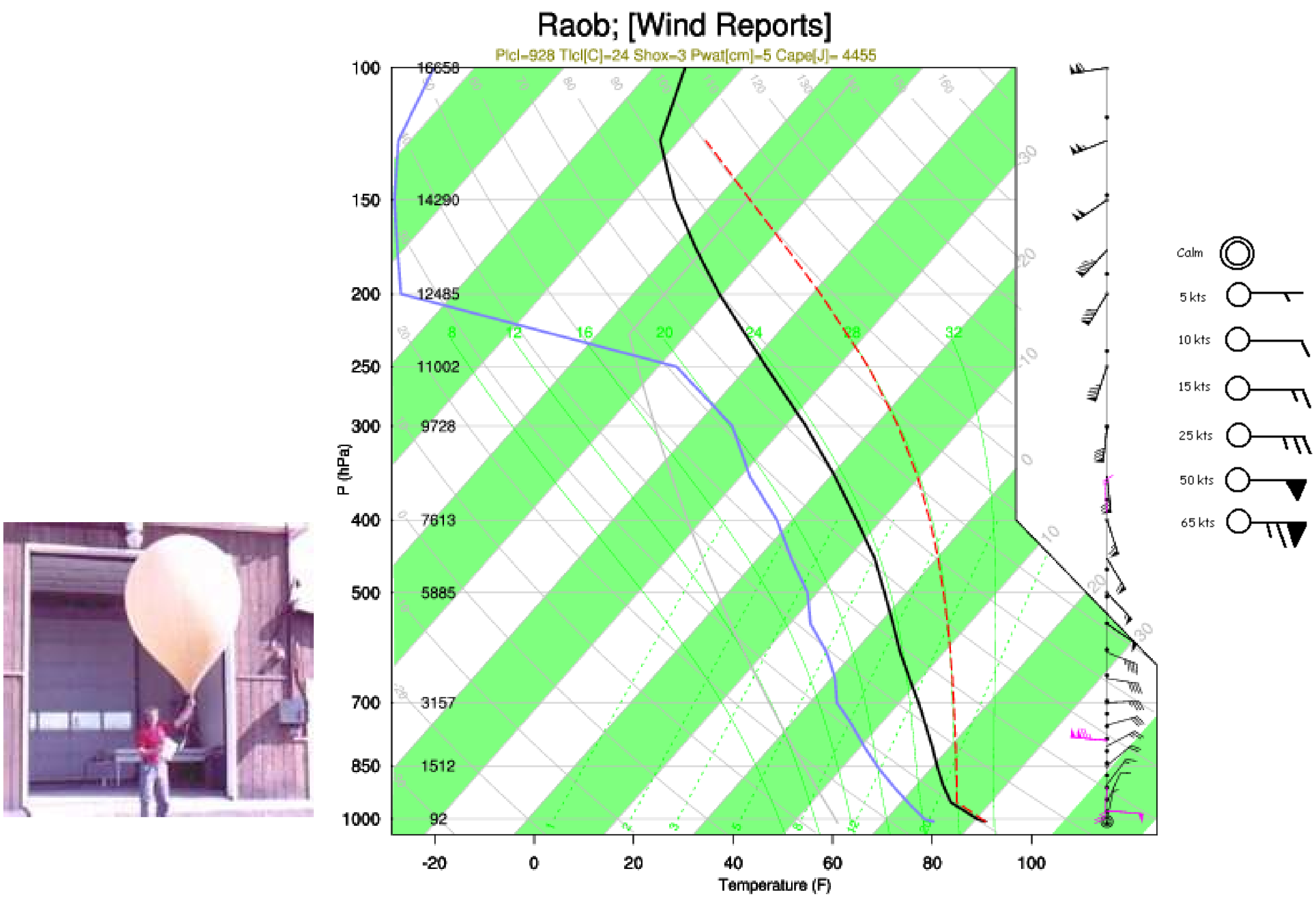


Figure 5. Rawinsonde balloon (left) and example vertical sounding profile (center) with key to wind barb display (right)

Boundary Layer Profilers (BLPs) are **UHF Doppler radars (Radio Sounding and Ranging)** report vertical profiles of horizontal winds starting about 100 m above ground level (AGL) and extending up to about 4 km above ground in layers each about 100 m deep (Figure 6).

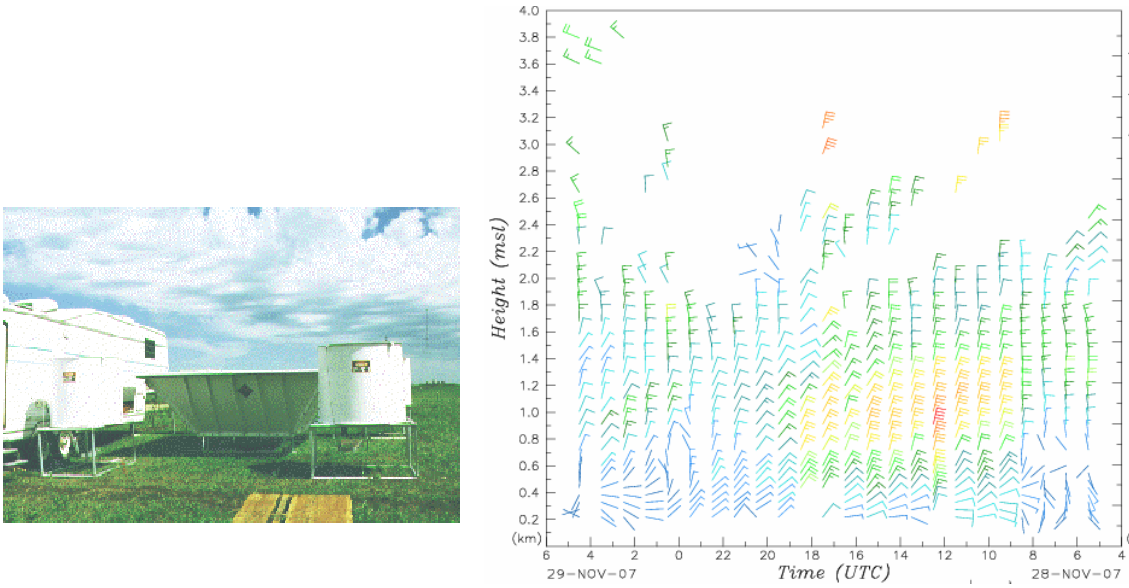


Figure 6. Boundary Layer Profiler with example wind profile graphical output

Sending upward radar pulses at frequencies around 915-924 MHz, Doppler wind profilers detect the back-scattered signal from multiple radar beams that are directed either vertically and at small angles from the vertical. Hundreds of measurements of the Doppler shift in the return frequency are used to calculate the mean 30–60-minute horizontal wind vector in each layer. With the addition of an optional **Radio Acoustic Sounding System (RASS)**, virtual temperature profiles up to about 1 km can also be measured. Data are publicly shared from about 100 BLPs around the US, many in major cities.

Similar to the use of radar pulses for the profilers, **Sound Detection and Ranging (Sodar)** systems (Figure 7) bounce acoustic pulses off the atmosphere to measure the Doppler shift in return frequency and calculate wind speed and directions multiple layers above ground. Audio frequencies are in the range 1300-4500 Hz with the lower frequencies attenuating at about 200 m AGL (minisodar), medium to 1 km (midrange sodar), and higher to 5 km (megasodar). The signal is transmitted as a series of "beeps" every few seconds at 60-100 decibels. Minisodars can be operated within 100 yards of a dwelling without being a source of aggravation, but medium or larger sodars have siting limitations due to the loud pulse. The receiving antennas are often shielded from ambient noise sources by hay bales or other barriers, with the resulting structure being up to 8 feet in height. Sodars produce wind profile data reports similar to the BLP.

Figure 7. Example minisodar on ground and on rooftop

More sophisticated and expensive techniques to measure upper air winds include deriving wind speed and directions from **Dual Doppler Lidar (Light Detection and Ranging).** Lidars detect the backscatter from a laser pointed upwards or tilted to measure winds, temperatures, water vapor concentrations, or the presence of aerosols. Dual-Doppler lidar provide profiles of turbulence in the planetary boundary layer that are inaccessible using traditional methods. However, the raw radial data must be processed in order to derive horizontal wind data.

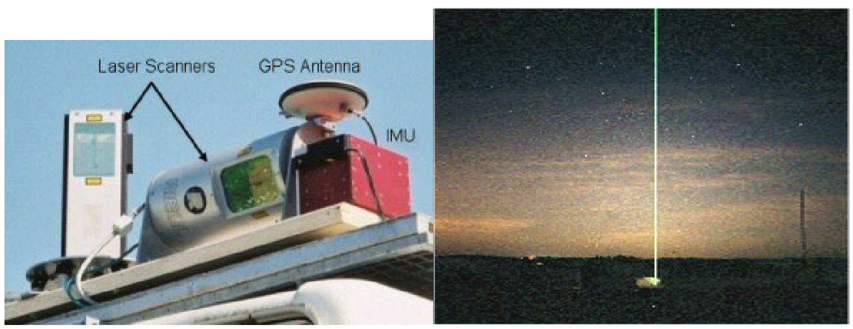


Figure 8. Lidar sensors and nighttime operations

Initialization of Dispersion Models

Local to mesoscale models

Meteorological observations are commonly used to initialize both wind and turbulence in operational dispersion models. Figure 9 illustrates how a three-dimensional dispersion model uses multiple surface and upper air profile stations to create an initial estimate of the three-dimensional "wind field" over a particular modeling volume, or "domain."

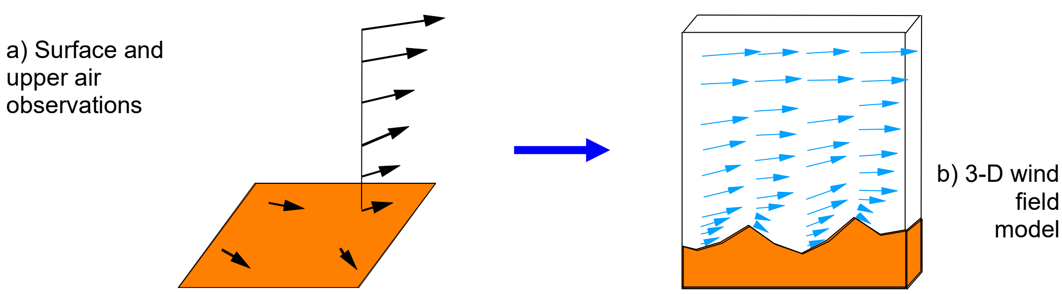


Figure 9. Data from (a) multiple surface towers and upper air profiles used to initialize a (b) 3-D wind field model

Three-dimensional models employ a grid system to solve various physical processes. The overall domain or extent of the grid system will be set to cover the extent of concern for a particular release. Figure 10 illustrates a sample model grid consisting of thousands of intersections of grid lines or grid points. The spacing between the grid points determines the ability of the model to correctly treat the scale of the physical process being simulated. To resolve wind and turbulence processes on a particular scale, many grid points are needed on a smaller spacing.

For example, to resolve winds flowing over buildings in the surface layer on the 2 to 20 km local scale, grid spacing could be set to a resolution of 250 m by 250 m by 100 m (east-west, north-south, vertical). To estimate wind vectors in street canyons on the 20 m to 2 km microscale, grid spacing would need to be on the order of 1 m by 1 m by 1 m. Some models use even grid spacing, but a more computationally efficient method is variable grids, where increased resolution is placed where processes are smaller scale. Such is the case with the grid system shown in Figure 10, where both horizontal and vertical grid spacing are smaller near the release point and in the surface layer.

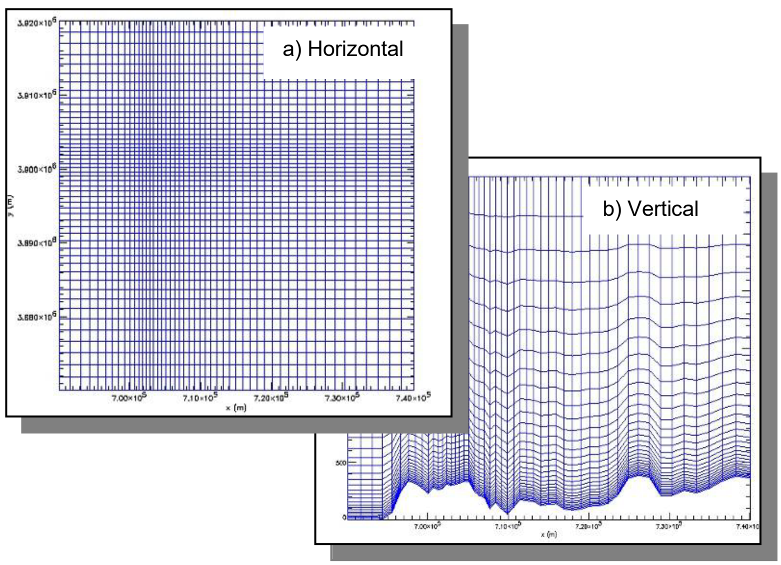


Figure 10. Example model grid system for a 3-D dispersion model

To generate a 3-D wind field, observed wind speeds and directions are extrapolated from their measured location to each model grid point. As wind flow is typically 10 to 100 times stronger in horizontal than the vertical, wind data can only be practically extrapolated in horizontal layers. The most common method of extrapolating measurement data horizontally to model grid points throughout the domain is an "inverse distance weighting" scheme. Each measurement is given a $1/r^2$ weight at every grid point, where r is the distance from the measurement to the grid point.

As measurements "at ground level" (typically on towers up to 10 m high) are relatively inexpensive to take, many of these are available in cities. With increased cost, towers placed on building tops are typically fewer. Due to the high cost, measurements in the PBL above buildings are relatively sparse. In most cities, typically only one profile in the Mixing Layer is available in or around a city to initialize the wind flow above the Surface Layer for the whole city. Figure 5 conceptually illustrates the extent of influence of different types of wind measurements on the area would have when used to initialize a wind model.

If sited in open areas at least 10 heights away from a building or other features, surface-based towers may represent winds up to a 0.5-1.0 km radius. Openly exposed sensors placed on rooftop towers can represent the flow up to several km in radius. Wind measurements in an upper air profile will represent conditions with increasing radius as a function of height. Measurements in the planetary boundary layer may represent flow in a radius of only a few km in the mountains, 10 or 15 km in hilly areas, or more than 25 km in flat terrain.

That said, at any time, a station's representativeness is a function of local weather conditions and seasonal effects, such as deciduous trees, or upwind fetch from a particular direction. Typically, when winds are strong, a station's representativeness is largest. When winds are light and variable, even upper air data will reflect only conditions in a small radius from the station.

Enough surface and building top measurements are usually available in cities to sufficiently initialize the surface layer in local to mesoscale dispersion models. Since wind flows are more uniform in the boundary layer above the surface layer, only a few widely-spaced profilers are needed to initialize the wind model. However, profilers are not available in most US cities.

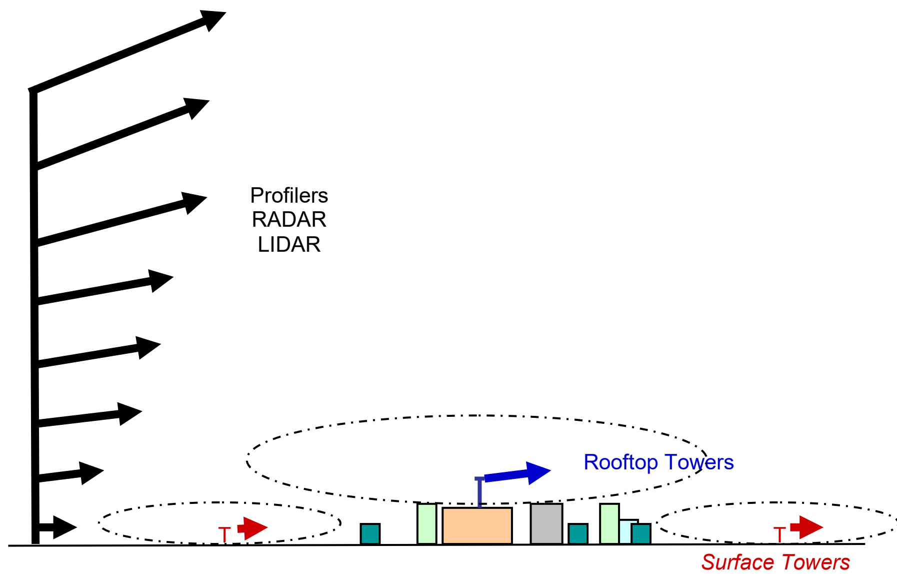


Figure 11. Illustration of the area of representativeness for urban meteorological measurements

To summarize, the accuracy of a model calculation strongly depends on the quantity and quality of input meteorological observations. A model's treatment of the physics of the wind flow and turbulence on the relevant atmospheric scales is also important to accurately characterize dispersion of a hazardous release. After observational data are extrapolated to model grid points, most operational local to mesoscale 3-D dispersion models use a set of equations to create a "mass consistent" flow in and around terrain features. This means that wind vectors at each grid point are calculated based on physical principles that determine if wind will flow over, around or be blocked by the terrain features. In addition, depending on the time of day and other factors, the model computes a small vertical wind component and 3-D turbulence parameters at each grid point.

However, atmospheric models at this scale do not have sufficient resolution or physics to compute microscale flows – that job is left to microscale models. That said some "building aware" local models employ parameterizations of the physics around buildings to produce maps which can approximate the channeling in and around street canyons.

Microscale Dispersion Models

Microscale models typically are based on equations that treat the full physics of wind flow and turbulence. They are the only practical way to produce estimates of winds at 1 m resolution which people experience at the street level. Relying on Computational Fluid Dynamic (CFD) framework, these models are typically run on domains of a km or two with millions of grid points and actual building geometries included in the surface layer. Even when run on supercomputers CFD codes take 1 hour of computer time to simulate 1 hour in the real world. Consequently, while they provide the most detail, they are not always timely for emergency response applications.

Figure 12 shows an example vertical cross section of wind vectors (in white) over color-shaded air concentrations. The release is the red spot in the building wake. West winds create swirls which bring down and trap some of the release on east side of the downwind buildings.

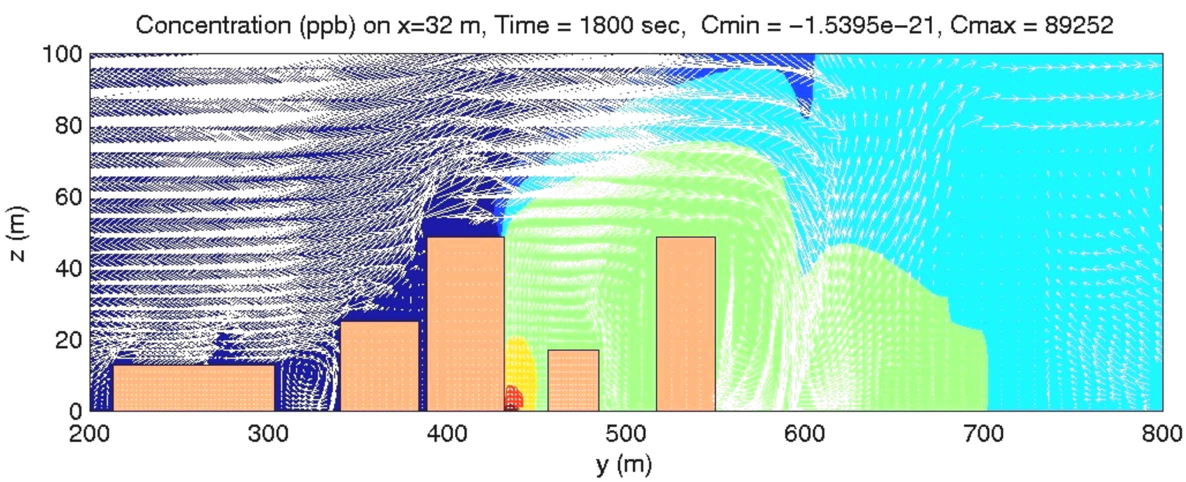


Figure 12. Illustration of microscale CFD dispersion model calculation

Meteorological Data in the National Capitol Region

In addition to federal ASOS and local data, NOAA has installed a network of 15 roof-top towers in the National Capitol Region (NCR). Figure 13 depicts this network and the exposure of a typical installation. DCNet provides excellent high-quality data to initialize surface layer winds in dispersion models.

Figure 14 illustrates the representativeness of wind data from four towers in Washington, DC. The "wind roses" show the frequency of wind directions for each of 16 compass points taken over a year's time. The colors indicate wind speed ranges. The three DCNet rooftop locations on the National Mall show similar flow conditions at 30-40 m above ground, while the lower-level ground-based tower (sensors at 10 m above ground level) at Reagan National Airport is influenced much of the time by channeling of winds along the Potomac River. These towers illustrate the spacing between towers needed to characterize the variation in wind flow in the surface layer over cities.

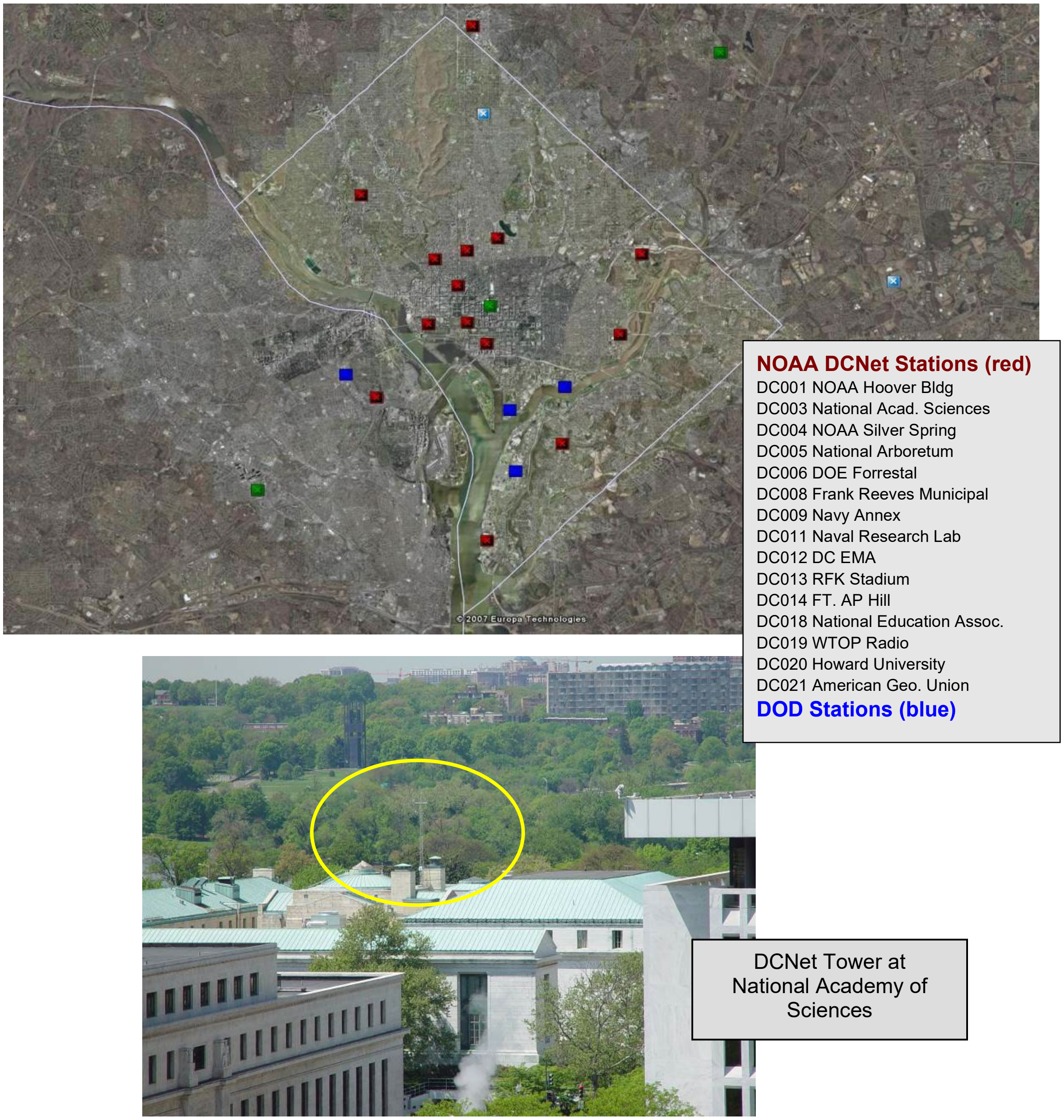


Figure 13. NOAA's DCNet rooftop towers
(Courtesy NOAA Air Resources Laboratory)

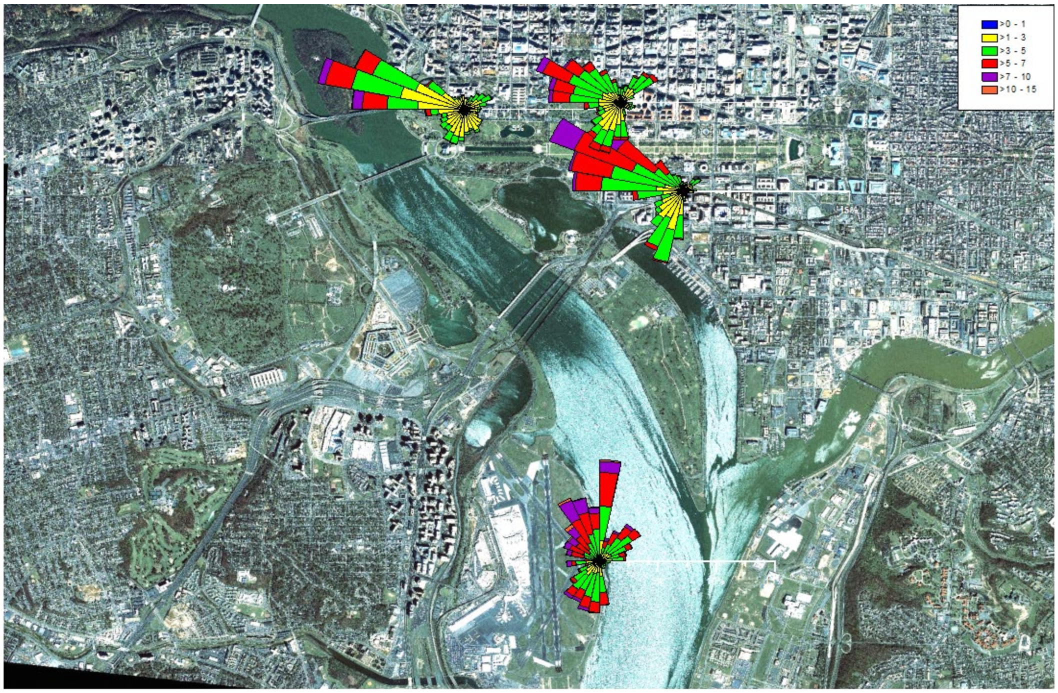


Figure 14. Comparison of annual wind roses at three DCNet rooftop towers around the National Mall with Regan National Airport surface tower (southern location)
(Courtesy NOAA Air Resources Laboratory)

Figure 15 illustrates the meteorological data available in the NCR. The example data represent a common prevailing WNW flow condition, in this case at 9 am EST on December 4, 2007.

The nearest rawinsonde in the NCR is at Dulles International, where the National Weather Service releases balloons twice daily at 0400 and 1600 local time (0000 and 1200 UTC). At over 30 km from the National Mall, the boundary layer winds measured at Dulles are likely only valid over the Mall during uniform moderate to high wind conditions (5-10 m/sec).

Figure 15 shows the location of the nearest Boundary Layer Profiler in the NCR at Beltsville, MD. The Maryland Department of the Environment makes this data available over the Internet through the NOAA's Meteorological Assimilation Data Ingest System (MADIS) Cooperative Agency Profilers project. During moderate wind conditions, the wind data from a few hundred meters above ground to the top of the profiler represent flows in the PBL about 10 or 15 km from the profiler.

The dashed green in Figure 15 illustrates the approximate 15-km radius arc for the two upper air stations in the NCR. This particular example morning hour is indicative of the predominant westerly wind flow that occurs much of the time in DC. Figure 16 illustrates two layers of a model-generated wind field, one at 10 m AGL and one at 500 m AGL. At 500 m AGL, winds were consistently from WNW over the whole NCR. Figure 17 shows the variation in surface winds over the smaller area around the National Mall south to Reagan Airport. While surface winds over the city that morning are about 7 m/s (~15 mph), winds over rural areas are mostly lighter and more variable. Relatively consistent directions are common throughout the entire boundary layer during these moderately strong wind conditions, but not so during lighter flows.

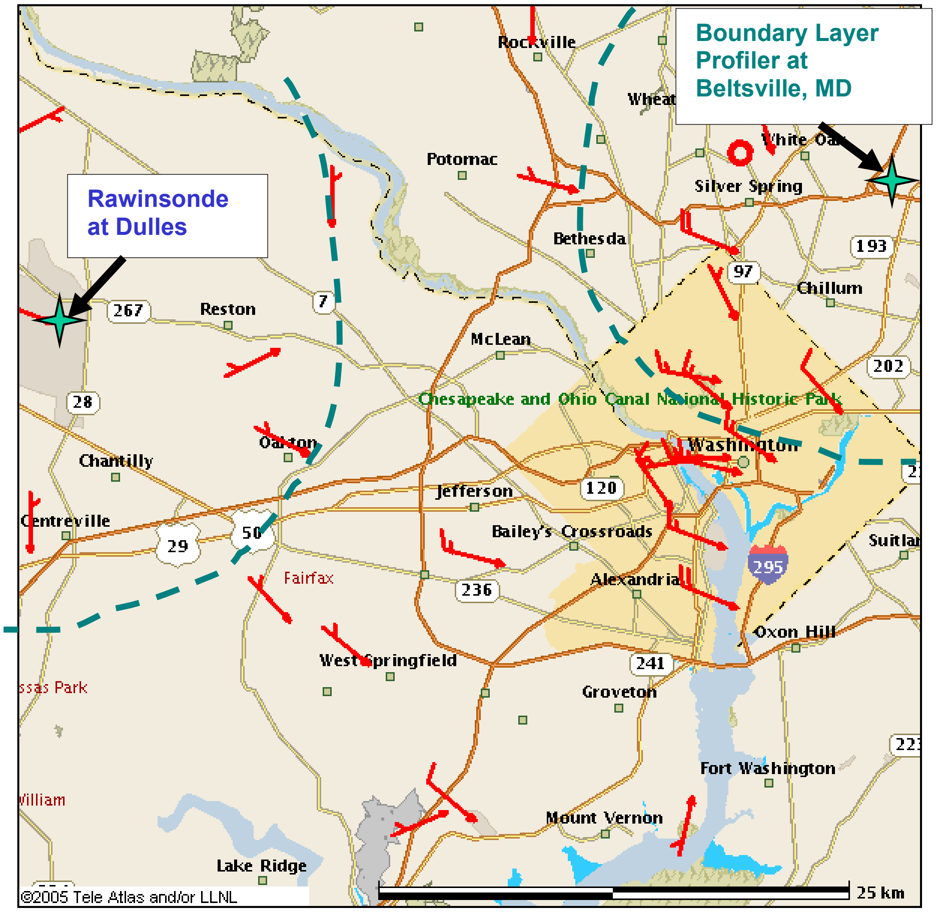
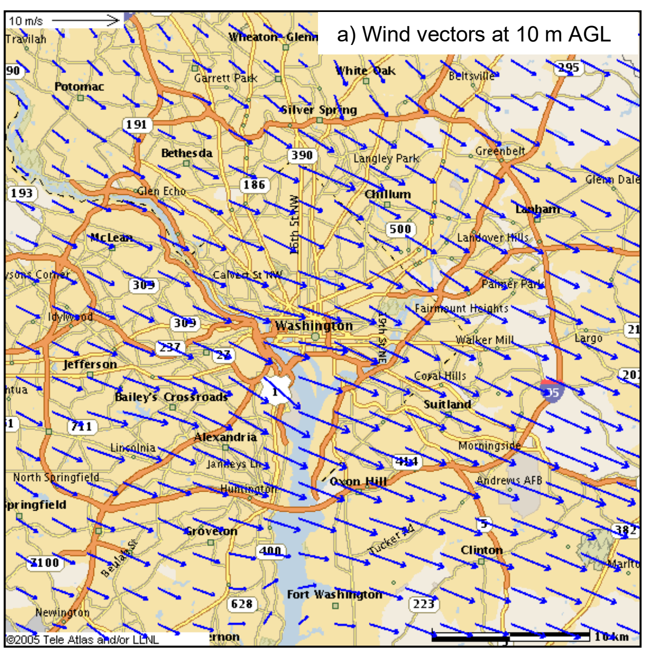


Figure 15. Example surface and upper air data available in the NCR at 9:00 am EST on December 4, 2007



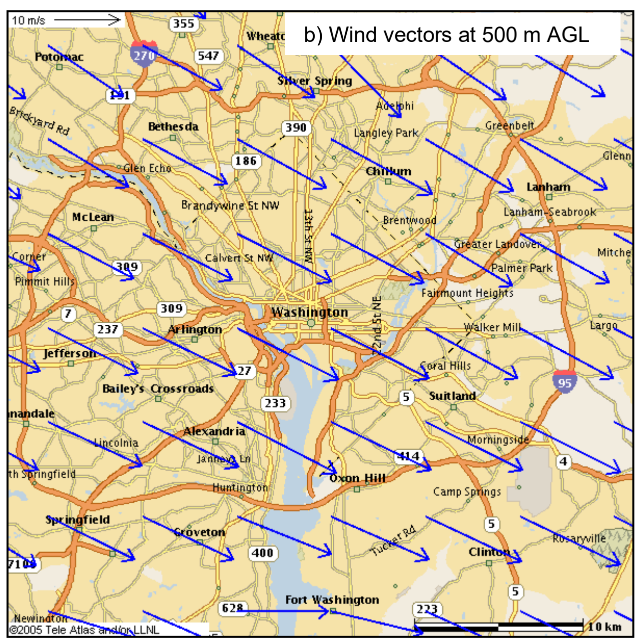


Figure 16. Example modeled wind fields over NCR at 9:00 am EST on December 4, 2007

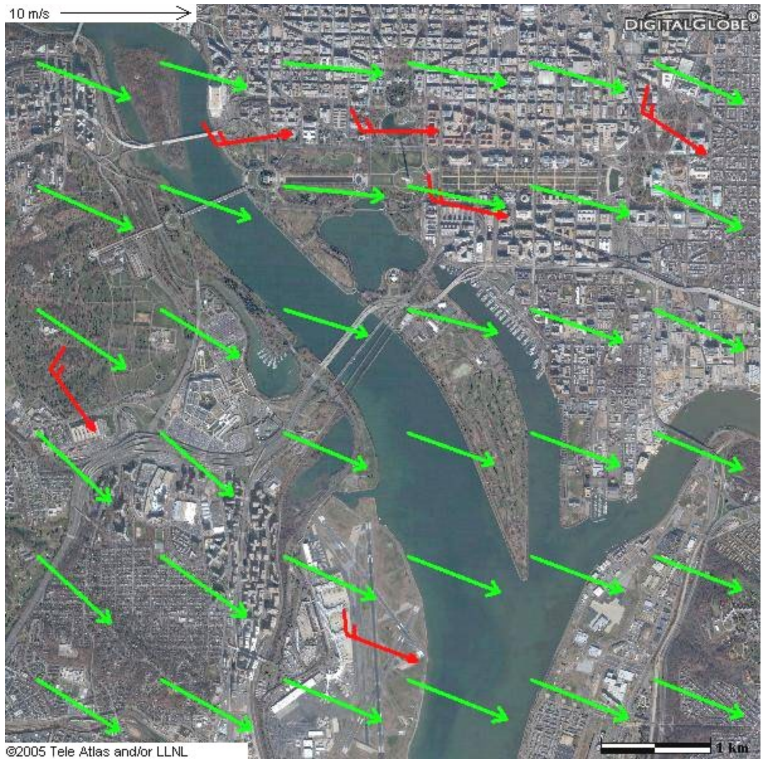


Figure 17. Modeled wind vectors at 10 m AGL (green) over Washington, DC
compared with surface and roof-top wind data (red barbs)
at 9:00 am EST on December 4, 2007

Pentagon Force Protection Agency

The DOD tested surface and vertical wind systems in the vicinity of the Pentagon (Warner, 2007). The Coherent Technologies, Inc. (CTI) *Windtracer* scanning Doppler lidar detects aerosols around the Pentagon and generates radial wind velocities in the PBL. In addition, the monitoring network during the 2004 tracer study included a minisodar with data to 200 m AGL.

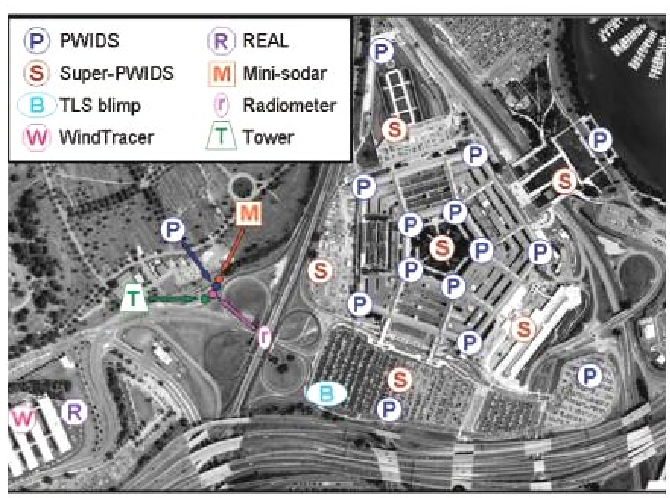


Figure 18. DOD sensors for the Pentagon Shield Program (Courtesy Warner, 2007)

Selected References

Mesonet data

- US National Mesonet Program –
- NOAA MADIS US-wide mesonet data: http://madis.noaa.gov/
- NOAA Upper Air rawinsonde data: http://www.ua.nws.noaa.gov/
- NOAA Earth System Research Laboratory Global Systems Division Boundary Layer Profilers: http://www.etl.noaa.gov/et7/data/
- NOAA DCNet Data: http://dcnet.atdd.noaa.gov/
- Quick Links | National Centers for Environmental Information (NCEI) formerly known as National Climatic Data Center (NCDC) (noaa.gov)
- NOAA ARL READY Current Meteorology (noaa.gov)
- MesoWest Data (utah.edu) – Data and mapped displays of surface stations
- University of Wyoming - Radiosonde observation (RAOB) graphics and data Atmospheric Soundings (uwyo.edu)
- University of Nevada Desert Research Institute - Remote Automated Weather Stations RAWS USA Climate Archive State Selection Map (dri.edu)
- California Air Resources Board (CARB) Subject Top Page: AQMIS 2 - Air Quality and Meteorological Information System
- WMO Guide to Meteorological Instruments CWOP-WMO8.pdf (weather.gov)

Mesonet instrumentation

- Warner, Thomas, *et.al*., 2007. The Pentagon Shield Program. *Bulletin of the American Meteorological Society. Feb. 2007:* 167-176.
- Fearon, M. G., T. J. Brown, and G. M. Curcio, 2015: Establishing a national standard method for operational mixing height determination. J. Operational Meteor., 3 (15), 172-189, doi: http://dx.doi.org/10.15191/nwajom.2015.0315.
- Tech Memos – Air Resources Laboratory (noaa.gov)
- Tech Memo ERL ARL-229 (PDF, 10.1MB) – A Study to Characterize Performance Statistics of Various Ground-Based remote sensors; Crescenti, G. H., 1999.

Weather Maps

- Colorado State University NWS DIFAX Map Archive (colostate.edu)
- NOAA Weather Archives - Data and Maps

Satellite Imagery

- NOAA GOES Geostationary Satellite Server
- University of Wisconsin GOES Online Geostationary Archive - Satellite Data Services (wisc.edu)
- NASA EOSDIS Worldview (nasa.gov)

Urban Modeling in DC

- High-Resolution Meteorological Monitoring over the National Capital Region: Data from the DCNet Network
- The Influences of Urban Building Complexes on the Ambient Flows over the Washington–Reston Region

Acronyms

AGL	Above ground level
ARL	Air Resources Laboratory (NOAA)
BLP	Boundary Layer Profiler
CFD	Computational Fluid Dynamics
CTI	Coherent Technologies, Inc. (manufacturer of *Windtracer*)
DCNet	Network of meteorological stations in Washington, DC (NOAA)
DOD	Department of Defense
Lidar	Light Detection and Ranging
MADIS	Meteorological Assimilation Data Ingest System (NOAA)
NCAR	National Center for Atmospheric Research
NCR	National Capitol Region
NOAA	National Oceanic and Atmospheric Administration
PBL	Planetary Boundary Layer
Radar	Radio Detection and Ranging
RASS	Radio Acoustic Sounding System
Sodar	Sound Detection and Ranging
UBL	Urban Boundary Layer
UDP	Urban Dispersion Program
US	United States of America

Appendix A. US EPA SCRAM Observational Meteorological Data

Air Modeling - Observational Meteorological Data | US EPA
Observed meteorological data for use in air quality modeling consist of physical parameters that are measured directly by instrumentation, and include temperature, dew point, wind direction, wind speed, cloud cover, cloud layer(s), ceiling height, visibility, current weather, and precipitation amount. These data are used in air quality models to capture the atmospheric conditions occurring at a source and/or receptor location, and therefore, play an important role as they effect the concentration of pollutants at receptors of interest. This site describes and provides the following programs and databases, as commonly utilized by the EPA in conducting air quality modeling:

Surface and Upper Air Databases - Surface data are meteorological data that are measured at the earth's surface and include physical parameters that are measured directly by instrumentation, such as temperature, dew point, wind direction, wind speed, cloud cover, cloud layer(s), ceiling height, visibility, current weather, and precipitation amount. Upper air data are meteorological data that are measured in the vertical layers of the atmosphere. Much of this data is reported by the National Weather Service (NWS).

EPA has compiled a database of observed meteorological data over the continental U.S. These data are used in adjusting air quality trends to account for year-to-year meteorological variability. A summary of the contents of the "MetDat" database is contained within the report Details on the Omnibus Meteorological Database (PDF).

Meteorological Processors and Accessory Programs - The meteorological processors are used to calculate important meteorological inputs for use in dispersion modeling. The accessory programs are applied to produce graphical or statistical outputs that can aid in the interpretation and understanding of the NWS data or dispersion modeling results.

Appendix B. US EPA SCRAM Mixing Height Data

The mixing height data offered at SCRAM Mixing Height Data | Support Center for Regulatory Atmospheric Modeling (SCRAM) | US EPA are from twice-daily values from the National Climatic Data Center (NCDC), Asheville, North Carolina. All files for a state are in TXT format and have been compressed into a single ZIP file for that state. A description of the mixing height data format (TXT) is provided. All mixing height meteorological data files have missing data filled as prescribed in the Procedures for Substituting Values for Missing NWS Meteorological Data for Use in Regulatory Air Quality Models (TXT), except where the guidelines could not be followed due to an excessive number of repetitive missing values. Please read the Missing Meteorological Data Report (TXT) to identify the station/years that are not complete. A list of mixing height data stations (TXT) are provided.

The data offered here are used in concert with the surface meteorological data for air quality modeling. The twice daily mixing height values are to be combined with hourly surface data using the PCRAMMET preprocessor program to obtain hourly interpolated mixing height values.