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Pacific Northwest
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Meteorological Integration for the Biological Warning and Incident Characterization (BWIC) System: General Guidance for BWIC Cities

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February 2007

Prepared for the U.S. Department of Homeland Security
Science and Technology Directorate
under a Related Services Agreement with
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Richland, WA 99352

Executive Summary

The U.S. Department of Homeland Security (DHS) is responsible for developing systems designed to detect the release of aerosolized bioagents in urban environments. The system that accomplishes this, known as BioWatch, is a robust first-generation monitoring system. In conjunction with the BioWatch detection network, DHS has also developed a software tool for cities to use to assist in their response when a bioagent is detected. This tool, the Biological Warning and Incident Characterization (BWIC) System, will eventually be deployed to all BioWatch cities to aid in the interpretation of the public health significance of indicators from the BioWatch networks. BWIC consists of a set of integrated modules, including meteorological models, that estimate the effect of a biological agent on a city's population once the agent has been detected.

For the meteorological models in BWIC to successfully calculate the distribution of biological material, they must have as input accurate meteorological data, and wind fields in particular. The purpose of this document is to provide guidance for cities to use in identifying sources of good-quality local meteorological data that BWIC needs to function properly. This process of finding sources of local meteorological data, evaluating the data quality and gaps in coverage, and getting the data into BWIC is referred to as *meteorological integration*.

There are three ways that meteorological measurements, particularly wind measurements, are used in BWIC: 1) as a simple indicator of conditions at a time and location of interest, 2) as input to a diagnostic model that provides three-dimensional fields of wind and other variables over the urban area of interest, and 3) as input, via the diagnostic model, to dispersion programs that provide best estimates of the concentration of a released agent at all times and locations in the urban area. Good meteorological measurements from an adequate number and distribution of locations are necessary for BWIC's dispersion calculations to be reliable. The number of stations is important because winds can be surprisingly variable in an urban area due to local terrain and other effects. Each city is unique in this regard, and the number and placement of meteorological sensors should be tailored to the individual city.

The good news for many cities is that meteorological measurement networks in addition to the National Weather Service are becoming increasingly common. Most of these networks allow their data to be distributed in real time, or nearly so, at no charge via the Internet. Thus, cities will often only need to evaluate the quality of available measurements and perhaps add a modest number of stations where coverage is poor. Sources for surface meteorological data fall into three basic categories:

- National resources—primarily federal agencies that maintain meteorological networks for weather forecasting, climate studies, air quality monitoring, and similar purposes of national significance.
- State and local resources—similar to federal agencies but smaller in scope. Meteorological networks from these sources serve environmental monitoring activities in particular.
- Private resources—range from private individuals who maintain weather stations motivated by amateur interest in the weather to companies who seek to profit from the generation and sale of meteorological data.

Sources of upper-air data are more limited than sources of surface measurements, primarily because the cost of the systems performing the measurements is much higher than that for simple weather stations. The primary options for upper-air data are 1) operational soundings, which are weather balloons launched twice daily by the National Weather Service at numerous locations in the United States and 2) local wind profiling systems, including sodar and radar. They are usually operated by environmental monitoring organizations, the National Oceanic and Atmospheric Administration, national laboratories, or universities.

If it is determined that additional surface meteorological stations are needed, the question becomes where to site them to best advantage. The question can be answered both subjectively and objectively.

- Subjective approach—identifies gaps in measurement coverage based on visual inspection of the distribution of existing systems and taking into account specific features of local meteorology.
- Objective approach—optimization techniques are available to objectively determine the best location for additional measurement stations. In many cases, the objective result corresponds closely to what would be selected subjectively. Because the objective technique requires both meteorological and statistical expertise, its use is probably best reserved for situations in which the deployment of additional stations is expensive and a subjective choice is not clear.

It may be difficult to justify the expense of procuring upper-air stations for BWIC if there is a relatively dense network of surface stations, *unless* there are also characteristic strong changes of wind with height. An added upper-air station provides detailed information about vertical changes in the meteorology but, by itself, no information about horizontal changes. If, in producing the gridded wind fields, its measurements influence a large horizontal area above the surface, it effectively eliminates horizontal variability above the surface that can be inferred from the surface measurements. If, to counter this, its influence is only a small horizontal area, it contributes little to the overall wind field, raising the question of whether its cost is justified. Preexisting upper-air stations should always be used, however, and the recommendation regarding the addition of stations applies exclusively to the BWIC context.

Acknowledgments

This research was supported by the U.S. Department of Homeland Security (DHS) through the Science and Technology Directorate under a Related Services Agreement with the U.S. Department of Energy (DOE) under Contract DE-AC05-76RL01830. Pacific Northwest National Laboratory is operated by Battelle for DOE. We are especially grateful to Dawn Myscofski and Teresa Lustig of DHS for their leadership in developing and advancing the BWIC program and for their support for BWIC's meteorological integration component.

Contents

Figures

Table

1.0 Introduction

The U.S. Department of Homeland Security (DHS) is responsible for developing systems designed to detect the release of aerosolized bioagents in urban environments. The system that accomplishes this, known as BioWatch, is a robust first-generation monitoring system. In conjunction with the BioWatch detection network, DHS has also developed a software tool for cities to use to assist in their response when a bioagent is detected. This tool, the Biological Warning and Incident Characterization (BWIC) System, will eventually be deployed to all BioWatch cities to aid in the interpretation of the public health significance of indicators from the BioWatch networks. In addition to providing guidance for responding to the detection of bioagents, BWIC also provides a training mode to be used in preparation for emergency response.

1.1 The Biological Warning and Incident Characterization System

BWIC consists of a set of integrated modules that estimate of the effect of a biological agent on a city's population once it has been detected. Ultimately, the effect of the agent is calculated by a combination of epidemiological and population-movement models. However, before these models can be used, it is necessary to know the geographic area in which people are likely to have been exposed. Two atmospheric models in BWIC provide this information. One, a source-identification model, uses the locations and times of detection at the BioWatch sensors to calculate likely release points upwind. The other is a conventional atmospheric dispersion model that uses release locations and meteorological conditions to calculate the geographical distribution of the biological agent.

For the meteorological models in BWIC to successfully calculate the distribution of biological material, they must have accurate meteorological data—wind fields in particular—as input. The purpose of this document is to provide guidance for cities to use in identifying sources of good-quality local meteorological data that BWIC needs to function properly. This process of finding sources of local meteorological data, evaluating the data quality and gaps in coverage, and getting the data into BWIC is referred to as *meteorological integration*.

1.1.1 How Meteorological Data Are Used

This discussion focuses on wind data because winds disperse biological agents and other contaminants in the atmosphere. Other meteorological variables such as cloud cover are required in BWIC, but winds are the critical input.

BWIC uses wind data in three basic ways, and this reflects their general application in many kinds of emergency response. First, wind measurements can be graphically displayed as arrows at their point of measurement (Figure 1.1a). These arrows can then be overlaid with other information to provide a sense of air movement during a particular period of interest. In most cases, though, there is not a uniform distribution of meteorological stations in a region, so it can be difficult to visualize the wind at a location that is not close to a measurement site or that is located near multiple sites that are reporting differing winds. The second way that winds are used in BWIC, therefore, is as input to a *diagnostic wind field model*, which effectively fills in the gaps in the observations (Figure 1.1b). BWIC uses the California

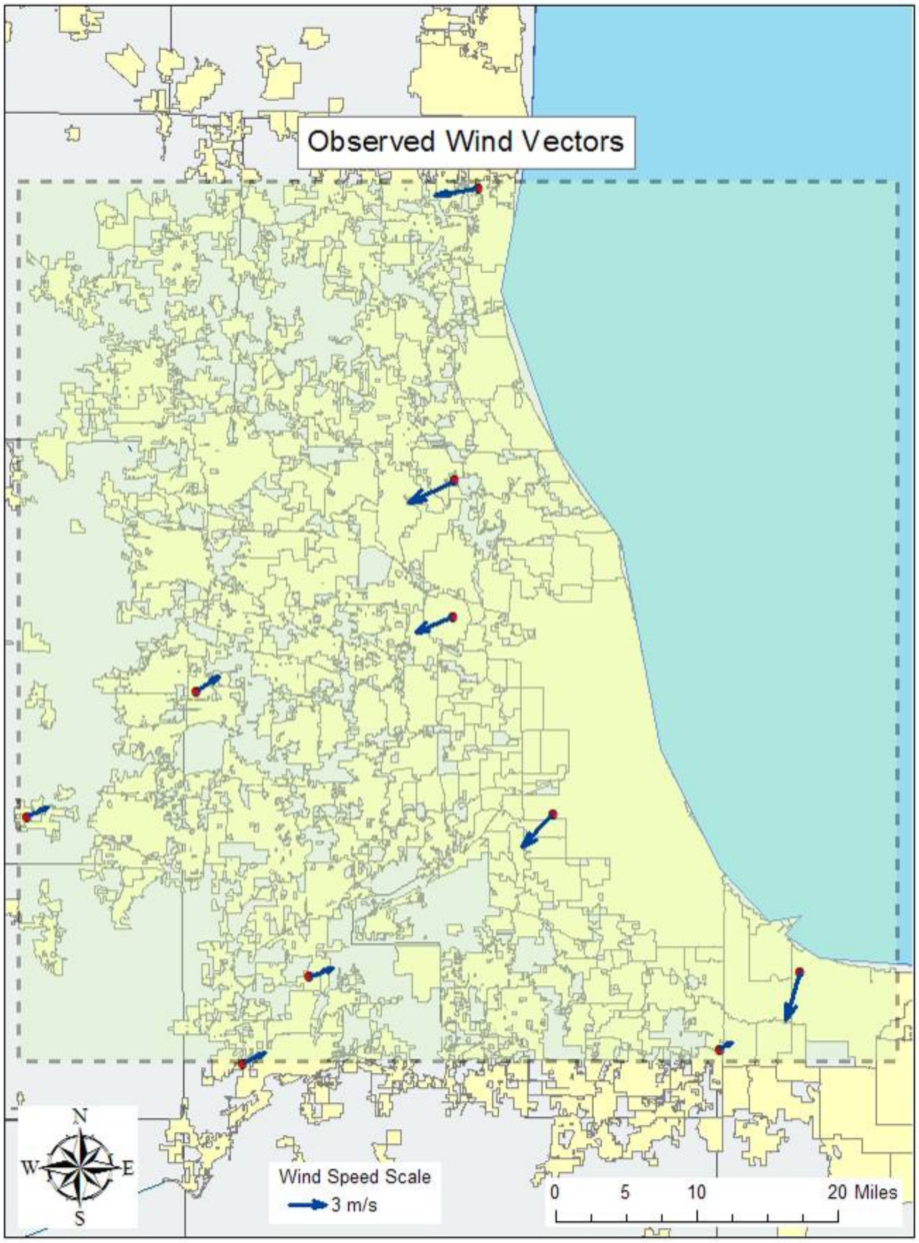

Figure 1.1a. Display of Raw Wind Observations in BWIC. The representation is from CALMET as used in a dust transport model (Allwine et al. 2006). The use in BWIC is identical.(a)

(a) Illustrations of wind information such as Figure 1.1 were created using DUSTRAN, a dispersion modeling tool developed at PNNL (Allwine et al. 2006). DUSTRAN uses some of the same components as BWIC to calculate wind fields and dispersion. Chicago was selected for illustration and in this document because it is a typical large U.S. urban area with some local complexity in the weather created by its proximity to Lake Michigan.

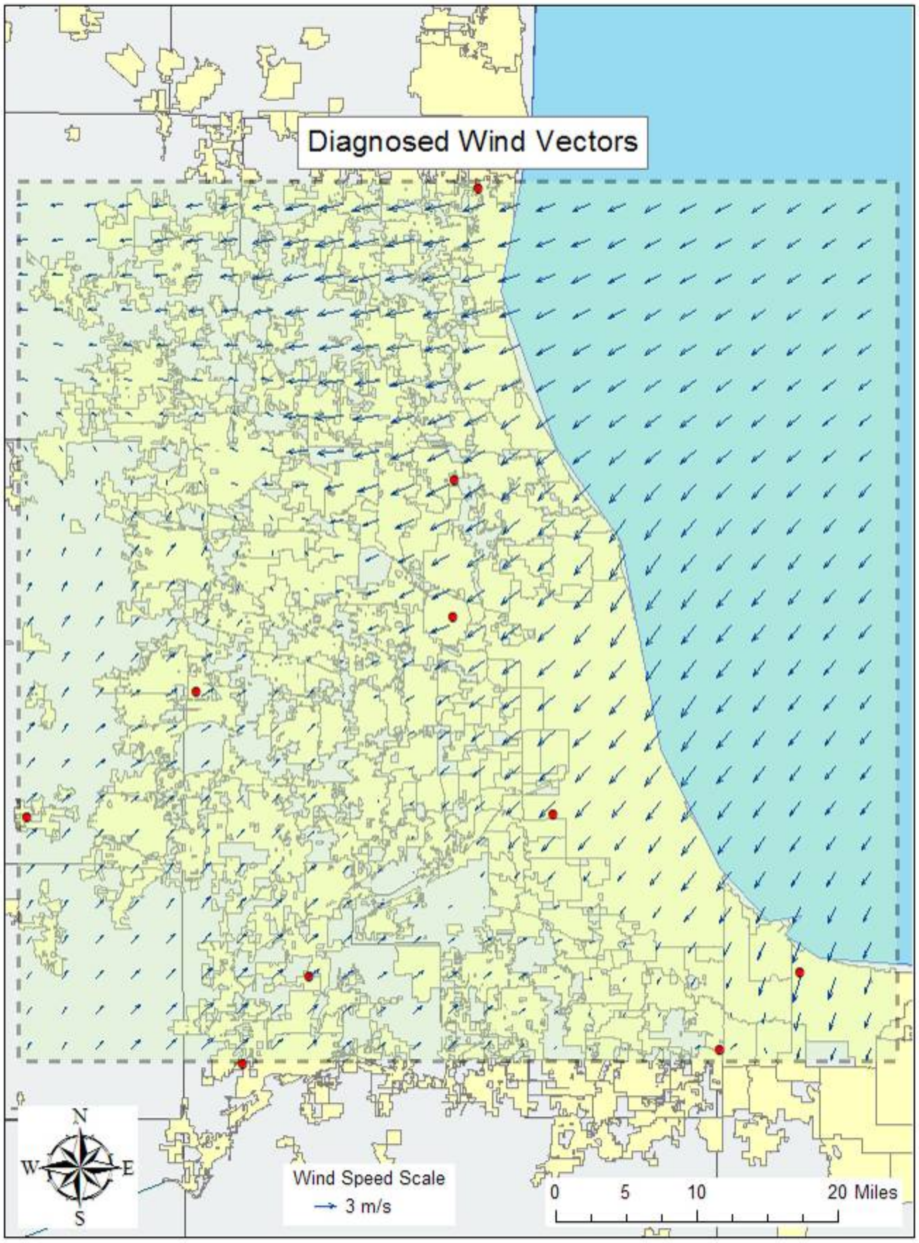

Figure 1.1b. The Surface Wind Field Diagnosed by CALMET

Meteorological model, CALMET,(a) to generate and display a gridded wind field to aid in understanding the likely transport path. Finally, BWIC also uses the wind estimates calculated by the diagnostic model to drive *dispersion models*. The dispersion models combine winds with estimates of a biological release and other information to provide a map of areas that are likely to have been affected by the release (Figure 1.1c). Sections 1.1.2 and 1.1.3 briefly describe how the diagnostic and dispersion models work.

(a) A technical description of CALMET is provided by Scire et al. (2000).

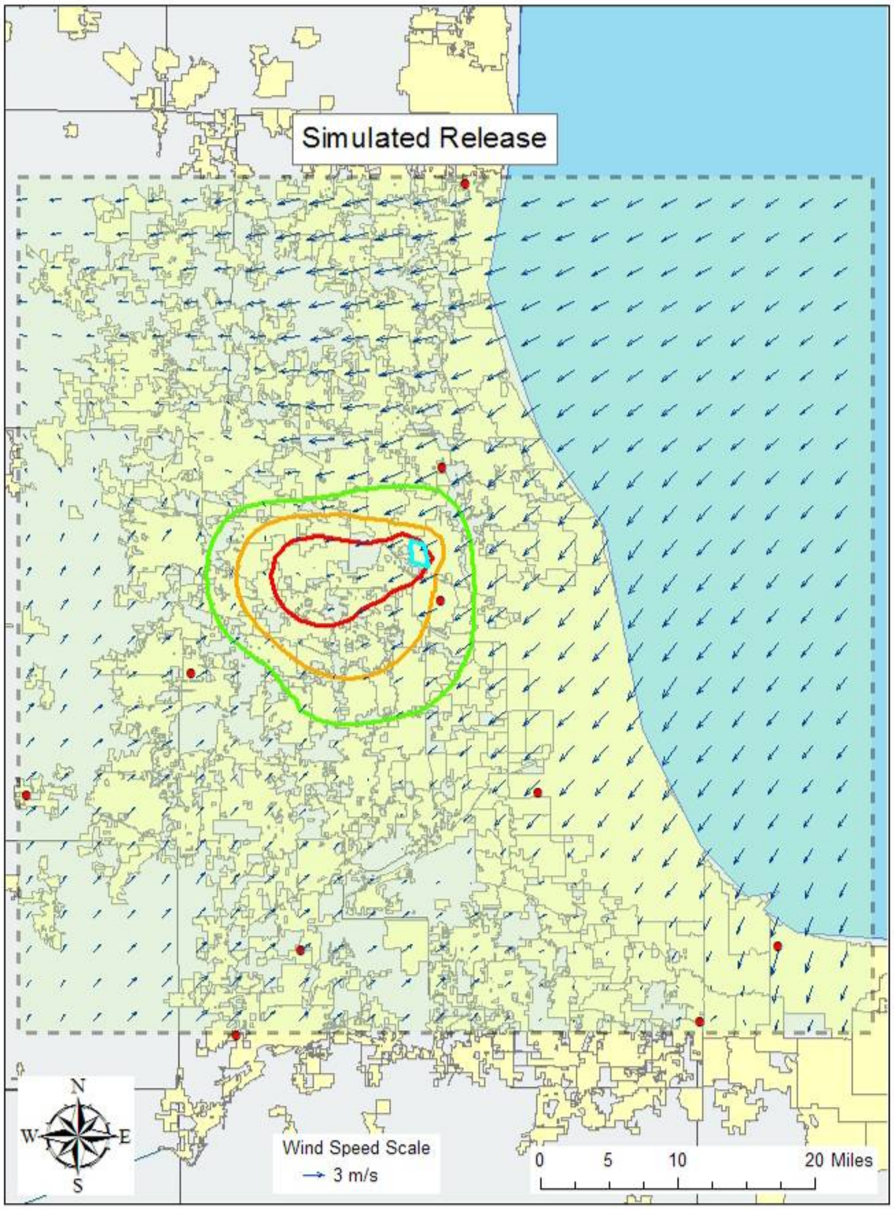

Figure 1.1c. Concentration Contours of Material Released into the CALMET Wind Field

1.1.2 Diagnostic Meteorological Modeling

The two basic categories of meteorological models are prognostic and diagnostic. Both reproduce winds and other variables, typically on a regular grid in three dimensions and in time. Thus, both can produce the necessary information to run an atmospheric dispersion model. Prognostic models generally attempt to account for all of the physical processes that move the atmosphere. Because they are also capable of calculating the future state of the atmosphere, this category includes weather forecast models. While these models are beginning to be used for the purpose of operational decision-making, their output is not yet routinely accessible for emergency response by all jurisdictions. In this regard, diagnostic wind models based on mass conservation still play an indispensable role due to their fast computation and relative ease of use by local agencies. Diagnostic models are able to account for the influence of terrain on winds, but they are not able to provide forecasts.

Over the past few decades, numerous diagnostic models have been developed for research and as tools in addressing air quality issues and responding to emergencies. After extensive use and testing, the U.S. Environmental Protection Agency (EPA) has sanctioned several models for regulatory use.(a) CALMET, the wind field model used in BWIC, is an EPA-preferred diagnostic model.

1.1.3 Dispersion Modeling

When a hazardous material is released into the atmosphere, the immediate, practical question is, Where does the material go? The answer can be determined by atmospheric dispersion models. In general, these models combine an assumed amount of material that is released with information about the atmosphere to calculate downwind concentrations at various later times.

The main categories of dispersion models are Gaussian plume, Eulerian, and Lagrangian. Gaussian plume models are the simplest and fastest. They use meteorological conditions at the time and location of the release and assume that conditions do not change with time as the material is carried downwind. Eulerian models calculate dispersion using a grid over the region of interest. Airborne material moves through the grid by wind values assigned to each point of the grid. These models are used when numerous sources of material are distributed throughout the region. Eulerian models are not typically used for emergency response. Lagrangian models are usually preferred for estimating dispersion of material released from point sources, especially if detailed information is needed about concentrations within a few kilometers of the release point. The two types of Lagrangian models are puff and particle. Lagrangian puff models represent a release with one or more “puffs” carried by the wind that spread as they move downwind. These models account for changing winds over time and distance. They require more computer time than Gaussian plume models but are still relatively fast. Lagrangian particle models represent a release of material with particles that are individually tracked as they move downwind and are affected by changing average wind and turbulence. Particle models are more flexible but require the most computational resources.

1.2 Issues for Meteorological Integration

There is a great deal of variability in the atmosphere. When the ground is heated during the day, small air currents known as turbulent eddies develop. Eddies are also generated when wind blows around trees, buildings, other obstacles, or simply over a rough surface. Turbulent eddies are a primary mechanism for spreading material released into the atmosphere. Eddies exist in what is known as the *boundary layer* of the atmosphere, which can extend from the surface to an altitude of 1–3 km on a summer afternoon. At night, the boundary layer with its turbulent eddies is usually much shallower (Figure 1.2).

(a) See the EPA website, http://www.epa.gov/scram001/dispersionindex.htm, for a list and description of the preferred models and other models.

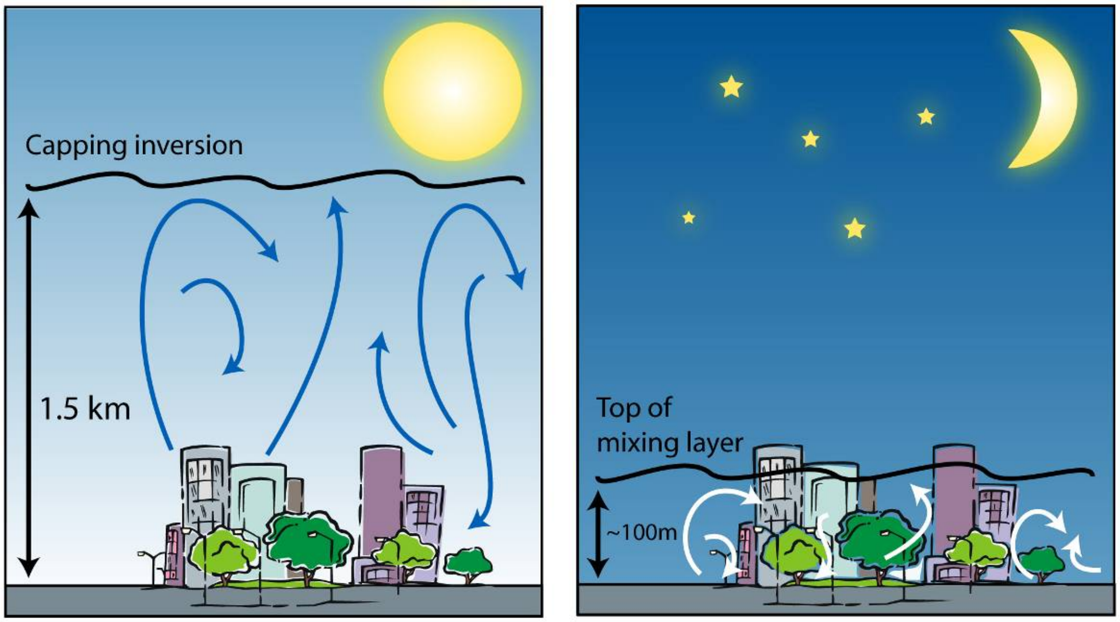

Figure 1.2. Sketches of Turbulent Atmospheric Boundary Layer in an Urban Area in the Daytime (left) and at Night (right)

At the same time, air motions often develop on a regional scale, known in meteorology as the *mesoscale*, as a result of differences in surface heating by the sun. Such differences in surface heating can occur between water and land surfaces. In coastal areas they generate the well-known sea breeze, which is actually a circulation in which air moves from water to land at low levels (the lowest few hundred meters of the atmosphere) and returns to sea in the next-higher few hundred to thousands of meters (Figure 1.3). At night, when the ground cools to temperatures lower than the water, the circulation can reverse. Similar circulations can occur near shorelines of large lakes; the lake breeze in Chicago is a notable example. Very often a front, in which there are sharp changes in wind speed and direction and in temperature and humidity, will develop at the leading edge of the sea or lake breeze circulation. Winds can shift by more than 90 degrees or even reverse in a few minutes and over distances of 1 km or less.

Mesoscale circulations also develop in the presence of complex terrain, an example of which is wind over sloping ground. In this situation, daytime heating of the terrain causes air to move up the slopes. At night, as the terrain becomes cooler than the air, winds tend to blow down the slopes (Figure 1.4). This sort of flow can become exaggerated in mountainous terrain, especially where canyons extend into the mountains. Salt Lake City, Utah, is an example of an urban area in such a location. Several prominent canyons extend into the Wasatch Range just east of the city. It is not uncommon for narrow jets of very strong winds to blow over the city from these canyons at night as cooling air from many mountain slopes sinks into the canyons. In addition to the effects of heating, valleys of rivers and streams can also channel winds mechanically. This has been observed, for example, in the deflection of breezes along the Potomac and Anacostia Rivers in Washington, D.C.(a)

(a) Channeling of flow by river valleys in the Washington, D.C. area was found by Berg and Allwine (2006) in an analysis at PNNL.

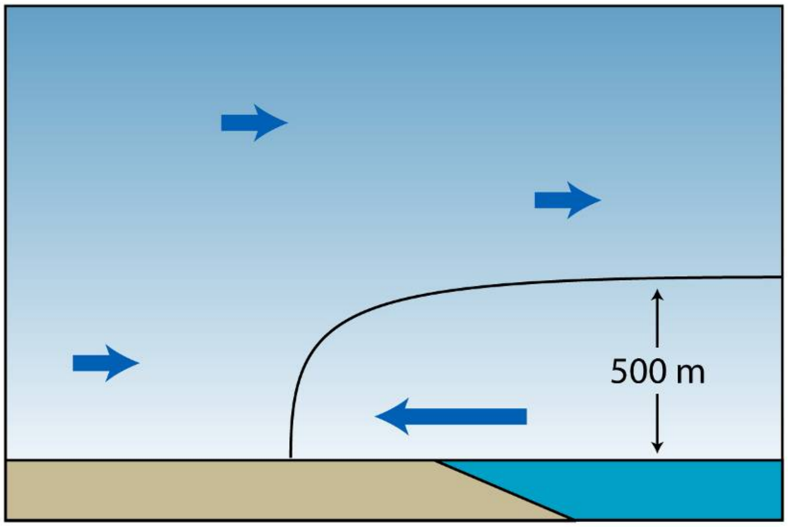

Figure 1.3. Schematic of a Lake or Sea Breeze and Associated Winds

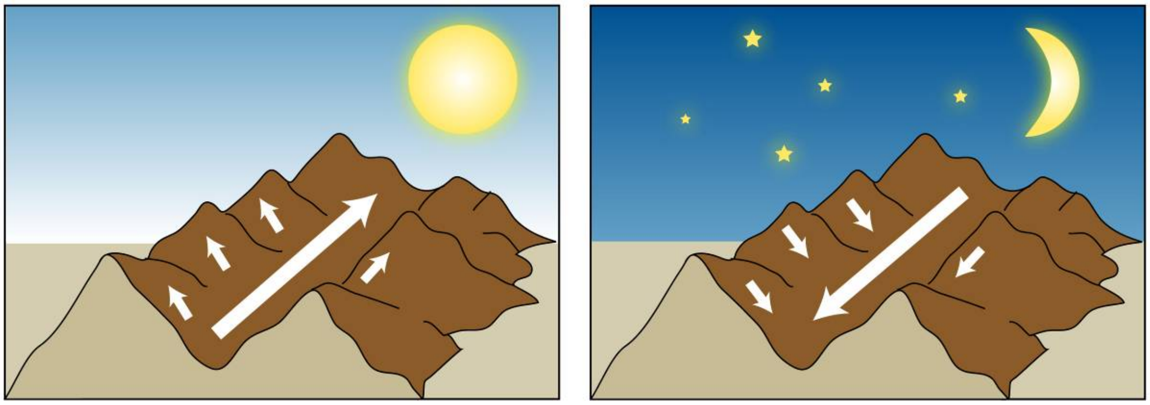

Figure 1.4. Illustration of Winds Moving up a Heated Slope in the Daytime (left) and down the Slope as it Cools at Night (right)

Strong changes in space and time also occur because of the movement of large-scale weather systems. Weather fronts associated with these systems typically concentrate changes in winds, temperature, and humidity across distances of 10 km or less. Because the fronts are generally in motion, the result of a frontal passage is a sharp time variability at a particular location. *Stationary fronts* do occur, however, and they move very little. In this situation, there can be sharp changes of wind and other variables with distance that persist in a region for many hours.

In addition to the conventional circulations described above, there are other atmospheric phenomena that can strongly affect local urban areas. Just as there are waves on a water surface, there can be waves in the atmosphere. When generated under the right conditions by the interaction of prominent terrain and large-scale weather systems, they can generate events such as the notorious pulsating winds that exceed 50 $\mathrm{m\ s^{-1}}$ and descend from time to time over Boulder, Colorado, from the Rocky Mountains. Another phenomenon that exerts significant local influence on cities of the Great Plains from northern Texas to Minnesota is the low-level jet. These southerly winds blow steadily at an altitude of a few hundred meters and at speeds of 10 m s^{-1} or so on many nights, particularly in the summer. They are a major reason that thunderstorms are most frequent at night in this part of the country.(a)

This discussion illustrates both the characteristic complexity of meteorology and the variety of phenomena that are determined by a city's location. To determine what observations are necessary to support the use of BWIC in a particular city, it is necessary to identify the conditions that result in strong local meteorological variability.

1.2.1 Need for Adequate Number and Placement of Sensors

Prognostic models attempt to account for all of the physical processes affecting the atmosphere in the region of interest. As a result, these models can begin with relatively simple and widely spaced observations and generate an accurate depiction of complicated fields such as fronts or sea breezes. Diagnostic models, on the other hand, do not have this ability. The best that diagnostic models can do is to fill in the gaps between observations.

This raises two important questions: How many wind instruments are needed to enable diagnostic models to create wind fields that are good enough for dispersion models to make reliable calculations for a particular region? and Where should those instruments be placed? The answers to these questions are unique to each city. Cities that are dominated by relatively simple meteorological conditions will need relatively few measurement locations. Other cities may have recurring complicated wind fields. Thus, part of the answer to the questions requires an individual assessment of the characteristic meteorology of each city.

A third question must also be addressed: What is the benefit of procuring, installing, and maintaining new sensors in a region? If it were possible to ignore practical issues such as cost and technological limitations, the simple answer to the questions of the last paragraph would be to measure everything everywhere all of the time. This is clearly not possible. While it is difficult to develop a helpful quantitative cost-benefit analysis because of the complexity of meteorological fields, it is possible to qualitatively determine how many additional stations are needed and where they should be located. Subsequent sections of this report will address this.

1.2.2 Need for Good-Quality Measurements

For many cities, multiple networks of meteorological measurements already exist. Taking advantage of these greatly reduces the need for additional expenditures for meteorological equipment. Because diagnostic wind field models assume that the data they have been provided are valid, it is important to review the quality of the measurements. The two prominent problem areas for pre-existing sensor installations are exposure and calibration.

Exposure refers to how well a sensor's measurements represent the surrounding area. If an anemometer is located near an obstruction, it may register a wind speed and direction that are very different from the general movement of the nearby atmosphere. Exposure problems are especially likely

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(a) This was discussed as early as the 1960s in a paper by Pitchford and London (1962).

to occur for meteorological sensors that are deployed as part of a measurement system whose purpose is not primarily meteorological. For example, it is common for cities to place anemometers with systems that monitor overpass temperatures (for icing) and freeway congestion. This has resulted in anemometers being placed underneath trees, which is not a good place for a representative wind measurement. It is therefore important to evaluate the exposure of sensors that provide meteorological data to BWIC.

Calibration is a particular concern with sensors that are inexpensive to begin with or that have been used for a long time. With propellers and cups, in particular, bearing wear will over time increase friction. This in turn causes the anemometer to register too low a wind speed. In Section 3.4 of this report, we discuss how to determine measurement quality in more detail.

1.3 Summary

We have introduced the meteorological component of the BWIC tool. To use the tool effectively, good meteorological information must be integrated into the BWIC data stream at the beginning.

- Meteorological measurements, particularly wind measurements, are used in three ways in BWIC: 1) as a simple indicator of conditions at a time and location of interest; 2) as input to a diagnostic model that provides three-dimensional wind fields over the urban area of interest; and 3) as input, via the diagnostic model, to dispersion programs that provide best estimates of the concentration of a released agent at all times and locations in the urban area.
- Good meteorological measurements from an adequate number and distribution of locations are necessary for BWIC's dispersion calculations to be reliable.
- Winds can be surprisingly variable in an urban area because of local terrain and other effects. Each city is unique in this regard, and the number and placement of meteorological sensors should be tailored to the individual city.

2.0 Required Meteorological Data

In this section, we examine the relationship between diagnostic meteorological models and dispersion models. We introduce the CALMET diagnostic meteorological model in BWIC and discuss its input data requirements and gridded outputs.

2.1 Dispersion Models

Dispersion models require certain meteorological input to make plume transport and diffusion calculations. The simplest dispersion models, known as Gaussian plume models, assume that meteorological conditions such as wind speed and wind direction do not vary horizontally or vertically across the region of interest or with time. As a result, meteorological observations are needed only at one representative location, and the modeled plume moves in a straight line down wind from the point of release. The plume diffuses both laterally and vertically as it moves down wind, according to the atmospheric thermodynamic stability classification at the release point.

More sophisticated dispersion models can use spatially and temporally varying meteorological fields to transport and diffuse plumes. This relaxes the constraint that plumes must travel in a straight line or that a plume's diffusion rate is fixed by the stability classification at the release point. These models can provide more realistic results, especially in situations where there may be considerable variation in meteorological fields, such as wind direction and wind speed near a front or changes in stability classification when moving from land to water. This class of dispersion models makes use of *diagnostic* meteorological models to assimilate observational data and generate regularly spaced gridded fields. *Dispersion* models can use these fields to transport the plume across the grid and adjust the lateral and vertical growth of the plume based on the stability of each grid cell.

2.2 Diagnostic Models

Diagnostic models are used to create gridded meteorological fields from irregularly-spaced surface and upper-air observations. The derived fields are a diagnosis, or snapshot, of the atmosphere valid at the time of observation. Certain meteorological fields such as wind are interpolated to a three-dimensional grid using surface and upper-air observations. Other fields, such as stability class, are calculated for a two-dimensional grid using surface observations alone.

Diagnostic models generate gridded fields for a user-specified area called a *domain*. Domain sizes can vary, but for a large city the domain would usually be on the order of 100 km square. The vertical extent is generally set to capture the flow that is responsible for plume transport, which is roughly within the lowest 3 km of the atmosphere. The domain is gridded horizontally and vertically to create *grid nodes*, which are the locations where meteorological variables are interpolated or calculated by the diagnostic model. The spacing of the grid nodes, called *resolution*, is generally 1 to 2 km in the horizontal for a 100-km domain, but varies vertically, with spacing increasing with height.

Once the domain has been defined, surface and upper-air stations need to be identified. These provide the observations from which the diagnostic model creates the gridded fields. Great care must be exercised when selecting these stations because the quality of the diagnostic fields depends directly on the quality of the underlying observations.

The diagnostic model reads in observations and then performs interpolations and calculations to create the gridded fields. These fields can be constrained and adjusted to account for certain physical processes such as modification to the wind field for terrain effects and mass conservation (i.e., making sure that air does not "accumulate" at particular locations).

The resulting gridded fields can be displayed or can be used in a dispersion model to estimate the downwind transport, diffusion, and deposition of a material release. BWIC uses CALMET to generate and display a gridded wind field to aid in understanding the likely transport path of a biological release. CALMET ingests local and regional observations and performs adjustments due to the underlying topography and surface features.

2.2.1 Required Input

Diagnostic meteorological models use surface and upper-air observations to generate gridded fields of measured or calculated variables. Because most diagnostic models are closely coupled with companion dispersion models, the required meteorological observations are dictated largely by the meteorological parameters required by dispersion models.

Most diagnostic models require observations of standard meteorological variables such as wind speed, wind direction, and temperature. Table 2.1 lists the meteorological observations that are required by CALMET, a diagnostic meteorological model used in BWIC. The listed variables are commonly required by most diagnostic models. Surface data are hourly observations; upper-air vertical profiles are available less frequently, normally twice daily (0000 and 1200 Coordinated Universal Time [UTC]). Not all variables need to be measured or reported at all stations. Multiple surface and upper-air stations may be used, and stations are not required to be within the model domain because CALMET interpolates data to the domain. The meteorological observations are written to specially formatted surface and upper-air files that can be read by the diagnostic model. In the case of BWIC, the BWIC system generates the observation files for use in CALMET.

Table 2.1. CALMET Meteorological Input Data

Surface Data (Hourly)	Upper-Air Data (Twice-daily)
Wind Speed and Direction	Wind Speed and Direction
Temperature	Temperature
Cloud Cover	Pressure
Ceiling Height	Elevation
Surface Pressure	
Relative Humidity	
Precipitation Type Code	

Geophysical data such as terrain elevations and land-use/land-cover may also be used in diagnostic meteorological model formulations. CALMET interfaces with standard, commonly available geophysical datasets to adjust winds for terrain effects such as flow blocking, channeling, and slope flows. In addition, the gridded geophysical fields are written to the CALMET output file and can be used in dispersion model calculations.

2.2.2 Merging Data from the Surface and Aloft

There are far fewer upper-air stations than surface observations stations. Upper-air stations generally provide measurements just twice daily, whereas surface stations typically record hourly observations. As a result, upper-air measurements are less resolved—both spatially and temporally—than surface measurements.

Diagnostic meteorological models can improve the quality of wind fields above the surface by propagating surface information vertically and merging the resulting data with upper-air observations. This is particularly true in complex flow regimes, where upper-air stations may be removed entirely from local flows that are governing transport. By propagating surface observations vertically in time, local processes tend to be better resolved, especially for highly sampled, uniformly spaced surface networks.

Well-established meteorological relationships have been developed to extrapolate surface wind observations vertically in a physically realistic manner. These relationships generally depend on atmospheric stability because turbulent eddies, discussed in Section 1.2, are responsible for transporting or *mixing* higher-momentum air from aloft to the surface. There is greater mixing over a larger depth of the atmosphere during unstable conditions and less mixing over a much shallower depth during stable conditions.

Two methods, called power-law and similarity theory, are commonly used to create vertical wind profiles from surface observations and mathematically describe this physical relationship. Both methods are available in CALMET.

Once surface wind data have been extrapolated vertically, they can be blended with actual upper-air observations to create a regular, three-dimensional gridded wind field. The degree to which the data are blended can be controlled within CALMET using a weighting mask called a bias, such that surface-based winds have progressively less weight in the derived wind field with increasing height. Used in this way, surface data provide added wind information in the lowest levels of the atmosphere above the surface, where the bulk of the plume transport is generally taking place.

2.3 Supplemental Data

2.3.1 Precipitation

Precipitation affects particle dispersion through a process called *scavenging*, which is simply the removal of material from a plume by precipitation. It has the overall effect of increasing particle deposition and decreasing in-air concentrations. Scavenging depends on the precipitation rate and type, either liquid (rain) or solid (ice). CALMET can assimilate hourly precipitation-type codes for use in dispersion model particle deposition calculations, although this capacity is not used in BWIC.

2.3.2 Measures of Turbulence

Atmospheric turbulence may be regarded as random velocity variations superimposed on the mean flow. In dispersion modeling, the mean flow is used to transport the plume downwind, and the random velocity variations (i.e., turbulence) determine the lateral and vertical growth of the plume.

Turbulence is generated through two means—thermal or mechanical. Thermal production of turbulence is caused by heating of the ground from the sun, which causes eddies, or thermals, to form as the warmer air near the surface rises through the comparatively cooler air aloft. Mechanical turbulence is caused by gradients in wind speed or wind direction and is commonly called wind shear. During the day, thermal turbulence tends to dominate over mechanical turbulence; at night, only mechanical turbulence is present.

In dispersion modeling, the amount of atmospheric turbulence is usually characterized through a parameter known as *stability class*. A letter classification system has been traditionally used to define the level of atmospheric turbulence—A (very unstable) through G (very stable). During unstable conditions, plumes tend to grow rapidly both laterally and vertically, whereas during stable conditions, plumes tend to stay more compact.

Methods have been devised to infer atmospheric stability from commonly measured meteorological variables. The most popular method uses a matrix of wind speed and cloud cover percentage as a function of day or night to define allowable stability classes. More recent methods use a technique called similarity theory, which requires time of day and year, as well as observations of cloud cover and cloud height, to infer atmospheric stability. CALMET calculates gridded fields using both methods from surface observation data. These gridded fields can be supplied to dispersion models for use in their diffusion calculations.

2.4 Summary of Required Data

In this section, we examined the relationship between diagnostic meteorological models and dispersion models. We introduced the CALMET diagnostic meteorological model in BWIC and discussed its input data requirements and gridded outputs. To summarize:

- Diagnostic meteorological models, such as CALMET, use surface and upper-air observations, such as wind speed and wind direction, to create regularly spaced, three-dimensional gridded fields for use in dispersion models.
- Diagnostic models also use observations to calculate or estimate specific parameters, such as stability class, which is used to determine the lateral and vertical growth of plume.
- Surface winds can be extrapolated vertically using well-established meteorological relationships and merged with upper-air observations to better resolve the horizontal wind field in each vertical layer.

3.0 Identification of Data Sources

There are more meteorological measurement sites in operation than one might suppose. While some cities may have little more than local installations of measurement sites operated by the National Weather Service (NWS), other areas have multiple networks of meteorological equipment operated independently by a variety of organizations.

The emphasis in identifying data sources for use with BWIC should be on routinely available operational measurements. Research organizations, including universities, often have sophisticated equipment. However, by its nature, research equipment tends to be used intermittently and thus may not be available during periods of emergency response. Research organizations on occasion do provide continuous measurements at a stable location, and these should be used if available. It is also best to focus on operational networks that provide data that can be easily accessed and freely shared by the research community. This provides the possibility BWIC users can directly benefit from research activities in specific cities.

We noted in Section 1 that some networks do not have meteorological measurements as their primary purpose. In addition, some networks that may be considered operational because of their readily available data streams have measurement sites that are not supervised by professional meteorologists. As a result, there are often questions of both exposure and calibration. We therefore recommend that, as much as is practical, sensor installations be visited and their quality control process determined as part of the meteorological integration process for BWIC in a given city.

3.1 Identification Process for Networks

There is no single source for all of the meteorological data that are collected by various organizations and individuals in a region. We recommend the following sequence as an efficient approach for identifying sources:

1. Consult MesoWest (operated by the University of Utah and described below) to make a preliminary identification of available local networks. Even though data provided by federal agencies such as the NWS are available elsewhere, data from many of these networks are acquired by MesoWest. Thus, MesoWest is an ideal first stop for local measurements.
2. Identify local installations that are operated by federal agencies. These data are generally readily available and have undergone extensive quality control.
3. Contact the state climatologist and state and local agencies whose mission includes environmental protection or air quality.
4. If there is personal knowledge of local networks, contact their operators regarding the availability and suitability of their data. These operators may know of additional local networks.

3.2 General Sources of Surface Data

Many sources of meteorological data can be used by BWIC. These sources range from long-term, federally funded monitoring programs to collected observations made by private citizens using their own resources. In this section we describe a variety of places to obtain meteorological data. This is not intended to be an exhaustive list of meteorological measurements in the United States; rather, it provides examples of the kinds of resources to look for when establishing data for BWIC input in a particular city.

3.2.1 National Resources

The primary federal agency for acquiring, archiving, and disseminating meteorological information is the National Oceanographic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce. Within NOAA are a number of organizations that acquire, analyze, archive, and otherwise manage a vast quantity of meteorological data for both research and operational purposes. Other federal agencies such as EPA and the Bureau of Land Management (BLM) collect and archive meteorological data for more specialized purposes.

3.2.1.1 National Weather Service

The NWS, which is part of NOAA, has general responsibility for creating and disseminating weather forecasts in the United States. To support its forecasting function, the NWS uses a variety of meteorological measurement facilities, including a nationwide network of surface measurement sites known as the Automated Surface Observing System (ASOS). Collection of data through these stations is jointly supported by the NWS, the Federal Aviation Administration (FAA), and the Department of Defense (DOD).

ASOS stations provide hourly observations of wind speed, wind direction, temperature, humidity, precipitation, sky cover, and other meteorological variables. The standard wind measurement height for these stations is 10 m above ground level with no nearby obstructions, although there can be some variation in the measurement height. The hourly winds reported are actually 2-minute averages of the wind at the top of the hour. ASOS data for the most recent reporting hour can be accessed directly from the NWS.(a) Data from previous hours are available from archiving organizations such as the National Climatic Data Center (NCDC) or MesoWest, both of which are described below.

3.2.1.2 National Climatic Data Center

The NCDC is part of NOAA and serves as the nation's resource for data related to climate. The NCDC archives data from many different sources, including the hourly observations from ASOS. Data are not available in real time from NCDC; therefore, this is not a source for operational BWIC data. However, for constructing training scenarios using historical weather events, NCDC could be a valuable

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(a) The URL to access surface meteorological data via the NWS is http://weather.noaa.gov/weather/metar.shtml. A comprehensive and updated list of currently operating stations is maintained as of this writing at http://www.rap.ucar.edu/weather/surface/stations.txt.

resource.(a) There is generally a fee for ordering historical data from NCDC, but some of the same data are available free from other archiving systems such as MesoWest.

3.2.1.3 Environmental Protection Agency

The EPA has primary responsibility for addressing national air quality issues. As part of this responsibility, EPA supports the monitoring of chemical compounds and particulate matter at numerous locations across the country, especially in urban areas. To support the dissemination of air quality data, EPA has developed AIRNow, which serves as both a data archive and a means for current and forecast air quality conditions via the internet.(b) Until recently, AIRNow did not archive meteorological information. However, many air quality stations include a basic set of meteorological measurements, and EPA is in the process of adding those to the AIRNow database. This represents a source of data that is independent of ASOS. Direct access to AIRNow data requires specific arrangements with the EPA.

3.2.1.4 National Buoy Data Center

The National Buoy Data Center (NBDC), also operated by NOAA, collects oceanographic and meteorological information from buoys in coastal areas and in some inland waters such as the Great Lakes. The density of measurement locations is low, particularly in inland waters, but these coastal or over-water sites can be useful for supplying supplemental data where no other observations are feasible. Current and archived data can be downloaded from the NDBC site.(c)

3.2.1.5 Remote Automated Weather Station Network

The Remote Automated Weather Station Network (RAWS) is indeed a network rather than a federal agency. The RAWS network represents a collaborative effort among the U.S. Forest Service, BLM, and several other agencies.(d) The initial motivation for developing the RAWS network was to provide meteorological information to support fighting wildfires during fire season. As a result, the RAWS sites tend to be in remote locations. There are approximately 2000 RAWS installations across the United States. In some areas, stations are near enough to urban areas to also support the meteorological needs of BWIC.

One notable difference between RAWS and ASOS wind data is the standard height of measurement. For ASOS, this height is about 10 m, while for RAWS it is about 6 m. The result is that in a mix of data from the two networks, the wind speeds will tend to be somewhat greater from the ASOS measurement sites. Zachariessen et al. (2003) provide a thorough description and evaluation of the RAWS network.

(a) NCDC can be contacted via the Internet at http://www.ncdc.noaa.gov/.
(b) The URL for EPA's AIRNow web site is http://airnow.gov/.
(c) Data from the NBDC are available at http://www.ndbc.noaa.gov/os.shtml. Begin by clicking on the map in the vicinity of interest and then refine the search around a specific latitude and longitude of interest.
(d) The U.S. Forest Service provides more information about RAWS on the internet at http://www.fs.fed.us/raws/.

3.2.1.6 Citizen Weather Observer Program

In addition to professionally administered meteorological measurement networks, there are a large number of privately owned weather stations across the country. With the advent of the Internet and World Wide Web, many of the station owners have made their data widely available. With proper installation of these measurement systems and adequate quality control, these sites can provide valuable supplemental data that increase the density of measurements in many urban areas.

In an effort to maximize the value of these private weather stations, NOAA has developed the Citizen Weather Observer Program (CWOP).(a) CWOP provides installation advice and feedback to the station owners through basic quality checking for the reported data. Data that at least minimally pass the quality tests have a quality flag applied and are made available to the general public. There are about 6000 active CWOP stations nationwide.

3.2.1.7 MesoWest

The preceding subsections have described organizations that coordinate or operate particular meteorological observation networks in the United States. MesoWest is a national resource that, in contrast, acquires data from the various networks and makes as much as possible available for research and operational use from a single location.(b) MesoWest is operated by the NOAA Cooperative Institute for Regional Prediction (CIRP) at the University of Utah. Dr. John Horel, the Director of CIRP, has provided a full description of the history and objectives of MesoWest in an article in the “Bulletin of the American Meteorological Society” (Horel et al. 2002). All of the networks described above, except those operated by EPA and NDBC, now supply data to MesoWest. MesoWest supplies archived data at no charge for research purposes. For operational use, which places a greater demand on the MesoWest system and personnel, MesoWest requests financial support. BWIC currently has a contract in place with MesoWest for operational support for the prototype deployments of the tool.

3.2.1.8 Meteorological Assimilation Data Ingest System

The Global Systems Division (formerly the Forecast Systems Laboratory) of NOAA’s Earth Systems Research Laboratory has in the last several years developed a resource similar to MesoWest but broader in scope. The Meteorological Assimilation Data Ingest System (MADIS)(c) seeks to mathematically assimilate all available observations to create gridded fields of variables such as wind and temperature. These gridded fields can then be used for meteorological modeling. In addition to the gridded fields, MADIS also makes archived and real-time observations available. Some of the data collected by MADIS are restricted with respect to further distribution, however.

(a) NOAA provides further information and interactive access to CWOP data at http://www.wxqa.com/ .

(b) The URL for MesoWest is http://www.met.utah.edu/mesowest/.

(c) More information about MADIS, including links to data, can be found at http://www-sdd.fsl.noaa.gov/MADIS/.

3.2.2 State and Local Resources

In addition to federally supported meteorological networks, numerous state, municipal, and tribal agencies maintain some sort of meteorological measurements. These measurements are motivated primarily by the need to support firefighting, air quality monitoring, or local transportation. Many of these organizations are formal partners in EPA's AIRNow program.(a) In many cases, representatives of organizations that appear on the AIRNow partners list have personal knowledge of other local networks. This can be a valuable path to identifying additional local sources of data.

Often, state and local agencies use the data from their meteorological instruments internally and do not routinely disseminate the data beyond their organization. In such cases, it is necessary to contact the agencies directly to determine whether their data can be made available to BWIC. In some cases, computer network security issues may provide a significant obstacle to acquiring data from these sources.

An additional prominent and valuable resource for identifying sources of meteorological measurements as well as for supplying knowledge of and references for local meteorological conditions is the state climatologist. As of this writing, 47 states and Puerto Rico have state climatologists.(b)

3.2.3 Private Networks

In addition to the resources discussed above, some private organizations offer meteorological data for sale. For these organizations, the data themselves are often considered to be proprietary. Arrangements to use propriety data can cause complications should the data need to be further distributed for system evaluation or research. Therefore, care should be exercised in establishing the arrangements by which data from these sources are incorporated into BWIC.

3.3 Upper-Air Data

3.3.1 Operational Soundings

Vertical profiles of pressure, temperature, humidity, and winds, known as *soundings*, are made by balloon-borne instrument packages at numerous locations in the United States. These instrument packages are called *radiosondes*. The earliest sounding systems generally did not measure winds. As technology developed, it became possible to track the balloons and to infer the winds from the rate of change of balloon location with time. Instrument packages with this capability are commonly referred to as *rawinsondes*. Operational soundings are made routinely twice a day (0000 UTC and 1200 UTC) and are the primary means for introducing upper-air data into a diagnostic meteorological model such as CALMET. The sounding variables above are all required by the CALMET model.

(a) For a list of state, local, and tribal partners of AIRNow, many of whom maintain meteorological measurement sites, go to the AIRNow website and click on the "Partners" tab at the top of the page. Alternatively, the current direct web address for this list is http://www.airnow.gov/index.cfm?action=airnow.partnerslist.
(b) For a listing of state climatologists with contact information, see http://www.stateclimate.org/.

A real-time archive for all U.S.-based operational upper-air stations is maintained by NOAA's Earth Systems Research Laboratory and is available via the Internet.(a) Data are searchable by state, weather bureau army-navy number, or latitude and longitude. The resulting ASCII text files can be readily formatted for use in CALMET.

3.3.2 Local Wind Profiling Systems

In the last several decades, surface-based measurement systems have been developed that can measure the wind variation with height using sound or radar. Devices that use sound are called *acoustic sounders* or *sodars* (for *so*und *d*etection *a*nd *r*anging, in analogy with radar terminology). Radar systems are referred to as *wind profiling radars*, *wind profilers*, or sometimes just *profilers*. Both sodars and profilers are relatively expensive; thus, far fewer of these measurement systems are deployed operationally than surface stations. Sodars are commonly deployed in air quality applications at locations such as power plants and water treatment plants. To our knowledge, there is no systematic catalog of operational sodars in the United States. Thus, identification of these resources is likely to depend on word of mouth.

There are several operational wind profiler facilities and networks in the United States. The most prominent of these is the NOAA Profiler Network (NPN),(b) which provides data to the NWS and other users. The NPN is a network of 35 wind profiling radars, 32 of which are in the central United States and three in Alaska. Smaller installations of profilers are used operationally to support space launches at Cape Canaveral and Vandenberg Air Force Base and work at the U.S. Army's White Sands Missile Range (OFCM 1998). Some of the NPN systems are relatively near urban areas and may therefore provide useful data to BWIC; most of the other systems are relatively remote and less likely to be of use.

3.4 Assessment of the Quality of Available Data

We have noted that once a complement of local meteorological observations has been identified for inclusion into BWIC, it is important to assess the quality of those observations. Two basic determinants of data quality are instrument calibration and instrument exposure.

3.4.1 Calibration

While it is not feasible to obtain calibration records for each instrument that supplies data to BWIC, it is worthwhile to establish which networks or individual instruments have a regular schedule of calibration. These instruments will be the most reliable in supplying accurate data for two reasons: 1) instruments that are calibrated are more likely to be well constructed and to use accepted measurement designs and 2) regular calibration serves to flag drifts in instrument characteristics that can indicate failing components. A notable example of this is bearing wear in cup or propeller anemometers. Over time, bearing wear will cause the anemometers to spin more slowly for a given wind speed. If uncorrected, this can cause affected instruments to report wind speeds that are much too low.

(a) The current internet address for the sounding archive is http://raob.fsl.noaa.gov/.
(b) NOAA provides a description of the NPN online at http://www.profiler.noaa.gov/npn/ .

In general, data sources referred to as "national" above are on a regular calibration schedule. The exception is the network of CWOP stations. Because these installations are maintained by individuals with varying resources and levels of interest, regular calibrations should not be assumed. However, as part of coordinating the data reporting, NOAA performs quality checks on all of the observations that are supplied from the CWOP stations before the data are passed on to users. Part of the quality checking consists of comparisons with nearby weather stations and with meteorological fields that are calculated from all the stations in a local area. Data that are supplied by some state and local sources may not have calibrations or other quality assessments. For these sources, it is important to establish what the quality control procedures are as part of bringing the data into BWIC.

3.4.2 Exposure

The expectation for any meteorological observation used by BWIC is that it must represent conditions not just at the station where it was measured but also over the area between that station and the next. The exposure of the sensors is important because the diagnostic models of BWIC cannot account, for example, for wind shifts that occur in the immediate vicinity of trees or buildings. Good exposure means that there are no nearby obstructions that appreciably deflect the wind flow to the anemometer (often referred to as the station's having a "good fetch") and for temperature that the sensor is shielded both from the sun and from the cold night sky while still allowing free air movement across the sensor.

Figure 3.1 is a photograph of a well-exposed meteorological station. The wind sensor is placed well above the surface and there are no nearby obstructions. The temperature (and humidity) sensor is housed within a structure that resembles a stack of upside-down white pie plates. This structure reflects much sunlight that falls on it while minimally obstructing air flow. In contrast, Figure 3.2 is a photo of a poorly exposed station. In this case, the station is immediately adjacent to a tree and the wind sensor is below the tree top. In this situation, air flow will be severely modified around the tree, and the wind speed and direction reported by the sensor will not be representative of the surrounding area.

Part of exposure is also the height of measurement above the surface. Figure 3.3 shows that there can be strong changes in wind with height near the surface. Therefore, to make measurements comparable between one station and another, it is helpful if they are made at a common height. The standard measurement height can vary from network for network, however. For example, the standard measurement height for winds at ASOS stations is 10 m above the surface (OFCM 1994); for RAWS sensors it is 6 m (NWCG 2005). CWOP station operators are encouraged to place their wind sensors 10 m above the ground.(a) The BWIC diagnostic models have the capability to adjust observations to a common height, but the corrections are based on an idealized atmospheric structure. Unless measurement heights are very different among the sensors, it is often best to simply use the winds as reported.

(a) The community-developed CWOP Weather Station Siting, Performance, and Data Quality Guide is available for downloading from the web at http://mywebpages.comcast.net/dshelms/CWOP_Guide.pdf, with a link from the CWOP webpage at http://info.aprs.net/wikka.php?wakka=Weather. This document contains helpful tables for dealing with siting compromises.

Figure 3.1. Meteorological Station Fairly Well Exposed to the Wind and Thus Representative of a Larger Area Around It

Figure 3.2. Example of a Meteorological Station Whose Exposure Is Obstructed. Its wind measurements will not be representative of a larger area.

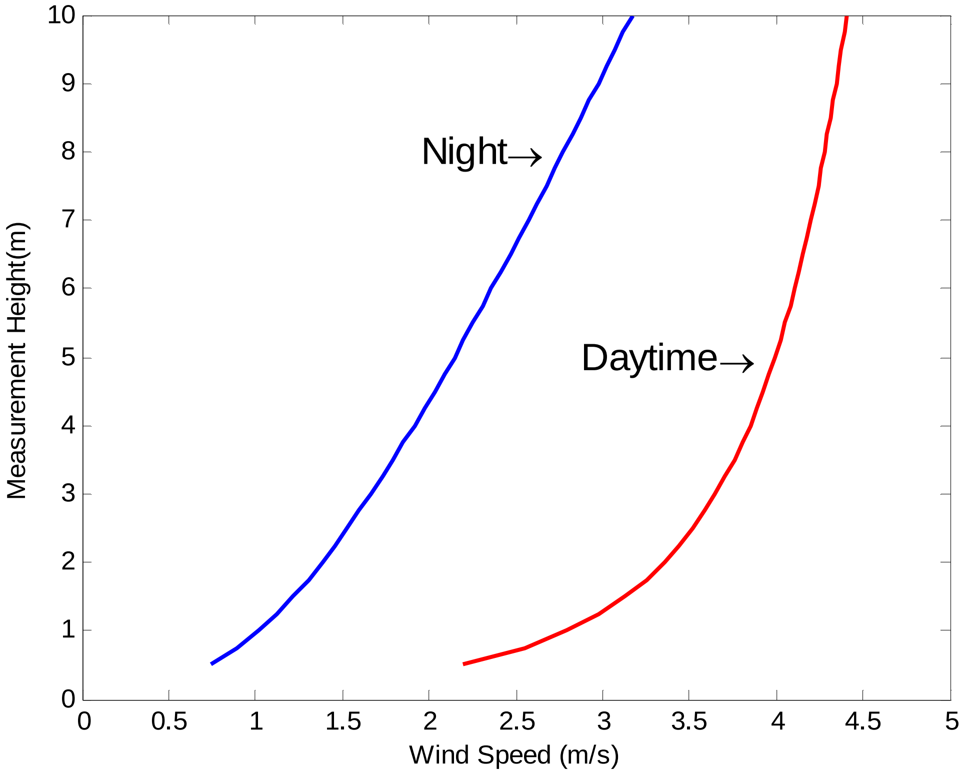

Figure 3.3. Schematic of Day- and Nighttime Changes of Wind with Height near the Earth's Surface. Above 5 m or so, the daytime changes are smaller because of turbulent mixing.

In practice, federally supported networks usually follow their respective siting standards closely. State, local, and privately operated sites may or may not follow recommended siting guidelines. Therefore, it is a good idea to inspect as many of the sites as possible that supply data to BWIC, particularly those that are not federal.

3.4.3 Using BWIC for Quality Assessment

Even with a review of calibration and exposure for sensor as described in the previous two sections, it is always possible that a previously satisfactory measurement site may begin to supply bad data. BWIC contains the capability to map meteorological variables like wind vectors at their measurement locations. Likewise, BWIC can overlay on the map a field of wind vectors produced by the diagnostic model. It is always a good idea to compare the observed wind vectors to make sure there are no individual values that are systematically inconsistent with the others. If there are stations providing inconsistent data (known as "outliers"), those stations can be removed from the calculations until the problem is resolved. It is also useful to compare the observations with the fields produced by the diagnostic model. If the values from the diagnostic model at locations of the measurement sites differ substantially from the observations at these sites, there may be a problem with the calculations of the model. This indicates a problem that should be resolved before calculation of dispersion can be considered reliable.

3.5 Summary of Identification of Data Sources

The good news for many cities is that meteorological measurement networks, in addition to the NWS, are becoming increasingly common. Most of these networks allow their data to be distributed in real time, or nearly so, at no charge via the internet. Thus, cities will often only need to evaluate the quality of available measurements and to perhaps add a few stations where coverage is poor. Sources for surface meteorological data fall into three basic categories:

- National resources—primarily federal agencies that maintain meteorological networks for weather forecasting, climate studies, air quality monitoring, and similar purposes of national significance.
- State and local resources—similar to federal agencies but smaller in scope. Meteorological networks from these sources particularly serve environmental monitoring activities.
- Private resources—range from private individual who maintain weather stations motivated by amateur interest in the weather to companies who seek to profit from the generation and sale of meteorological data.

Sources of upper-air data are more limited than those for surface measurements. This is primarily because the cost of the systems required to make the measurements is much higher than for simple weather stations. The primary options for upper-air data are:

- Operational soundings—weather balloons launched twice daily by the NWS at numerous locations in the country.
- Local wind profiling systems—sources including sodar and radar. They are usually operated by environmental monitoring organizations, NOAA, national laboratories, or universities. Many of these systems are operated on a research basis, which means that they may change location or be turned off for extended periods.

Having identified the existence of measurement systems with data streams available to BWIC, it is important to be sure that the data being provided are of good quality. The two fundamental contributors to data quality are calibration and instrument exposure.

- Calibration—Ideally, instruments that provide data to BWIC will be calibrated on a regular basis because their response to the atmosphere can change over time. Thus, most government agencies have a regular program of calibration for their operational instruments. BWIC does not control the instruments whose data it uses, however, and it is therefore not possible to insist on regular calibrations. However, the existence of a calibration history can help determine whether an instrument that reports “odd” data should be retained in the data stream.
- Exposure—Instrument exposure determines how well an instrument represents some area around it. Poorly exposed instruments installed, for example, against a building or lower than trees that are beside them are not good indicators of how the wind would generally move material in their vicinity. Better exposure involves siting the instruments in open spaces where there are no significant nearby obstructions in any direction.

4.0 Local Climatology

In previous sections, we have discussed the kinds of the meteorological applications that are part of BWIC, the data required by those applications, and how to identify data sources for a particular city. As a general rule, the more good-quality observations that can be provided to BWIC, the better the meteorological fields and resulting calculations will be. This raises an important question, though: How many surface and upper-air stations are enough? It is easy to say that more is better; however, the installation, maintenance, and communications costs of new stations must be weighed against the improvement that they bring to the BWIC calculations.

The number of stations that may be needed to supplement existing sites for BWIC depends on the specific locations of the existing stations and the complexity of the local meteorology. In this section, we describe how to assess the important local meteorological patterns.

4.1 Determination of Essential Weather Patterns

Earlier we noted that characteristic meteorology varies from city to city because of local variations in land surface features, terrain, and even latitude. To reach conclusions about the appropriate deployment of meteorological sensors for BWIC, the unique meteorological features of a city need to be established.

The weather patterns important to identify are not necessarily the ones that occur most often. For example, weather fronts often sweep through the midwestern part of the country with strong north- or southwesterly winds behind them. Because the barometric pressure changes associated with these fronts are rather large-scale meteorological phenomena, the winds may persist for several days and change relatively little over an urban area. Thus, a single, well-exposed anemometer may provide all of the wind information needed for an accurate calculation of dispersion of biological agents under these conditions.

More challenging weather patterns occur when the forces that drive the wind arise primarily locally. These most often are factors when large-scale weather forces are relatively weak. Under such conditions, local variations in terrain or surface types cause local variations in winds that, in turn, can cause large errors in plume calculations if not measured and included in the calculations. Thus it is particularly important to account for local circulations in planning and executing emergency response.

Thus the practical question is how to identify important circulations that should influence the siting of meteorological measurements for a specific city. This evaluation will be at least partially subjective. There is generally neither the expertise nor the resources to do an original climatological study of a particular urban area. The following questions need to be answered with respect to local circulations:

- <u>How often does a particular kind of circulation occur</u>? An event that was very interesting but occurred only once is not likely to be of concern. An example might be a gust front associated with a strong thunderstorm. On the other hand, circulations that occur on many days, such as sea or lake breezes, must be considered. Some circulations frequently occur on a daily basis (known as *diurnal* circulations) and can be more important at night than during the day. An example of this is the outflow from canyons and valleys that occurs over cities near mountainous terrain.

- What part of the city is affected by the local circulation? For cities affected by phenomena such as canyon outflow, only part of the city may be affected. For cities affected by sea breezes, the entire city is likely to be affected by the associated wind shifts at some time during the day.
- Over what distances do wind shifts associated with the circulation occur? Typical distances over which the wind shifts markedly are often referred to as the *scale* of the wind variation. In many cases, these shifts will happen in only a few kilometers. It is important to know this in order to determine the appropriate density of meteorological sites to describe the meteorological fields.

Fortunately, many urban areas with notable local circulations have already been studied extensively. The following resources can provide excellent and specific information about an urban area:

- State climatologists. Except in the (currently) four states that do not support a climatologist, the state climatologist should probably be the first contact in identifying information about local circulations for an urban area.(a) They are likely to be familiar with local meteorology of the urban area in question, perhaps having performed significant studies themselves. If significant studies have already been done, they will know of many of them. They may be able to supply very helpful reports that are not otherwise available.
- Local forecasters. The NWS has local forecast offices across the country.(b) One reason that the NWS uses local offices is that numerical weather forecast models are not always fully successful in accounting for effects such as local terrain and land use on the weather. Local forecasters over time develop a subjective understanding of how and under what kinds of weather conditions forecast models are likely to err, and they can adjust their forecasts accordingly. This experience also tends to keep them keenly aware of significant local meteorological phenomena.
- Meteorological literature. Another source of useful information about local circulations in cities is the peer-reviewed meteorological literature. These papers are published in professional meteorological and geophysical journals. They can be somewhat arcane, but they generally represent professional analyses that are beyond the resources of a city to produce. Such papers are found in the journals of organizations such as the American Meteorological Society, the American Geophysical Union, and others. They are best identified by individuals with some familiarity with meteorology, who can make use of search references such as the Science Citation Index. Examples of peer-reviewed articles that are helpful in identifying local circulations are the numerous papers by W. Lyons that examined the lake breeze phenomenon in Chicago and its effect on the dispersion of pollutants (e.g., Lyons 1972, Lyons and Olsson 1973).

(a) For a list of state climatologists and contact information, visit http://www.stateclimate.org/.

(b) The NWS has identified public contacts for each local forecast office. The URL for an interactive map of offices and contacts is http://www.nws.noaa.gov/stormready/contact.htm. Alternatively, the website for the Western Region of the NWS provides an interactive map of offices and contacts at http://www.wrh.noaa.gov/wrh/nwspage.php. The links on this second map may be followed to the website of each local office. Some offices provide minimal contact information; others provide job titles and contact information for all office staff.

Papers that are case studies, as opposed to statistical summaries, are often particularly valuable. One pitfall of statistical studies is that the statistics can mask some of the variability that is of particular interest for dispersion processes. An example of a statistical graph that is commonly used to describe the climatology of an area is the wind rose, which is a classic method for illustrating the frequency with which winds at a location blow from a particular direction. Figure 4.1 shows a wind rose for the city of Chicago, which we know from the Lyons papers cited is commonly affected by a lake breeze. This figure suggests that winds blowing from the lake are much less frequent than winds from the south and west. However, the Lyons found that a lake breeze developed on 36% of summer afternoons, making it a significant local meteorological event to consider in deploying weather stations and in training.

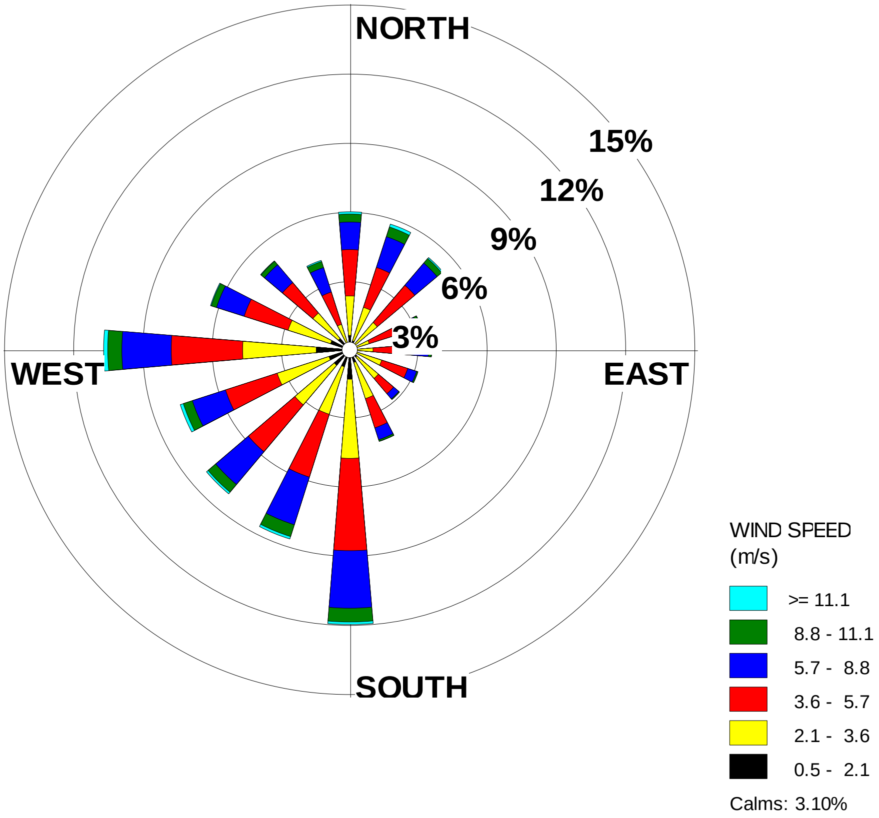

Figure 4.1. Wind Rose Showing the Distribution of Wind Speed and Direction at Chicago's Midway Airport over a 30-Year Period. This is a longer period of data than that used by Lyons in his lake breeze analyses. From this figure alone, one would not guess that Chicago experiences easterly winds from a lake breeze on a large fraction of summer afternoons.

4.2 Supplementary Simulations

In many locations, characteristic but locally unique weather conditions have received considerable study and documentation. We note several of these in Section 1 of this document. For some cities, however, local weather conditions may have received relatively little attention. In this case, numerical studies of weather conditions may be very helpful in identifying local wind characteristics in order to site meteorological sensors most effectively. Such computer modeling of local weather requires a meteorological expert and is therefore comparatively expensive. We suggest the following approach to determine whether such modeling is needed:

1. Determine whether the available meteorological networks are relatively dense. If there are usable stations every 10 km or so over the area of interest, local circulations in most places will be represented well in the diagnostic fields.
2. Determine whether there are sharp changes in terrain elevation in or near the BWIC domain. On occasion, severe variations in elevation can cause significant wind variations over distances less than 10 km.
3. Contact local forecasters to find out what they have observed about local situations that are difficult to forecast or involve sharp changes in meteorological conditions over the local area. If such situations are rare, computer simulations will probably not be needed.
4. If local weather variations characteristically show sharp spatial and temporal changes, consult the literature to see whether these variations have been documented. The literature may provide the information needed to select additional instrument locations.

If the above approach indicates that the measurement network is relatively sparse, that sharp changes in meteorological fields characteristically occur, and that these changes in the area have not been studied, it would be appropriate to conduct a modeling study.

5.0 Assessment of Need for Additional Measurements

We noted that many cities have significant meteorological measurement networks already in place. However, in many cases the measurement sites have not been chosen with the goal of being able to generate the most accurate wind fields for dispersion calculations. There are likely to be areas that have few or no meteorological sensors. Cities are then left to determine, within the constraints of finite budgets, how many and what kinds of additional sensors are needed and where they should be installed.

There are two basic ways to approach assessing the need for additional meteorological measurements. One way is subjective, in which one reviews the locations of current measurements and looks for gaps in coverage that need to be filled. The second is objective, in which modern computational techniques of optimization can be employed. The improvement to the wind field by either approach can be evaluated using one of the approaches illustrated below.

5.1 Subjective Assessment

In general, common sense guides the subjective assessment of how many additional sensors are needed and where to place them. In a subjective assessment, there are basically two questions that drive the evaluation of needed sites:

- <u>Are there areas where stations are too far apart to realistically represent the local circulations?</u> The answer to this question depends on having assessed the local circulations, as discussed in Section 4, and the intended use of the data. In BWIC, the data are used to make dispersion calculations once per hour. The calculations are made using a wind field whose grid points are nominally 2 km apart in the horizontal. There is therefore little value in placing stations closer together than that. Other practical factors can further relax the number of stations needed. For example, for phenomena such as sea or lake breezes, the wind often shifts sharply over distances of 5 km or less at the leading edge of the breeze. However, the wind shift boundary typically moves inland at a speed of several meters per second. This means that the wind shift boundary can easily move a distance of 10 km during the typical reporting interval of one hour for the meteorological measurements. If the sea breeze is the primary source of local variability of the wind field, there is no real need to have stations closer to each other than 10 km or so.

  Once the basic separation among stations has been decided for a particular city, it is straightforward to estimate the number of surface measurement sites that would provide a good measurement of the wind field over the BWIC domain. As an example, the typical extent of the CALMET grid for BWIC is 100 km in both the east–west and north–south directions. A grid of measurement sites spaced evenly every 10 km along the edges as well as internally in the domain would require 121 stations. Preliminary reviews of instrumentation deployed in some cities indicates that 121 stations is more than one is likely to find already in use. However, it is quite possible to find half that number in some cities, and if these are well distributed, CALMET should still be able to produce an effective wind field for dispersion calculations. As stations become fewer, the likelihood that CALMET will smooth over important changes in the wind field becomes greater.

A further consideration beyond the number of required measurement sites is their distribution. In the previous paragraph, we assumed a uniform distribution of stations to estimate an appropriate number. In practice, of course, existing meteorological stations will not be uniformly distributed. They are most likely to be concentrated in urban areas outside the immediate downtown. Stations are relatively few in the downtown because the concentration of large buildings severely limits the number of possible sites. Siting is easier in suburban areas far from downtown, but as the population density decreases, so do many of the motivations for atmospheric monitoring. Therefore, it is quite possible to find that the median distance of stations from their nearest neighbor is 10 km or less and large areas where no measurements are made at all. Such areas can include the downtown core as well as outlying areas. Because diagnostic models such as CALMET have the most freedom to adjust wind fields to match physical constraints in areas that are farthest from observations, large areas with no meteorological sensors are most susceptible to wind field errors. They are therefore prime places to consider adding measurement sites.

As an example, Figure 1.1a shows measurement locations of sensors operated by the NWS in the Chicago area. The box indicates an area for which winds could be needed for BWIC dispersion calculations. Inspection of the figure shows that stations tend to be located near the center of the figure and toward the shore of Lake Michigan. Obvious gaps in sensor coverage occur in the northwest and southwest corners of the box as well as over the lake. For the existing stations, the median separation is in fact less than 10 km. However, the areas that have no instrumentation are likely to have (and in fact have been found to have) occasional larger errors in the wind field. The lake presents a special problem, but there are meteorological buoys available that could be used in this more difficult location.

In addition to outlying areas and water bodies, another area that may lack a sufficient density of measurements is the urban core itself. We noted that it is usually not a good idea to place instruments in areas with poor exposure. This includes the urban canyons of downtown areas, where buildings strongly channel the winds at the surface. If downtown areas are very large, it may be necessary to place wind sensors on the tops of taller buildings. Ideally, there will already be a radio tower or other support that can be used on the top of such buildings. If not, a small tower should be installed so that the instruments are mounted approximately 10 m above the building surface. This will reduce the effect of the building on the measurements of wind speed and direction. The winds measured from the building tops are corrected for their height above the surface within the diagnostic wind field model.

- <u>Do the stations cover a broad-enough area to provide data to account for plume paths over realistic distances</u>? To a large extent, the area for which measurement coverage is needed is determined by the selection of the CALMET domain for calculating the wind field. It is tempting to think of the central urban areas, where most people live and work, to be the most important for instrumentation. However, the purpose of the meteorological measurements and fields is to help determine where a release may have originated and where it most likely moved downwind. We noted that a release can easily travel 10 km in one hour with relatively light winds. Depending on wind direction, a release at any point in the CALMET domain can reach the downtown area in just a few hours, and a release near the center of the domain can affect populations near its edge in about the same amount of time. Therefore, good wind fields are needed several hours upwind and downwind of a detection point, not just in the urban core.

5.2 Objective Assessment

It is also possible to use modern computing power to calculate the ideal locations for additional meteorological stations. This objective method, known as *optimization*, identifies locations for additional stations that will minimize a measure of error in the wind fields that the diagnostic wind model produces. This approach requires the use of mesoscale meteorological models and sophisticated analysis techniques, as well as the assistance of meteorologists and statisticians. However, we do not expect cities to perform optimization studies using their own resources exclusively, and we do not provide a full description of this option here. We do summarize the concept and briefly illustrate its use in the Chicago area.

5.2.1 Summary of Objective Approach

The basic idea of optimization is to adjust the “tuning knobs” of a model so it does the best job of approximating observations. Figure 5.1 (a) shows what a person might report who counted the number of chirps in a minute produced by the snowy tree cricket at various temperatures. The points seem to lie roughly along a line. Therefore, a model for this situation might be the straight line:

$$C = aT + b$$

The calculated counts per minute C are related to the temperature T through the “tuning knobs” a and b, which are, respectively, the slope and intercept of the line. For a given slope and intercept, a standard way of measuring the distance between the line and the observations follows. For each temperature at which chirps were counted, calculate the number of chirps estimated by the model above and compute the difference between the model and the number actually counted at that temperature. The difference between a sample and the calculated value from the model is illustrated in Figure 5.1 (b). For each sample, square each of the differences and add them all together. Mathematically, this could be written as

$$S = \sum_{i=1}^{N} \left(counts_i - C_i \right)^2$$

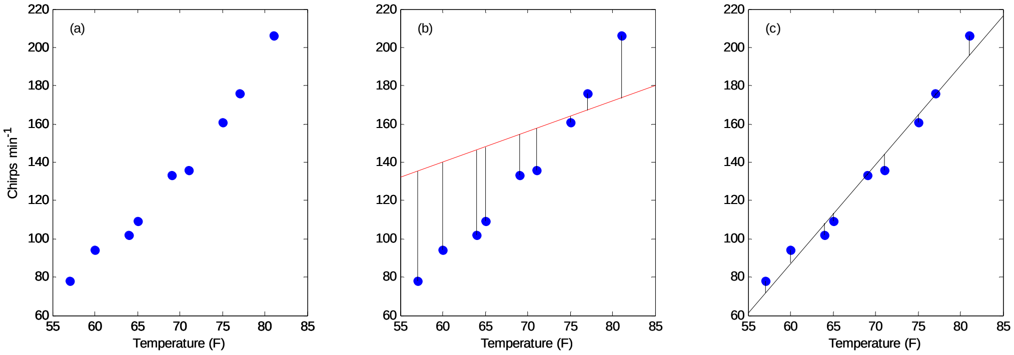

Figure 5.1. Simple Illustration of Optimization: (a) number of chirps per minute of snowy tree cricket; (b) difference between observations and arbitrary line; (c) difference between observations and optimized line that passes overall closest to all the points

It is clear from Figure 5.1 (b) that other values of a and b could be selected that would make the line pass closer to all of the points. The *best* straight-line model for this case would be the one with values of a and b that together make S as small as possible. This model is shown in Figure 5.1 (c). For the straight-line model, there is always a single, absolute minimum value of S, and it can be found by direct calculation. Most models, including the approach that we have followed, are much more complicated than this and cannot be optimized by a simple, direct calculation. Whatever the approach to optimization, though, the goal is to minimize some function like S (which is formally called a *cost function*).

For BWIC, we want to find the best locations to add additional meteorological stations. Like the simple case above, we need both a model and data to compare it with. Because we want to improve the wind fields, the model is CALMET. The tuning knobs are the locations where we place one or more additional stations. Ideally the data would be three-dimensional, time-varying measurements of the wind field at the same horizontal and vertical spacing as the CALMET grid. However, no devices exist that can provide this information. (If they did, we wouldn't need CALMET.) As a substitute, our data are sampled from wind fields produced by a modern mesoscale meteorological model.

The model we used is called MM5 (for Mesoscale Model version 5), which has been developed over many years of collaboration between The Pennsylvania State University and the National Center for Atmospheric Research. Because MM5 is a prognostic model with fairly complete treatments of atmospheric physical processes, it does a very good job of representing details of atmospheric phenomena like lake breezes, even when sufficient measurements to resolve those details are unavailable. We treat the output of MM5 as if it were the real atmosphere. This allows us to create observations at any location in time and space. Therefore, when we sample the MM5 fields at the locations of the existing and potential surface locations, CALMET uses these as input data. When we sample the MM5 fields at the locations of the grid nodes of the CALMET output, we have a means of comparing the CALMET fields with the MM5 data to see how well CALMET was able to reproduce the complexities of a realistic atmosphere.

The method of measuring how close the CALMET fields have come to reproducing the real atmosphere is essentially the same as for the cricket example above. To do this, we express the wind at any point and time, not in terms of speed and direction but in terms of vector components. Thus at each point there is a value u, which represents how fast the wind is moving to the east (or west if the value is negative), and v, which represents how fast the wind is at the same time moving to the north (or south if the value is negative). The measure of how closely the CALMET output matches the MM5 fields is computed from an expression that is basically the following:

$$S = \sum_{i=1}^{\text{All locations and times}} \sqrt{\left(u_i^{CALMET} - u_i^{MM5}\right)^2 + \left(v_i^{CALMET} - v_i^{MM5}\right)^2}$$

In this expression, the index i represents a particular grid node at a particular time. In the actual calculation, some adjustments are made to the sum so the errors well above the ground are not considered as serious as differences at the surface. The idea of the objective approach is then to find locations of additional measurement stations that will make the cost function S as small as possible.

5.2.2 Optimization Method

In the cricket example of optimization that we used as illustration above, the function to be optimized (a straight line) is simple. As a result, the optimization (finding the values of a and b so that the line passes closest to the data) can be done analytically—that is, by direct calculation from a formula. Most of the time, this is not the case. The CALMET model is in effect a much more complicated function than a straight line. As a result, we resort to optimization techniques that are available for this purpose.

One of the optimization techniques is known as the Genetic Algorithm.(a) This procedure takes an approach to optimization that attempts to mathematically mimic the principles of genetics and natural selection. We can illustrate how this works with an example—the case of adding a single surface station to the ones that already exist. (This example is simple enough that the genetic algorithm is not really required. It is the easiest example for visualizing the genetic algorithm, however.) For illustration, we optimize the location of a single additional surface station in the area around Chicago.

As in the example of the optimum straight line above, it is necessary to construct a cost function that allows a quantitative measure of how much an additional station improves the overall wind field. It is also important that the additional station improve the winds when they are blowing from a number of different directions. Therefore, the cost function is calculated from all of the grid points in the horizontal and vertical and at many different times. This more complicated cost function is

$$S = \sum_{x=1}^{nx} \sum_{y=1}^{ny} \sum_{z=1}^{nz} \sum_{t=1}^{nt} w_z \cdot \sqrt{\left(u_{x,y,z,t}^{CALMET} - u_{x,y,z,t}^{MM5}\right)^2 + \left(v_{x,y,z,t}^{CALMET} - v_{x,y,z,t}^{MM5}\right)^2}$$

In this formula, x and y are east–west and north–south horizontal coordinates, respectively; z is vertical; and t is time. The index t changes because CALMET calculates a new wind field every hour. While the nested summation signs may look complicated, all the formula really does is add up the differences between CALMET winds and MM5 winds at every grid point in the horizontal and vertical and for every hourly wind field calculated for the period of interest.

There is one other difference from the first formula, and that is the presence of the weight variable, w_z. This variable changes only with height and has the effect of allowing us to control how important CALMET wind errors are at any altitude in determining the best location for additional stations. For example, errors at altitudes well above the surface can occur because the atmosphere changes dynamically with height in a way that CALMET cannot account for using just surface observations. Therefore, errors at these higher altitudes should be less important than those at lower altitudes in establishing the best location for additional surface sensors. Accordingly, the values of the weights, w_z, are larger near the surface than aloft for identifying the best new sites for surface sensors. Conversely, because additional upper-air stations (like sodar) provide information at many levels above the surface, we weight errors equally at all heights when assessing the best location for additional stations of this kind.

Figure 5.2 shows existing surface stations in the CALMET domain in the Chicago area. The figure also shows the outline of the city boundary and the Lake Michigan shoreline. There are two areas in the

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(a) The Genetic Algorithm was developed in the 1960s and 1970s by Howard (1975).

northwest and southwest of the domain that have no available surface stations. In addition to the absence of meteorological buoys, there are no stations over the lake. The color coding in the figure corresponds to the value of S at each grid point if a single additional surface weather station were added at that particular grid point. Cooler colors indicate the smallest values of S after the station is added, and warmer colors are largest. In this simple case, the greatest improvement in the wind field due to adding a single surface station would be gained by adding a meteorological buoy in the bluest area over the lake. The greatest gain over land would come from adding a station in the relatively large area in the northwest part of the domain that has no stations.

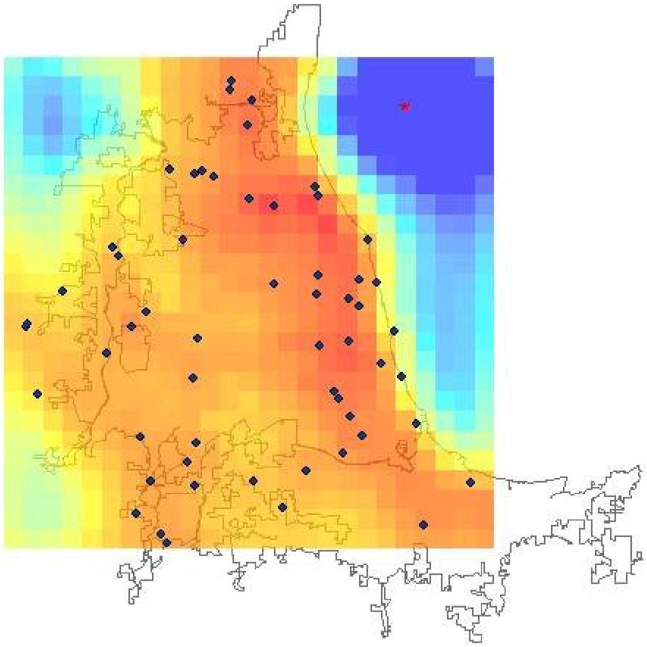

Figure 5.2. Locations of Existing Surface Meteorological Stations in the Chicago Area (black symbols) on a Map of the Values of S for Placement of an Additional Station in Each Grid Location. The best location, in terms of minimizing S, would be in Lake Michigan (red symbol; obviously necessitating a buoy).

So far we have not used the sophisticated optimization techniques that are available. In fact, if only a single station were to be added, mapping the S value at each of the CALMET grid locations would provide a fast objective indicator of where to place the new station. However, there is no guarantee that following this procedure sequentially for multiple additional stations would be as effective as finding the optimum location for all proposed new stations as a group. A way to do the latter is to use more comprehensive techniques such as the genetic algorithm.

The way the genetic algorithm mimics genetics and natural selection may be illustrated by applying it to our example of finding the best location for a single additional surface meteorological station. In this method, potential best sites can be thought of as individuals with two genes: the east and north coordinates of the new station location. In the domain of interest (which, for this example, is the CALMET domain for Chicago), 100 individuals (possible station locations) are created with random genetic values (east and north locations within the domain). For each individual, an S value is calculated.

The individuals are then ranked according to S. Those with the smallest values of S are considered fittest and therefore most suitable for survival and reproduction.

Based on the fitness ranking, individuals are selected for survival. The survivors then randomly undergo crossover and mutation based on probabilities assigned by the genetic algorithm. *Crossover* is a reproduction process in which genetic material from the parents is exchanged and children are created. In this specific application, the children are new station locations that result from a linear combination of locations of two existing stations. *Mutation* is a process in which the genes (station coordinates) of a single individual are altered to produce a new individual in the next generation. Some parent stations may reproduce and survive, while others may reproduce and not survive to the next generation. Some parent stations may neither reproduce nor survive. All of this is done in such as way as to maintain a constant population through successive generations. Once a new generation is created, fitness rankings are determined and the process repeats until a convergence criterion is satisfied; that is, until children are essentially the same as the parents.

For the current illustration, we have used wind fields from a weather situation that occurred in Chicago on July 5, 2005, when a lake breeze circulation developed. This event provided 30 separate hourly wind fields for the optimization around the hours of lake breeze passage. It also represents a common kind of wind variability that occurs in the Chicago area. Typical surface wind fields (extracted from the MM5 prognostic model) associated with this weather situation are shown in Figure 5.3, which shows relatively uniform winds across the Chicago area in the early morning. By mid-afternoon, however, the lake breeze begins to move inland. The lake breeze front is quite apparent as the line along which the wind direction shifts sharply. The change of wind with height associated with the lake breeze is shown in Figure 5.4. The wind reversal above the low-level easterly wind flowing from the lake is a good example of the variability that CALMET and other diagnostic models are not designed to reproduce purely from surface observations. It is also why we have chosen not to weight the differences between CALMET and MM5 as heavily at upper altitudes for the surface station optimization.

The initial step in optimizing the location of a single additional station using the genetic algorithm is shown in Figure 5.5a on the same S mapping that was shown in Figure 5.1. In this case, however, the dots represent the 100 randomly selected locations where one might place a single additional surface observing station. (Note that although they are not shown in Figure 5.5, all the existing surface weather stations shown in Figure 5.1 are still present when determining the best location for a new station.) At this point, the genetic algorithm begins the processes of crossover, mutation, survival, and death for successive generations.

The locations of the 100 stations in the final generation are shown in Figure 5.5 (b). By this last generation, the 100 stations are mostly clumped together at locations of the smallest values of S, which indicates that the genetic algorithm is successfully finding good locations for a new surface station in this simple example. Because this is a statistical process, it is reasonable to run the algorithm multiple times for this case. Figure 5.6 shows the genetic algorithm’s best (lowest S) solution for each of 10 runs as just described. The procedure can be refined with other statistical techniques, but the key result is that it does indeed consistently identify the best area to place an additional station.

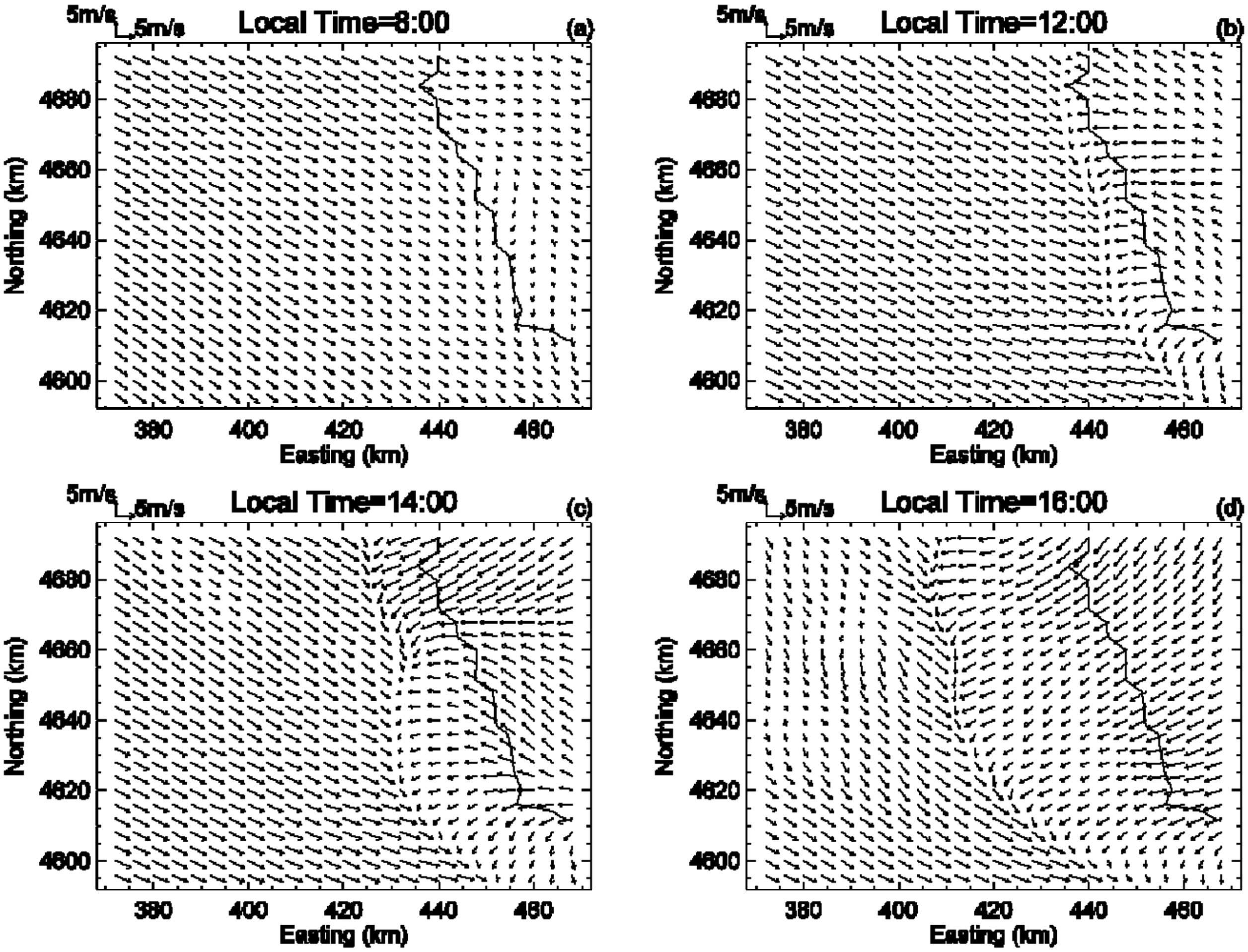

Figure 5.3. Reference Wind Fields from the MM5 Numerical Model Used in the Optimization of Station Locations. The panels show the surface winds at different times on a day when the lake breeze passed over Chicago. The wind shift associated with the lake breeze front is apparent at the later three times.

The power of the genetic algorithm is that it is readily adapted to jointly finding the best locations for multiple new measurement stations even though it is not possible to visualize the solution as we have done for this simple example. To extend the approach to multiple stations, one creates individuals with "genes" for multiple station locations. For example, to search for the optimum locations for two additional stations simultaneously, an individual would have two pairs of genes: the first pair being the east and north coordinates for one station and the second pair being the coordinates for the second station. The gene sets for individuals can be generalized to allow for any number of additional stations.

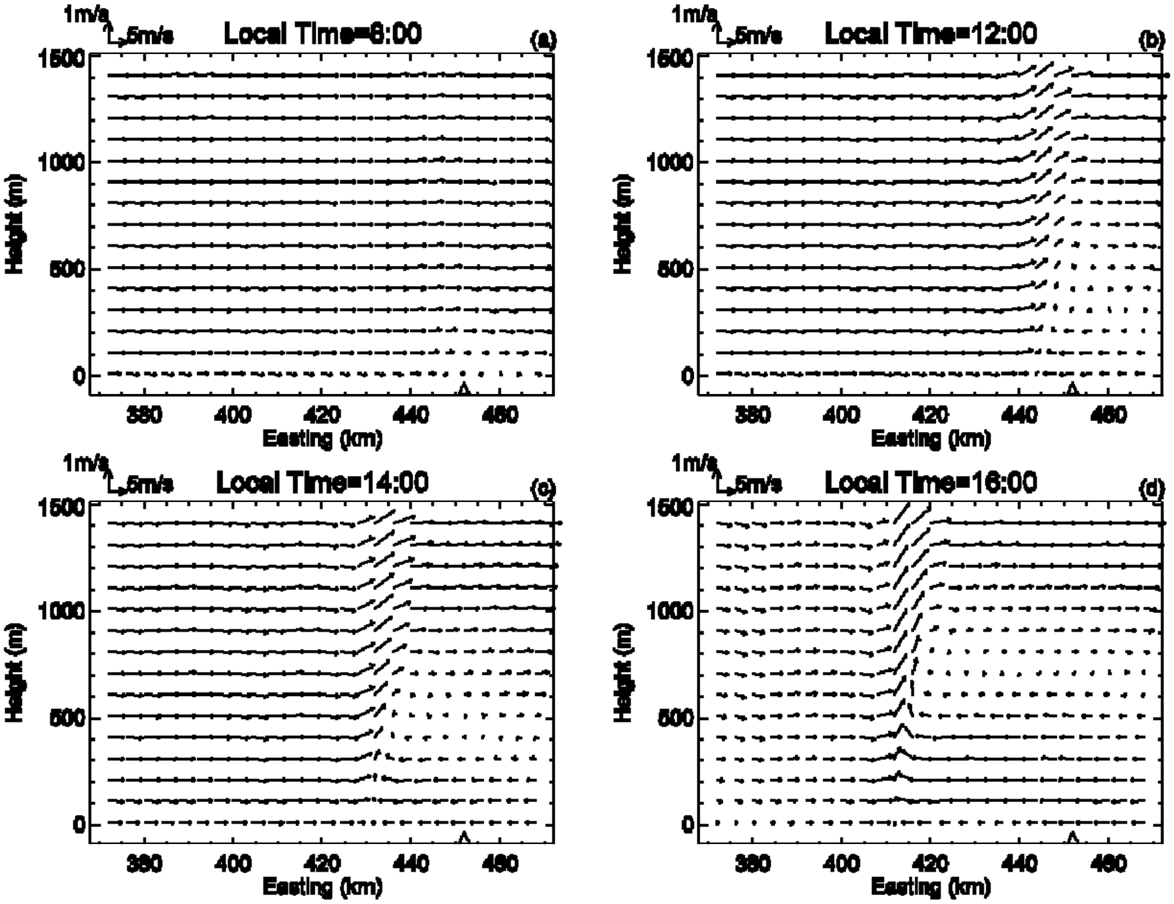

Figure 5.4. Time-Height Cross-Sections of the Same Wind Fields as in Figure 5.3, Showing the Vertical Structure of the Lake Breeze for One East-West Slice Across Chicago

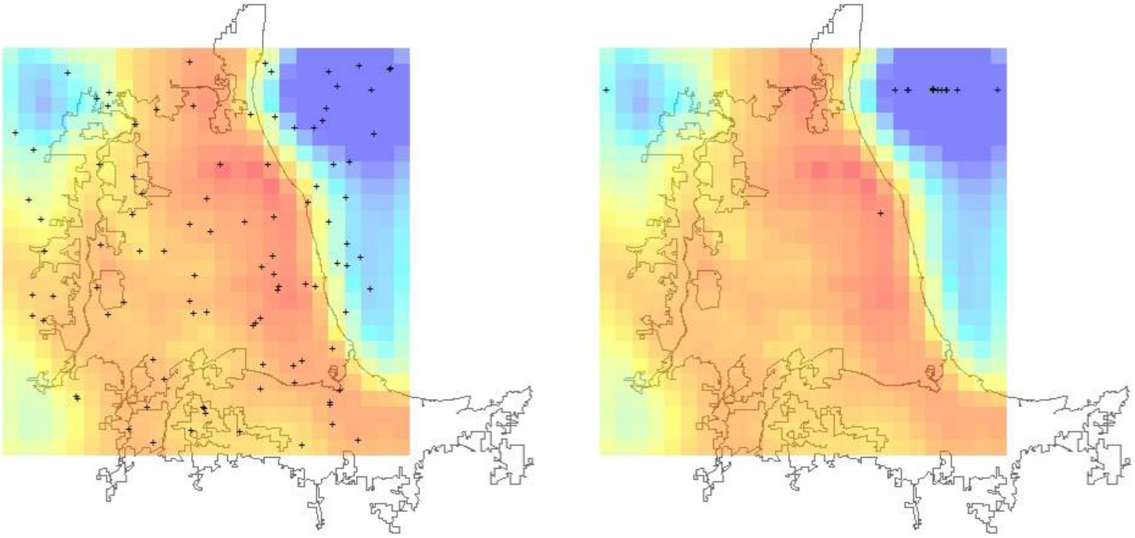

Figure 5.5. (a) Illustration of Starting Point for Optimization for Adding a Single Station Using Genetic Algorithm; points are 100 randomly selected possibilities for locating stations; colored background same as Figure 5.2; b) locations of 100 stations in final generation (after mutations, reproductions, and death).

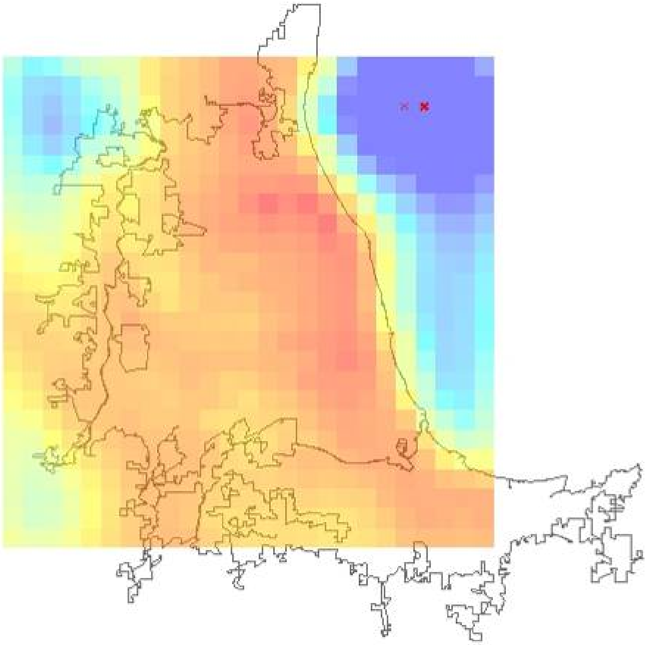

Figure 5.6. The Genetic Algorithm's Best Solutions for 10 Separate Runs

5.2.3 Utility of Adding Upper-Air Stations

The discussion to this point has been directed toward the deployment of surface meteorological stations. Upper-air stations, which provide information on the vertical structure of the atmosphere, are another source of information that can be used for determining the plume dilution and direction of plume transport. As discussed in Section 3.3 upper-air measurements are made through direct sampling with radiosondes or remotely from the surface using sodars or profilers. Diagnostic meteorological models, such as CALMET in BWIC, can assimilate upper-air measurements into their calculations of gridded fields of wind and temperature at various vertical levels.

Because operational radiosondes are only available twice daily and, in some cases, are far removed from the domain of interest, one might ask whether adding an upper-air station, such as a sodar or profiler, substantially improve the fields calculated by the diagnostic meteorological model. In regions where the upper-level wind field tends to be spatially homogenous and already well-resolved by existing networks, the answer is no—the cost of implementing and maintaining an upper-air station far outweighs any incremental improvement that may be realized in the diagnostic model. A less obvious answer exists for regions where the upper-level wind fields tend to be spatially and temporally complex, such as regions that are affected by lake or sea breezes or that have terrain-induced flows. To assist in answering this question for these regions, it is helpful to review how the diagnostic model creates the gridded fields from the measurements.

Section 2.2.2 described how CALMET uses meteorological measurements to create wind fields at various vertical levels. In generating these fields, both upper-air and surface observations are used. The surface observations are used in well-established formulations used to generate approximate profiles above the surface. These profiles, in combination with upper-level observations, determine the wind speed and direction at a given location and altitude on the grid. Therefore, at a given vertical level, the wind field reflects actual observations at that level along with an interpolated form of any spatial gradients and temporal shifts that are occurring at the surface. The degree to which the surface-derived profiles influence the vertical wind fields is controlled through a level-by-level weighting parameter. Normally, the weights are set such that the surface stations have the greatest weight near the surfaces and become progressively less important with increasing height.

For sparse surface networks, then, where there may be too few surface stations or large gaps in coverage, it is likely that a sodar or profiler will result in improved gridded wind fields simply because it would provide observations where no previous information existed. In areas where there are frequently strong variations of the wind with height, such as mountainous regions where pools of cold air form or in other areas where nighttime conditions lead to strong variations of the wind with height, sodars and profilers are also valuable.(a) For dense surface networks having a good spatial distribution, however, it is likely that the addition of a sodar or profiler would result in limited improvement in the gridded wind fields because its observations would be overwhelmed by neighboring computed profiles derived from the surface observations. If the weights are adjusted so that the surface-derived profiles have less influence on the gridded fields above the surface, information on the spatial and temporal variability of the wind field is unnecessarily removed. Put another way, numerous profiling systems would be needed to recapture the spatial variability aloft that was already captured in the surface observation network.

As a result, the addition of an upper-air station for the purpose of improving the wind fields generated by the diagnostic meteorological model should be weighed against the density and coverage of the surface observation network. It may be that adding one or more surface stations will improve the calculated wind fields above the surface at less cost. (We note that this conclusion applies strictly to the BWIC application here. Sodars and radars can be very valuable for real-time emergency response, especially if surface observations are otherwise sparse. If such a system is already available, its data should certainly be included in the BWIC diagnostic model.)

5.3 Summary

If it is determined that additional surface meteorological stations are desirable, the question is where to site them to best advantage. The question can be answered either subjectively or objectively:

- Subjective approach—identifies gaps in measurement coverage based on visual inspection of distribution of existing systems and taking into account specific features of local meteorology.
- Objective approach—Optimization techniques are available to objectively determine the best location for additional measurement stations. In many cases, including the example in this section, the objective result corresponds closely to what would be selected subjectively. Because the objective technique requires both meteorological and statistical expertise, its use is probably best reserved for situations in which the deployment of additional stations is expensive and a subjective choice is not clear.

(a) Allwine et al. (1992) performed tracer studies of mixing processes in atmospheric cold pools. Bonner (1968) provided one of the early general descriptions of the nighttime low-level jet that commonly forms in the southern Great Plains of the United States.

It may be difficult to justify the expense of procuring upper-air stations for BWIC if there is a relatively dense network of surface stations, unless there are also characteristic strong changes of wind with height. This is because an added upper-air station provides detailed information about vertical changes in the meteorology but, by itself, no information about horizontal changes. If, in producing the gridded wind fields, its measurements influence a large horizontal area above the surface, it effectively eliminates horizontal variability above the surface that can be inferred from the surface measurements. If, to counter this, its influence is only a small horizontal area, it contributes little to the overall wind field, raising the question of whether its cost is justified. Preexisting upper-air stations should always be used, however, and the recommendation regarding the addition of these stations applies exclusively to the BWIC context. For many other applications, the addition of upper-air stations is essential.

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