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OVERVIEW OF METEOROLOGICAL MEASUREMENTS FOR AERIAL SPRAY MODELING

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ABSTRACT. The routine meteorological observations made by the National Weather Service have a spatial resolution on the order of 1,000 km, whereas the resolution needed to conduct or model aerial spray applications is on the order of 1–10 km. Routinely available observations also do not include the detailed information on the turbulence and thermal structure of the boundary layer that is needed to predict the transport, dispersion, and deposition of aerial spray releases. This paper provides an overview of the information needed to develop the meteorological inputs for an aerial spray model such as the FSCBG and discusses the different types of instruments that are available to make the necessary measurements.

INTRODUCTION

Meteorological processes are often classified according to time and space scales. The time scale is determined by the lifetime or period of an atmospheric system, and the space scale is determined by the typical size or wavelength of the system or event. Atmospheric motions generally are classified as synoptic scale, mesoscale, or microscale. Because these scales of motion overlap, the boundaries between them are not distinct. Synoptic-scale systems, which are the systems depicted on weather maps, include high- and low-pressure centers with horizontal scales on the order of 800–8,000 km and lifetimes from 1 day to 1 wk. Mesoscale systems have horizontal scales on the order of 1–800 km and time scales of a few hours to about 1 day. Examples of mesoscale systems include nighttime drainage winds in complex terrain and land/sea breeze systems. Although mesoscale systems significantly affect atmospheric transport and dispersion processes, they rarely can be defined using routine synoptic-scale meteorological observations. Microscale systems include turbulent eddy motions with time scales on the order of 1 sec to tens of minutes and spatial scales of less than 100 to about 1,000 m. Although the general flow defined by synoptic and/or mesoscale systems is important, the microscale is of most interest to the aerial spray applicator.

The interaction of all of the scales of atmospheric motion results in a 3-dimensional wind vector at any given point in the atmosphere. This wind vector varies continuously in time. Over a specific time interval, each of the 3 orthogonal (perpendicular) wind components can be resolved into a mean component and fluctuations about the mean. For example, if the mean horizontal wind speed and wind direction are determined for a specific period, the mean horizontal velocity normal to the mean wind direction is 0 by definition. However, the variability of the wind direction about the mean direction indicates that there are crosswind velocity fluctuations about the zero mean crosswind velocity. These turbulent velocity fluctuations arise from microscale eddies that generally are so small and chaotic they cannot be individually defined and followed. Consequently, microscale circulations normally are described by their statistical properties.

DISPERSION MODELING

Atmospheric transport and dispersion models predict the distribution of material released into the atmosphere. In order to predict this distribution, models must account for all of the factors that can affect the material's concentration at any point. At a minimum, these factors include the source (i.e., the location and quantity of the release and whether it is instantaneous, quasicontinuous, or continuous), transport of material by the mean wind, and 3-dimensional atmospheric dispersion (turbulent transport). If there are significant removal mechanisms (for example, deposition of all or part of the material mixed to the surface), these mechanisms must also be considered, as must evaporation and any chemical reactions or other transformations that affect the released material. It is relatively easy to write a differential equation that accounts for (conserves the mass of) all of the released material. However, the functional forms of many of the terms of this dispersion equation must be hypothesized using theoretical and/or empirical relationships. Some "numerical" dispersion models make assumptions about the various terms in the dispersion equation that are sufficiently complex that they preclude an analytic solution. These dispersion models are computer intensive because they must use numerical techniques to solve the dispersion equation for even the simplest modeling problems. On the other hand, most current operational models make assumptions that are sufficiently simple that an analytic solution can be obtained.

The majority of current operational dispersion models, including the Forest Service Cramer–Barry–Grim (FSCBG) model (Teske et al. 1993), are based on the concept of a Gaussian cloud or plume. The Gaussian model can be derived from simple physical reasoning beginning with the observation that, on the average, the concentration of material instantaneously released into the atmosphere to form a cloud decreases with increasing distance from the cloud center, and the assumption that the concentration profile for a cloud cross section has a Gaussian (bell) shape. The Gaussian "dispersion coefficient" in a given direction (such as the downwind direction) is the standard deviation of the concentration distribution in that direction. Gaussian dispersion coefficients can be determined as empirical functions of downwind distance (or transport time) and meteorological parameters, or they can be estimated from theory by making certain idealized assumptions. Most Gaussian dispersion models use empirical coefficients. The major Gaussian model assumptions are that meteorological conditions are approximately constant (steady-state) over the transport and dispersion time of concern, and that meteorological conditions are horizontally uniform over this time. It follows from these assumptions that a cloud or plume is predicted to follow a straight-line trajectory over the time of concern. If either of the 2 major model assumptions is violated, the predictions of a Gaussian dispersion model become unreliable. A Gaussian dispersion model is expected to be accurate in predicting only the mean results for a number of repetitions of the same release under the same meteorological conditions. Model predictions can differ significantly from what is measured during a single release.

Version 4.3 of the FSCBG model (Teske and Curbishley 1994) is the most recent version of a Gaussian dispersion model jointly developed by the U.S. Army Dugway Proving Ground, and the U.S. Department of Agriculture Forest Service for application to aerial spray releases. The FSCBG includes aircraft wake, forest canopy penetration, and drop evaporation modules. The model can be used to calculate above-canopy concentration or dosage as well as spray drop deposition within and below the canopy for multiple line sources. (In the absence of a forest canopy, the FSCBG can be used to calculate concentration or dosage at any height above the surface and deposition at the surface.) The FSCBG can compute the effects of aircraft (fixed-wing or helicopter) wake vortices on the initial spread of spray drops using either a numerical solution to the 2-dimensional equations of motion (the AGDISP model of Teske 1990) or a simple wake effects algorithm (Dumbauld et al. 1980). The model uses a unique analytic solution for a finite line source with any orientation to the mean wind direction. Although the original FSCBG used a computer-intensive Monte Carlo technique to calculate drop penetration through a forest canopy, the current model includes as an option an analytic canopy penetration algorithm (Bjorklund et al. 1988) that yields equivalent results in a fraction of the time. The FSCBG makes the simplifying assumption that drops penetrating below the top of a forest canopy follow simple ballistic trajectories that are unaffected by below-canopy turbulence.

In a Gaussian dispersion model, the major model elements used to characterize the effects of meteorology on the atmospheric dispersion of a cloud or plume are the mean transport wind speed $\bar{u}$ and direction; the dispersion coefficients σ_x, σ_y, and σ_z; and the depth of the surface mixing layer H_m. The FSCBG model uses semiempirical relationships between meteorological variables and the model elements of mean transport wind speed and dispersion coefficients. The meteorological variables required by these relationships are the model's meteorological inputs. The remainder of this paper discusses the types of meteorological instrumentation that can be used to derive the information needed to develop Gaussian dispersion model meteorological inputs. It provides an overview of meteorological sensor types, capabilities, and limitations for 3 general categories of instrumentation: those that make measurements at fixed points in space, remote sensing instruments, and airborne instruments. For a more detailed discussion of meteorological instrumentation, the reader is referred to sources such as Randerson (1984) and Houghton (1985).

FIXED-POINT INSTRUMENTS

Fixed-point instruments such as anemometers, wind vanes, and thermometers are the most common and usually the least expensive meteorological sensors. They are often mounted on meteorological towers or in instrument shelters. Fixed-point sensors offer the advantages of well-understood operating characteristics and simplicity. Instrument output is usually related to the measured variable through a transfer function defined in a laboratory, and many have simple calibration procedures. However, a fixed-

Table 1. Suggested meteorological instrumentation for aerial spray modeling.

Suggested instrumentation	Measurement level 2 m	8 m	10 m	16 m	32 m
Minimum					
Wind vane			X		
Cup anemometer			X		
Resistence thermometer	X				
Chilled-mirror hygrometer	X				
Desired					
Wind vane	X	X		X	
Cup anemometer	X	X		X	
Resistance thermometer	X				
Thermocouple	X	X		X	
Chilled-mirror hygrometer	X				
Tethersonde					
Net radiometer					
Research-grade					
2-Axis sonic anemometer	X			X	
3-Axis sonic anemometer		X			X
Fiberoptic–quartz thermometer	X	X		X	X
Chilled-mirror hygrometer					
Sodar					
Tethersonde					

point instrument is limited to sampling the portions of the atmosphere that flow past its sensor. Because of their physical presence, fixed-point sensors and their supporting structures perturb the atmosphere in which they are immersed. Also, measurements made at a fixed point can be unrepresentative of meteorological conditions occurring at locations where measurements are needed, especially when the measurements will be used to derive dispersion model meteorological inputs.

Fixed-point wind sensors include mechanical instruments (cup and propeller anemometers, horizontal and bidirectional wind vanes) and nonmechanical instruments (sonic anemometers, hot-wire and hot-film anemometers). Mechanical wind sensors are most commonly used for operational wind measurements.

REMOTE-SENSING INSTRUMENTS

Advances in electronics, sensor technology, and wave propagation theory have led to the development of remote-sensing meteorological instruments. These instruments typically obtain information from a forward- or backscattered electromagnetic or acoustic signal emitted by the instrument's transmitter. A major advantage of remote sensing is that the classic problem of an instrument's size or thermal mass interfering with the measurement is eliminated. Also, remote measurements obtained along a propagation path can offer temporal and spatial resolution advantages and can be more appropriate for some applications than measurements made at a single point. Remote-measurement paths can be horizontal, slant range, or vertical. In some cases, remote sensing may be the only means of making measurements at inaccessible sites.

The disadvantages of remote sensors include the technical competence required to operate the equipment and interpret the results and the relatively high cost of the instrumentation. Accuracy is not defined for these instruments because the return signals cannot be directly related to the measured variable through transfer functions, as can be done with most point sensors. Instead, the signals are typically processed through a series of mathematical filters, transformations, and analysis routines. Remote-sensor output should therefore be viewed as an interpretation of the signal rather than a measurement that can be traced to a standard reference.

AIRBORNE INSTRUMENTS

Most airborne meteorological instruments are fixed-point sensors mounted on a moving platform. Airborne sensors are used to extend measurements higher into the atmosphere or over greater horizontal distances than would otherwise be possible. The advantages of using an airborne sensor rather than multiple fixed-point sensors to sample along a measurement path are that the effects of differences in instrument calibration and response are eliminated, and the required number of sensors is minimized. Some airborne sensors are mounted on platforms designed to travel with and measure within a cloud or plume.

The limitations of airborne meteorological measurement systems are primarily attributable to the airborne platform. Time-on-station is limited by airborne platform endurance. An ascending balloon, for example, makes a single pass through the atmosphere. Sensor ventilation rates vary with speed, altitude, and angle of exposure, and the field of view is often limited by platform or structural requirements.

SUGGESTED METEOROLOGICAL INSTRUMENTATION

The instrumentation deployed during an aerial spray program or research trials will vary depending on the goals of the experiment and the resources available. However, if the spraying is to be modeled with the FSCBG, a minimum amount of instrumentation is required. Table 1 lists a hierarchy of instrumentation depending on the level of effort. If a forest canopy is present, wind measurements should be made both within and above the forest or in an open area at least 10 tree heights away from the forest. Barometric pressure can be obtained from the nearest National Weather Service observation and adjusted for altitude using the hypsometric equation (Randerson 1984).

The tethersonde referred to in Table 1 is a tethered, blimp-shaped balloon that is used as a platform for wind, temperature, and humidity sensors. The balloon can be raised and lowered by a winch to obtain vertical profiles of these meteorological parameters to a height of several kilometers if wind conditions permit. The sodar or Doppler acoustic sounder is a ground-based remote-sensing instrument that uses the acoustic Doppler effect to measure wind and turbulence profiles above its antenna array. Most sodars are designed to provide profiles from 60 to 600 m above ground and occasionally higher as conditions permit.

The tower wind, temperature, and relative humidity measurements can be entered by height directly into the open- and below-canopy meteorological inputs sections of the FSCBG model. The tethersonde wind, temperature, and relative humidity data can also be entered directly as meteorological inputs. The tethersonde and sodar wind information can be used by a trained meteorologist to determine the height of the surface mixing layer for input to the model. The net radiometer can be used to estimate the net radiation, which is required if the model must estimate the turbulent state of the atmosphere. The actual measurement of the turbulent state of the atmosphere is made using wind data from the sonic anemometers, which, when properly analyzed by a meteorologist, provide turbulence intensities for direct input to the model.

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