Lesson 5

Meteorological Instruments

Goal

To familiarize you with the meteorological instruments that measure and record the atmospheric variables of wind speed, wind direction, temperature, radiation and mixing height—especially those useful for air pollution studies.

Objectives

Upon completing this lesson, you will be able to do the following:

1. List the four key meteorological variables that are important in air pollution studies.
2. Identify two types of wind speed instruments and briefly describe the operation of each.
3. Identify a wind direction instrument and briefly describe its operation.
4. Describe how instruments should be sited and explain the importance of proper instrument siting.
5. Describe how solar radiation is measured.
6. Describe how mixing heights are measured.
7. Explain the importance of following a quality assurance plan.

Introduction

In order to understand and predict the transport and dispersion of air pollutants, it is imperative to understand the basic atmospheric processes that influence pollutants in the atmosphere. Measuring and recording meteorological variables provides the necessary information to manage the release of air contaminants into the atmosphere and to understand the transport and dispersion of emitted air pollutants. These same variables can be used to make qualitative and quantitative predictions of ambient air quality pollutant concentrations resulting from the release of pollutants.

Meteorological variables that influence how air pollutants are transported and dispersed include turbulence intensity, wind speed and direction. The turbulence intensity of the atmosphere is typically referred to as atmospheric stability. Characterization of atmospheric stability for atmospheric dispersion modeling purposes is presented in Lesson 6 and involves measurements of temperature, radiation intensity, and wind speed. Mixing height, another atmospheric variable that impacts transport and dispersion of air pollutants, is typically calculated from data reported by radiosondes released by the National Weather Service. (A radiosonde is an instrument that is carried aloft by a balloon to measure atmospheric variables and transmit the data to a ground station where a profile of the atmosphere is created.)

The focus of this lesson will be to review the instrumentation needed to measure meteorological variables most useful in air pollution studies, namely, wind speed and direction, ambient temperature and vertical temperature difference, solar radiation and mixing height.

Many systems are available for measuring these atmospheric parameters. Choosing the most appropriate sensors depends on the type of application for which the data is to be used. In addition to sensors, other equipment for signal conditioning, recording, and perhaps electronic data logging may be needed. Strict procedures for specifying, siting and maintaining instruments need to be followed to ensure the collection of representative data.

Wind Speed

Although wind is a vector quantity and may be considered a primary variable in itself, it is more common to consider wind speed (the magnitude of the vector) and wind direction (the orientation of the vector) separately as variables. Wind speed determines the amount of initial dilution experienced by a plume. Thus, the pollutant concentration associated with a plume is directly related to the wind speed. Wind speed also influences the height that a plume will rise after being emitted. As wind speed increases, plume rise decreases as the plume is bent over by the wind. The effect of this is to lower the plume height which keeps the plume closer to the ground and allows it to impact the ground at shorter distances downwind. Wind speed is routinely used in conjunction with other variables to derive atmospheric stability categories used in air quality modeling applications.

Two main types of instruments that measure wind speed are the **rotating cup anemometer** and the **propeller anemometer** (depicted in Figure 5-1). Both types of anemometers consist of two subassemblies, the sensor and the transducer. The sensor is the device that rotates by the force of the wind. The transducer is the device that generates the signal suitable for recording. A complete instrument package may also include electronics to capture and record the electronic signals generated by the transducer. For instance, the signal may need to be conditioned so that a reportable quantity can be derived from the signal. This is accomplished with a signal conditioner. Finally, the conditioned signal needs to be displayed and/or recorded for it to be useable. Data recorders and loggers accomplish this task.

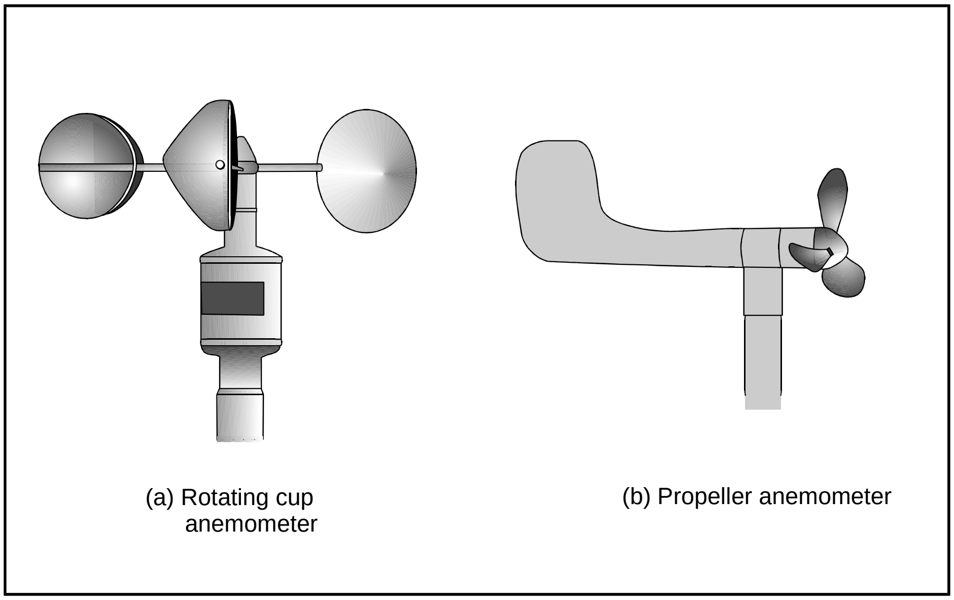


Figure 5-1. Two types of anemometers

Rotating Cup Anemometers

The rotating cup anemometer usually consists of three hemispherical or cone-shaped cups mounted symmetrically about a vertical axis of rotation. The rate of rotation of the cups is essentially linear over the normal range of measurements, with the linear wind speed being about 2 to 3 times the linear speed of a point on the center of a cup, depending on the construction of the cup assembly.

Vane-Oriented and Fixed-Mount Propeller Anemometers

The **vane-oriented propeller anemometer** [Figure 5-1 (b)] usually consists of a two, three or four-bladed propeller which rotates on a horizontal pivoted shaft that is turned into the wind by a vane. There are several propeller anemometers which employ light-weight molded plastic or polystyrene foam for the propeller blades to achieve low starting threshold speeds. Some propeller anemometers are not associated with a moving vane (see Figure 5-2). Rather, two orthogonal fixed-mount propellers are used to determine the vector components (i.e. speed and direction) of the horizontal wind. A third propeller with a fixed mount rotating about a vertical axis may be used to determine the vertical component of the wind if desired.

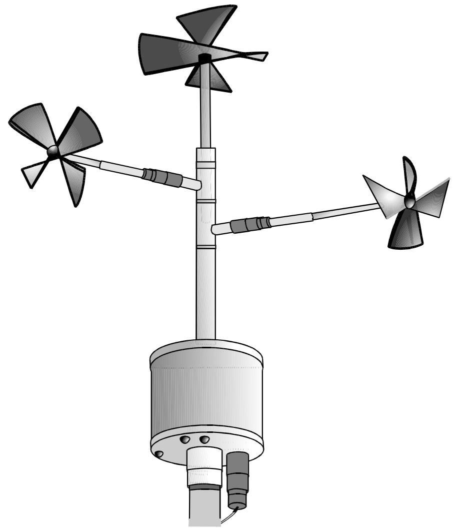


Figure 5-2. Fixed mount (uvw) anemometer

Wind Speed Transducers

There are several mechanisms that can be used to convert the rate of the cup or propeller rotations to an electrical signal suitable for recording and/or processing. The selection of the transducer is determined by the nature of the monitoring program—how responsive the instrument needs to be and what type of data readout or recording is needed. The four most commonly used types of transducers are the DC generator, the AC generator, the electrical-contact, and the interrupted light beam. Many **DC** and **AC generator** types of transducers in common use have limitations in terms of achieving low thresholds and quick response times. It is important to use instruments, such as those anemometers that employ miniaturized DC generators, which have low starting thresholds. The AC generator transducers eliminate the brush friction, but the signal conditioning circuitry must be carefully designed to avoid spurious oscillations in the output signal that may be produced at low wind speeds. **Electrical-contact** transducers are used to measure the total passage of the wind (wind-run) instead of instantaneous wind speeds, and may be used to determine the average wind speed over a given time increment. These devices are typically not appropriate for use in air pollutant dispersion studies. The **interrupted light beam** (light chopping) transducer is frequently used in air quality applications because it exhibits less friction and therefore is more responsive to lower wind speeds. This type of transducer uses either a slotted shaft or a slotted disk, a photo emitter and a photo detector. The cup or propeller assembly rotates the slotted shaft or disk, creating a pulse each time the light passes through a slot and falls on the photo detector.

The frequency output from an AC generator or a light chopping transducer may be transmitted through a signal conditioner and converted to an analog signal for various recording devices, such as a continuous strip chart or a multipoint recorder, or through an analog-to-digital (A/D) converter to a microprocessor type of digital recorder. Several modern data-loggers can accept the frequency type signal directly, eliminating the need for additional signal conditioning. The recording and processing of the data needs to be considered in designing a monitoring program.

Wind Direction

Wind direction is generally defined as the orientation of the wind vector in the horizontal. Wind direction for meteorological purposes is defined as the direction from which the wind is blowing, and is measured in degrees clockwise from true north. For example, a westerly wind is blowing from the west, 270^o from north. A north wind is blowing from a direction of 360^o. Wind direction determines the transport direction of an emitted plume.

Wind Vanes

The most common instrument for measuring wind direction is the **wind vane**. Wind vanes point in the direction from which the wind is blowing. Wind vanes come in many different shapes and sizes: some with two plates joined at their forward edges and spread out at an angle (splayed vanes) and others with a single flat plate or perhaps a vertical airfoil. Vanes are commonly constructed from stainless steel, aluminum, or plastic. As with anemometers, care should be taken in selecting a sensor that has a proper balance of durability and sensitivity for a particular application. Examples of wind vanes are depicted in Figure 5-3.

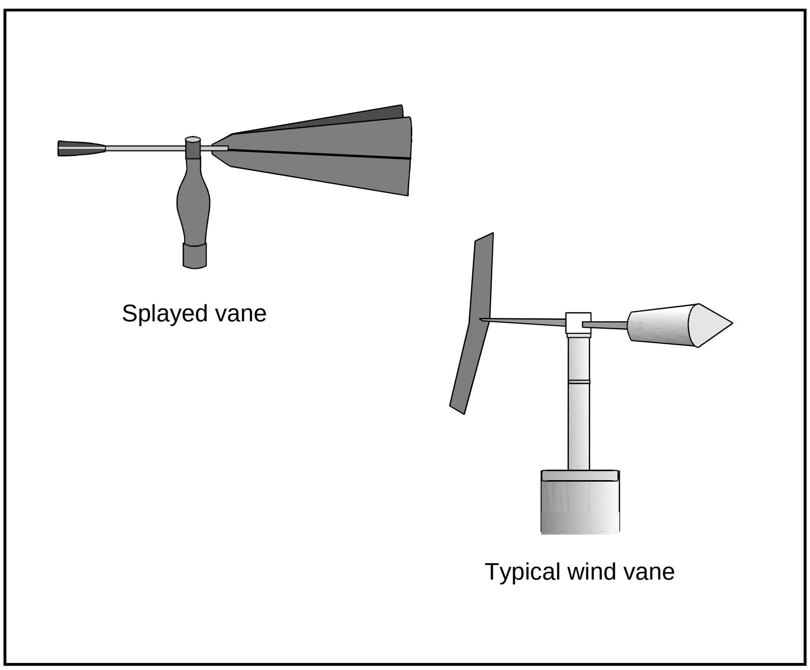


Figure 5-3. Wind vanes

The horizontal (azimuth) and vertical (elevation) components of the wind direction can be measured with a bi-directional wind vane (bivane). The bivane generally consists of either an annular fin or two flat fins perpendicular to each other, counterbalanced and mounted on a gimbal so that the unit can rotate freely both horizontally and vertically.

Fixed-Mount Propeller Anemometers

Another method of obtaining the horizontal and/or vertical wind direction is through the use of orthogonal fixed-mount propeller anemometers (mentioned earlier). The horizontal wind direction can be determined computationally from the orthogonal wind speed components. Vertical velocity can also be measured by adding a third propeller mounted vertically. This device is often referred to as a UVW anemometer.

Wind Direction Transducers

Many kinds of simple commutator-type transducers utilize brush contacts to divide the wind direction into eight or 16 compass point sectors. However, transducers that provide at least 10^o resolution (36 compass point sectors) in wind direction measurements are preferred for use in air quality applications.

A fairly common transducer for air quality modeling applications is a **potentiometer**. The voltage across the potentiometer varies directly with the wind direction. A potentiometer is a variable resistor. When the wind direction changes, the shaft of the wind vane moves and changes the resistance across the potentiometer. This change is directly related to wind direction.

Siting and Exposure of Wind Measuring Instruments

Proper instrument siting is a key to obtaining representative meteorological data for use in air pollution studies. Instruments need to be located in areas away from obstructions that can influence the measurements. Secondary considerations such as accessibility and security should not be allowed to compromise data quality.

The standard exposure height of wind instruments over level, open terrain is 10 m above the ground. Open terrain is defined as an area where the distance between the instrument and any obstruction (trees, buildings, etc.) is at least 10 times the height of the obstruction (See Figure 5-4). In some cases where emission releases occur substantially above 10 m, additional wind measurements may be needed at higher elevations. Appropriate measurement heights would be established on a case-by-case basis depending upon the application. Mounting wind instruments on an open-lattice tower is recommended when possible. Tower-mounted wind instruments should be placed on the top of the tower or, if mounted on the side of the tower, instruments should be placed on booms at a distance of at least twice the diameter/diagonal of the tower extending outward toward the prevailing wind direction (See Figure 5-5).

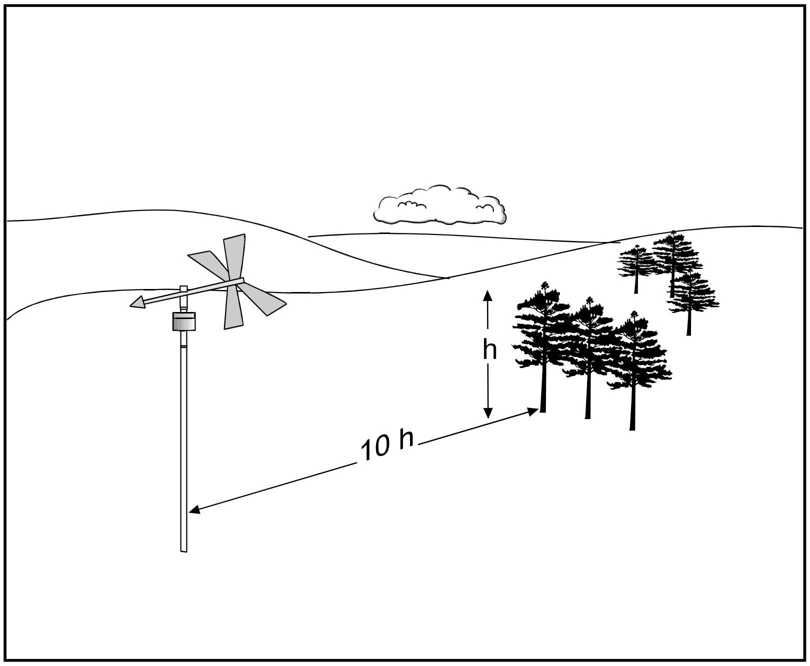


Figure 5-4. Distance siting criteria for wind measuring instruments

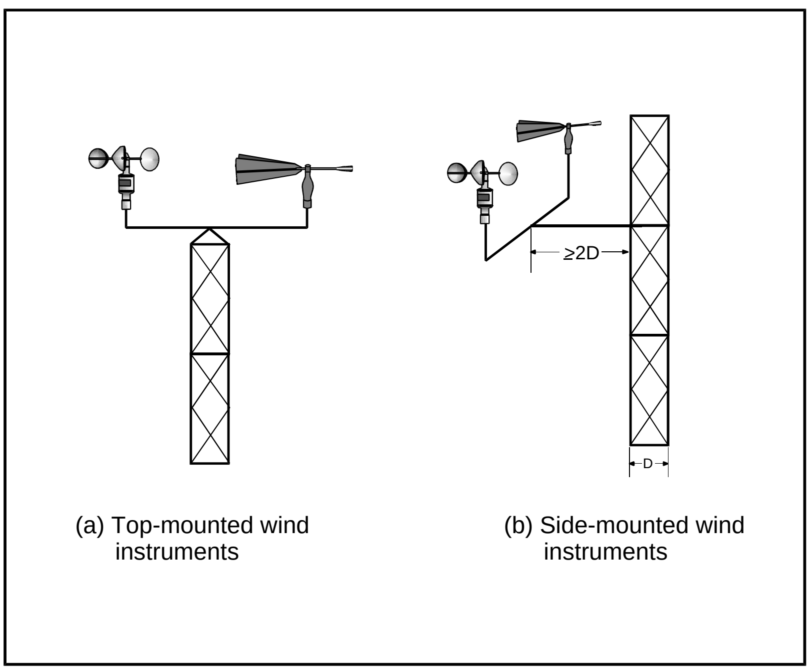


Figure 5-5. Recommended mounting locations for wind instruments

Temperature and Temperature Difference

Both ambient air temperature at a single level (typically 1.5 to 2 m above ground) and temperature difference between two levels (typically 2 m and 10 m) are useful in air pollution studies. These temperature measurements are useful in calculations of plume rise and can be used in determining atmospheric stability.

Classes of Temperature Sensors

The three main classes of temperature sensors are based on: (1) thermal expansion; (2) resistance change; and (3) thermoelectric properties of various substances as a function of temperature. The alcohol and mercury liquid-in-glass bulb thermometers are common examples of thermal expansion sensors. However, these are of limited value in on-site or remote monitoring networks because they lack the means for automated data recording.

A common type of sensor for on-site meteorological measurement programs is the **resistance temperature detector (RTD)**. The RTD operates on the basis of the resistance changes of certain metals, usually platinum or copper, as a function of temperature. These two metals are the most commonly used because they show a fairly linear increase of resistance with rising temperature. A second type of resistance change thermometer is the **thermistor**, which is made from a mixture of metallic oxides fused together. The thermistor generally gives a larger resistance change with temperature than the RTD. Because the relation between resistance and temperature for a thermistor is non-linear, systems generally are designed to use a combination of two or more thermistors and fixed resistors to produce a nearly linear response over a specific temperature range.

Thermoelectric sensors work on the principle of a temperature dependent electrical current flow between two dissimilar metals. Such sensors, called **thermocouples**, have some special handling requirements for installation in order to avoid induction currents from nearby AC sources, which can cause errors in measurement. Thermocouples are also susceptible to spurious voltages caused by moisture. For these reasons, their usefulness for routine field measurements is limited.

Temperature Difference

The basic sensor requirements for measuring vertical temperature difference are essentially the same as for single ambient temperature measurement. However, matched sensors and careful calibration are required to achieve the desired accuracy of measurement.

Siting and Exposure of Instruments to Measure Temperature and Temperature Difference

Ambient air (surface) temperature should be measured at a height of 2 m. The standard height for temperature difference measurements is 2 and 10 m. If elevated emission levels are of concern, it may be appropriate to make additional temperature measurements at higher elevations. These elevations would be determined on a case-by-case basis depending upon the application. The temperature sensor should be located over an open, level, and well-ventilated area of at least 9 m in diameter. Additionally, temperature sensors should be located at a distance of at least four times the height of any obstruction and at least 30 m from larger paved areas. The surface under the temperature sensor should be covered by a natural earth surface or short grass and located away from low lying areas that hold standing water. Instruments should be shielded to protect them from thermal radiation and should also be well-ventilated using aspirated shields.

Radiation

Solar radiation is related to the stability of the atmosphere. Cloud cover and ceiling height (height of the base of the cloud deck that obscures at least half the sky) data, taken routinely at National Weather Service (NWS) stations, provide an indirect estimation of radiation effects, and are used in conjunction with wind speed to derive an atmospheric stability category. If representative information is not available from routine NWS observations, it may be appropriate to measure solar radiation for use in determining atmospheric stability.

The instrument that is used most frequently to measure solar radiation is a pyranometer. A picture of a pyranometer is shown in Figure 5-6. The **pyranometer** measures direct and diffuse radiation on a horizontal surface. In this instrument is a small flat disk with sectors of the disk painted alternating black and white. When exposed to solar radiation the black sectors become warmer than the white areas. This temperature difference is detected electronically. An electrical voltage proportional to the incoming solar radiation energy is produced. A standard optical glass dome is installed over the disk which is transparent to wavelengths from about 280 to 2800 nm. Some pyranometers use a silicon glass dome in order to measure radiation in different spectral intervals.

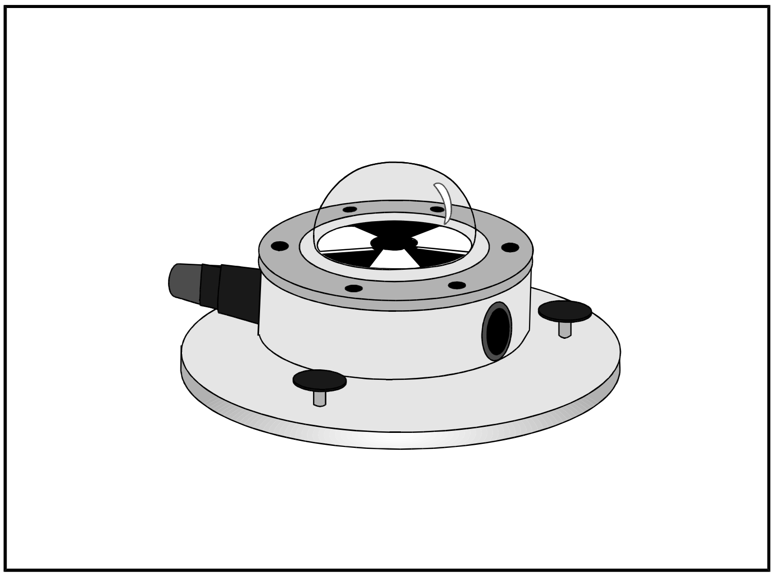


Figure 5-6. Pyranometer

Another type of sensor is the **net radiometer**, which is an instrument that measures the net difference between the upward and downward components of solar and terrestrial radiation. The primary application of a net radiometer would be to determine the daytime and nighttime radiation balance as an indicator of stability. However, nighttime stability categories commonly used in air pollution studies are based solely on wind speed and cloud cover conditions.

Siting and Exposure of Radiation Measuring Instruments

Pyranometers used for measuring incoming (solar) radiation should be located in open areas with an unrestricted view of the sky in all directions during all seasons. They should be located to avoid obstructions casting a shadow on the sensor at any time. Also, siting the instrument near light colored walls and artificial sources of radiation should be avoided. Sensor height is not critical for pyranometers. A tall platform or rooftop is a desirable location.

Net radiometers should be mounted about 1m above the ground. The ground cover under a net radiometer should be representative of the general site area. Net radiometers should also be located to avoid obstructions to the field of view both upward and downward.

Mixing Height

The vertical depth of the atmosphere where mixing takes place is called the mixing layer. The top of the mixing layer is referred to as the mixing height. The mixing height determines the vertical extent of the dispersion process for air pollutants that are released below the mixing height. The mixing height is an important variable in air quality studies as it restricts vertical dispersion of pollutants. Although mixing heights are not typically measured directly, they can be approximated from routine meteorological measurements.

Morning and afternoon mixing heights are typically estimated from the vertical temperature profiles observed at selected National Weather Service stations taken at 1200 Greenwich Median Time (GMT) and surface temperature measurements. Vertical temperature profiles are measured with radiosondes, instruments transported aloft by lighter-than-air balloons (i.e. balloons typically filled with either hydrogen or helium). For air quality modeling studies used in regulatory applications, hourly mixing heights are estimated from the twice-daily mixing height values, sunrise and sunset times, and hourly stability categories by the meteorological preprocessor computer program developed for use with EPA regulatory models. A further discussion of this technique can be found in EPA documents (see Holzworth, 1972).

The Doppler SODAR (an acronym for **So**und **D**etection **A**nd **R**anging) systems are gaining recognition as effective tools for remote measurement of meteorological variables at heights up to several hundred meters above the surface. A SODAR transmits a strong acoustic pulse into the atmosphere and listens for that portion of the pulse that is scattered and returned. There has been an increased interest in using SODARs to develop the meteorological data bases required as input to dispersion models. SODAR returns can also be analyzed to estimate the mixing height.

System Performance

Monitoring the proper meteorological variables that are representative of atmospheric dispersion conditions at a specific location is crucial in a monitoring program. It is equally important that the performance of the monitoring system be adequate to produce representative data. The accuracy and response characteristics of meteorological monitoring systems are important factors in defining system performance.

System Accuracy

Accuracy is the amount by which a measured variable deviates from a value accepted as true or standard. Accuracy can be thought of in terms of individual component accuracy or overall system accuracy. For example, the overall accuracy of a wind speed measurement system includes the individual component accuracies of the cup or propeller anemometer, electronic circuitry such as a signal conditioner and data recorder.

The accuracies recommended for on-site meteorological monitoring systems producing data to be used in regulatory modeling applications are listed in Table 5-1. These are stated in terms of overall system accuracies, since it is the data from the measurement system which are used in air quality analyses. Recommended **measurement resolutions**, i.e., the smallest increments that can be distinguished, are also provided in Table 5-1. These resolutions are considered necessary to maintain the recommended accuracies.

The accuracy specifications and resolutions provided in Table 5-1 are applicable to the primary measurement system, which is recommended to be a microprocessor-based digital system. For analog systems used as back-up the recommended accuracy limits in Table 5-1 may be increased by 50%. Resolutions for such analog systems should be adequate to maintain the recommended accuracies.

Table 5-1. Recommended system accuracies and resolutions

Meteorological variable	System accuracy	Measurement resolution
Wind speed	± (0.2 m/s + 5% of observed)	0.1 m/s
Wind direction	± 5 degrees	1 degree
Ambient temperature	± 0.5°C	0.1 °C
Vertical temperature difference	± 0.1°C	0.02 °C
Radiation	± 5% of observed or 25 W/m^2*	10 W/m^2
Time	± 5 minutes	

*whichever is greater

Source: U.S. EPA 1987 (Revised February 1993).

Response Characteristics of On-Site Meteorological Sensors

Response characteristics help define how quickly an instrument will respond to changing meteorological variables. Certain response characteristics of meteorological sensors proposed for on-site monitoring programs must be known to ensure that data being collected are appropriate for the intended application.

The following definitions apply for terms commonly associated with instrument response characteristics and the inherent properties of meteorological sensors:

Calm - Any average wind speed below the starting threshold of the wind speed or direction sensor, whichever is greater.

Damping ratio - The motion of a wind vane is a damped oscillation and the ratio in which the amplitude of successive swings decreases is independent of wind speed. The damping ratio is the ratio of actual damping to critical damping which is a measure of a vane's mechanical resistance to movement.

Delay distance - The length of a column of air that passes a wind vane such that the vane will respond to 50% of a sudden angular change in wind direction.

Distance constant - The distance constant of a sensor is the length of fluid flow past the sensor required to cause it to respond to a given change in wind speed. Distance constant is a characteristic of cup and propeller (rotational) anemometers.

Range - This is a general term which usually identifies the limits of operation of a sensor, most often within which the accuracy is specified.

Threshold (starting speed) - The wind speed at which an anemometer or vane first starts to perform within its specifications.

Time constant - The period of time that is required for a sensor to respond to a given change in the parameter the sensor is measuring.

Table 5-2 lists recommended sensor response characteristics for use in regulatory modeling applications.

Table 5-2. Recommended response characteristics for meteorological sensors

Meteorological Variable	Sensor Specification(s)
Wind speed	Starting speed ≤ 0.5 m/s Distance constant ≤ 5 m
Wind direction	Starting speed ≤ 0.5 m/s Damping ratio 0.4 to 0.7 Delay distance ≤ 5 m
Temperature	Time constant ≤ 1 min
Temperature difference	Time constant ≤ 1 min
Radiation	Time constant ~ 5 second Operating temperature range -20^{o}C to +40^{o}C at specified accuracy

Source: U.S. EPA June 1987, (Revised 1993).

Quality Assurance and Quality Control

Quality assurance (QA) applied to meteorological monitoring consists of both "the system of activities to provide a quality product" (traditional quality control) and "the system of activities to provide assurance that the quality control system is performing adequately" (traditional quality assurance) (Finkelstein, P.L. et al. 1983). The first of these quality control (QC) functions consists of those activities performed by equipment operators directly on the instruments, e.g., preventive maintenance, calibrations, etc. The purpose of the second set of activities is to manage the quality of the data and administer corrective actions as necessary to ensure that the data quality requirements are met. Formal plans for quality assurance must be presented in a document called the QA Plan. This document lists all necessary quality-related procedures and the frequency with which they should be performed. It is imperative that a QA Plan be developed and followed to ensure that representative data of good quality are obtained. Specific information to be included in a QA Plan is described below.

Project personnel responsibilities: responsibilities of personnel performing tasks that affect data quality.

Data reporting procedures: brief description of how data are produced delineating functions performed during each step of the data processing sequence.

Data validation procedures: detailed listing of criteria to be applied to data for testing their validity, how the validation process is to be carried out, and the treatment of data found to be questionable or invalid.

Audit procedures: detailed description of what audits are to be performed, how often they are to be performed, and an audit procedure (referencing document procedures whenever possible). Also, description of internal and external systems audits including site inspections by supervisory personnel or others.

Calibration procedures: detailed description of calibration techniques and frequency for calibrating each of the sensors or instruments being used. Both full calibrations and zero and span checks should be defined.

Preventive maintenance schedule: detailed listing of specific preventive maintenance functions and the frequency at which they should be performed. Includes not only routine equipment inspection and wearable parts replacement but also functional tests to be performed on equipment.

Quality reports: the schedule and content of reports submitted to management describing status of quality assurance program. The quality assurance program includes the implementation of all functions specified in the QA Plan. This implementation involves personnel at all levels of the organization. Technicians who operate equipment must perform preventive maintenance and QC checks on the measurements systems for which they are responsible. They must perform calibrations and, when required, participate in internal audits of stations run by other technicians. Their immediate supervisors should check to see that all specified QA tasks are performed, and should review logs and control charts to ensure that potential problems are corrected before significant data loss occurs.

Review Exercise

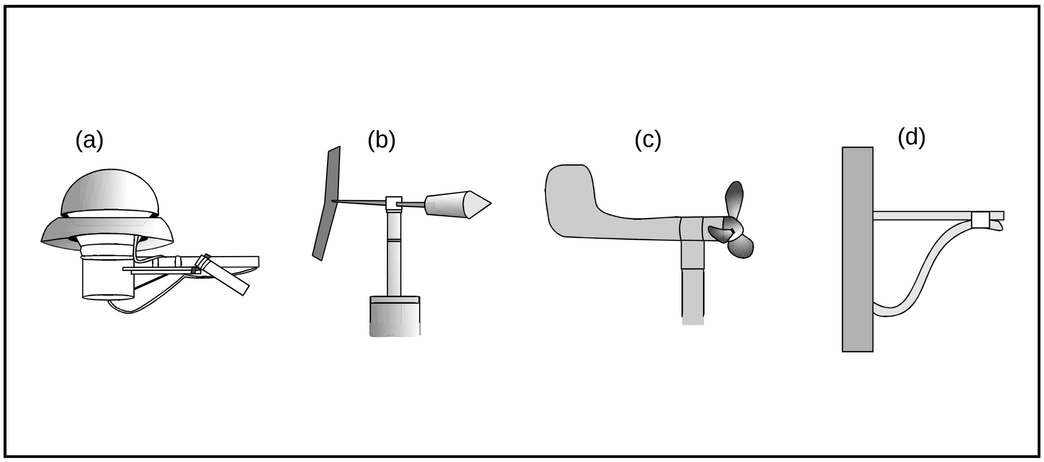
1. List four key meteorological variables that are important in air pollution studies.

   ____
   ____
   ____
   ____

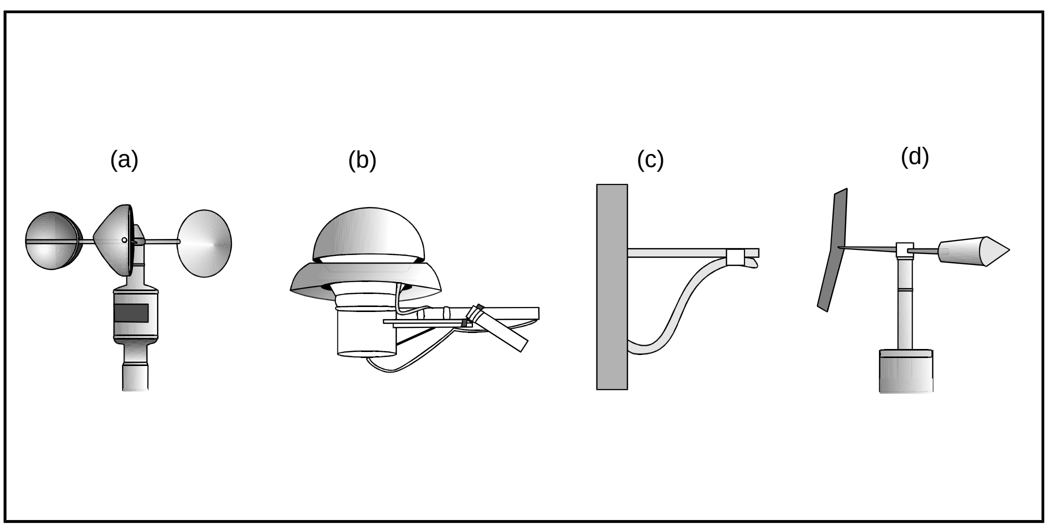
For questions 2 through 4, match the appropriate meteorological instruments with the atmospheric variable that it measures.

2. Anemometer   a. Wind direction
3. Wind vane   b. Wind speed
4. Thermometer   c. Temperature

5. From the following meteorological instruments, choose an anemometer.



6. From the following meteorological instruments, choose a wind vane.



7. A transducer is required in an anemometer system to:
   a. Change rotational motion into an electrical signal
   b. Record wind information
   c. Record the time the instrument is operating
   d. None of the above

8. True or False? A temperature sensor with an aspirated shield that uses electrical resistance to measure temperature is the most common type of sensor used in air pollution studies.
   a. True
   b. False

9. How far away should wind instruments be located from an obstruction?
   a. One times the height of the obstruction.
   b. Two times the height of the obstruction.
   c. Ten times the height of the obstruction.

10. A temperature sensor:
    a. Must always be located next to the wind sensors
    b. Should never be mounted near heat sources
    c. Is not necessary for air pollution studies
    d. Measures total solar radiation through temperature readings

11. What is the typical height for a single level temperature sensor?
    a. 1 m
    b. 2 m
    c. 10 m

12. An instrument that measures direct and diffuse solar radiation is called a(n) ____________________.

13. A sensor that measures the difference between solar and terrestrial radiation through a horizontal surface is called a(n) ____________________ ____________________.

14. True or False? Response characteristics help define how quickly an instrument will respond to changing meteorological variables.
    a. True
    b. False

15. Mixing heights are typically determined from radiosondes launched by the National Weather Service at a frequency of:
    a. Twice a day
    b. Four times a day
    c. Every hour

16. True or False? Quality Assurance Plans are necessary to ensure that representative data of good quality are obtained.
    a. True
    b. False

17. True or False? Sensor height is critical when siting pyranometers.
    a. True
    b. False

Review Exercise Answers

1. **Wind speed and direction**
   Ambient temperature and vertical temperature difference
   Solar radiation
   Mixing height

   Four key meteorological variables that are key in air pollution studies include (1) wind speed and direction, (2) ambient temperature and vertical temperature difference, (c) solar radiation, and (d) mixing height.

2. **b. Wind speed**

   Anemometers measure wind speed.

3. **a. Wind direction**

   Wind vanes measure wind direction.

4. **c. Temperature**

   Thermometers measure temperature.

5. **c.**

   An anemometer is shown in option “c.”

6. **d.**

   A wind vane is shown in option “d.”

7. **a. Change rotational motion into an electrical signal**

   A transducer is required in an anemometer system to change the rotational motion into an electrical signal.

8. **a. True**

   A temperature sensor with an aspirated shield that uses electrical resistance to measure temperature is the most common type of sensor used in air pollution studies.

9. **c. Ten times the height of the obstruction**

   The distance that wind instruments should be located from an obstruction is equal to ten times the height of the obstruction.

10. **b. Should never by mounted near heat sources**

    A temperature sensor should never by mounted near heat sources.

11. **b. 2 m**

    The typical height for a single level temperature sensor is 2 m.

12. **Pyranometer**

    An instrument that measures direct and diffuse solar radiation is called a pyranometer.

13. **Net radiometer**

    A sensor that measures the difference between solar and terrestrial radiation through a horizontal surface is called a net radiometer.

14. **a. True**

    Response characteristics help define how quickly an instrument will respond to changing meteorological variables.

15. **a. Twice a day**

    Mixing heights are typically determined from radiosondes launched by the National Weather Service at a frequency of twice a day.

16. **a. True**

    Quality Assurance Plans are necessary to ensure that representative data of good quality are obtained.

17. **b. False**

    Sensor height is not critical when siting pyranometers.