How to Monitor Meteorology in Support of Pesticide Application

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Abstract

The correct measurement of the weather is critical to understanding the movement of pesticide spray droplets in the atmosphere. However, due to the commitment of resources required to monitor the weather, local measurements are often not taken. Further, even when meteorological monitoring is attempted it is often done incorrectly. Compilation of 'bad' data leads to misinterpretation of drift events and a reluctance by applicators to rely on available data resources. This paper focuses on the correct way to collect data, what data to collect and how to discern good data from bad data. This paper also discusses techniques that have been used successfully in the past as teaching tools.

What to Measure and How to Measure It

Wind Speed and Direction

Routine measurement of wind speed is typically accomplished with cup anemometers (Figure 1). These instruments work by measuring how many times the cup set turns. The cups are manufacturer calibrated so that each turn represents some length of wind passage. Say that a cup set turns once every time 1m of air passes it, if it turns once in a second, then the wind is moving at 1 ms^{-1}.

The most common scheme for recording turning in modern cup anemometers is called a photochopper. This utilizes a slotted disk mounted on a post in the horizontal plane. The cups are mounted on the top of the post. As the cups turn, the disk turns through a narrow vertical beam of light. The light impinges on a photo diode that generates a current when the diode sensor is illuminated. As the slots on the disk pass under the light, a square wave electrical signal is generated. The slot allows the light to pass and illuminates the diode, the light beam is interrupted between the slots and the diode is dark and not generating a signal. Using the example above, a disk with eight slots (an eight slot photochopper) will show a square wave cycle after .125 m of fluid passes. If 1m of air passes in a second (1 ms^{-1} wind) then the resolution of the photochopper is .125 ms^{-1} (1m of air passage/ 8 slots passing through the beam of light in a second).

Figure 1. Cup and vane set R.M. Young Model 03002 Wind Sentry (Courtesy John Campbell, R.M. Young Company, Traverse City, MI).

Fortunately, most modern data loggers make the internal working of the anemometer fairly transparent to the user as discussed below. Two important things to remember about cup anemometers:

1) All cup anemometers overcome a certain amount of friction to turn. The reason that photochoppers have become the design of choice is that a physical contact is not required to monitor turning. Older designs actually close a physical contact as they turn, much like a child touching a ring at a fixed point as the child rides around a merry-go-round. Physically closing a contact exerts drag on the cup set and lessens its response. However, even a cup anemometer utilizing photochopper technology

has to overcome a certain amount of drag as the post sits on bearings. The implication of this is that cup anemometers have a finite start-up speed that is relatively high, can be a significant error in near surface measurements and makes them almost useless in plant canopies. A typical cup anemometer might have a start up speed of .3 ms^{-1} (.67mph). Some data loggers will allow a software switch so that zero (stalled cup set) is logged as the stall speed. A more reasonable approach that might better preserve the real average is to change all zeroes to the intermediate speed between zero and the stall speed.

2) Cup anemometers only measure horizontal wind speed. If there is a significant vertical component to the wind, the cup anemometer misses it. The vertical component is important in plant canopies and near obstructions. Also, if there is interest in how much material is moving upward, it is difficult to infer from a cup anemometer.

The most used scheme to sample wind direction is a vane which turns a potentiometer. A potentiometer is a continuously varying resistance component so that resistance changes as the vane is moved around in a circle. The potentiometer is simply calibrated to indicate a specific direction at a given voltage output related by Ohm's Law to the varying resistance. The most important thing to remember about this measurement is that direction is a circular function so that directions of 5° and 355° do not average to 180°. The solution to the problem of averaging circular functions is discussed in detail in Mardia, 1972. Most modern data logger packages will handle the circular average as part of the preliminary data processing. Also, keep in mind that the wind direction signal is relative to the position of the potentiometer. Most vanes have an orientation scheme. For instance, a set screw is positioned connecting the vane post to the mounting arm so that the vane wing is fixed parallel to the mounting arm and toward the tower. The arm is then positioned with a compass to point directly north. The potentiometer is factory calibrated so that voltage output at this position indicates north. The set screw is removed and then the voltage varies as the potentiometer is turned and yields the other compass directions as the potentiometer resistance changes.

Another commonly used instrument is the propeller anemometer. These are often very light weight propellers that turn a small brush generator. The voltage off the generator is calibrated to the speed the propeller is turning and thus the wind speed. A commonly seen scheme of twenty years ago was to array three propellers to get three dimensional wind speed. These three dimensional propeller anemometers are still used but have largely been replaced by other three dimensional anemometers. An advantage of the brush generators is that they don't require input power as they generate a signal. One configuration using a propeller that is still common is the vane anemometer. In this configuration, the propeller is on a vane so that the propeller orients into the mean wind and the direction is recorded from the vane set. There are many other anemometers, some of which are discussed below.

Advanced Anemometry

Two instrument systems that are advanced beyond the needs of most drift monitoring but have made substantial in-roads are discussed here. These are sonic anemometers and SoDARS.

Sonic anemometers use a high frequency transmitted acoustic signal that is sent across a short path (typically 15-20cm) to a receiver. The change between the transmitted and received acoustic frequency is due to a Doppler shift caused by the motion of the intervening fluid. This can be interpreted as the wind speed in the component direction in which the transmitter receiver pair is aligned. By arraying three such receivers, three dimensional wind speed can be determined. The primary advantage of the sonic anemometer is that the threshold velocity is very low, so that they are suitable for very low velocity environments. Of most interest to us are in-canopy and near canopy environments where cups are often below stall speed. In these settings, significant interpretation errors can occur. For instance, a wind averaging .25 ms^{-1} will move a neutrally buoyant particle 900m in an hour yet this velocity is below stall speed for most cup sets. Experience tells us that in dense canopies, typical cup sets are usually stalled. Also, a three-dimensional sonic anemometer (three sensors arrayed in different orientations) yields three dimensional flow. These are used by the scientific community to study flux of quantities away from the surface. Sonic anemometers are still generally research instruments, though they are becoming easier to use and the price of some models is coming down.

SoDAR technology is also making a contribution to the understanding of pesticide drift. This instrument allows wind velocity and direction to be determined at intervals through the atmospheric surface layer. An example profile is shown in Fig. 2 . This technology directs an acoustic pulse upward from the surface, uses the timing of echoes to determine the height at which the individual echo originated and uses the shift in frequency of the echo to calculate wind speed and direction at that height. Using this instrument, it is possible to know the speed and direction of the wind through the depth of the volume in which spray material is moving. Using an analysis of the variance of the readings, stability can be estmated. This instrument is also primarily a research instrument but is now used as a continuous meteorological monitor in some high value air pollution applications.

Relative Humidity

Relative Humidity can be a very important variable when considering drift as it controls evaporation of volatile droplets and thus their size. Relative Humidity is defined as:

$$RH = e/e_s \times 100$$

where e is vapor pressure (mb) and e_s is the saturation vapor pressure (mb). The thing to note about Relative Humidity is that:

$$\log_{10} e_s = 0.02604T + 0.82488$$

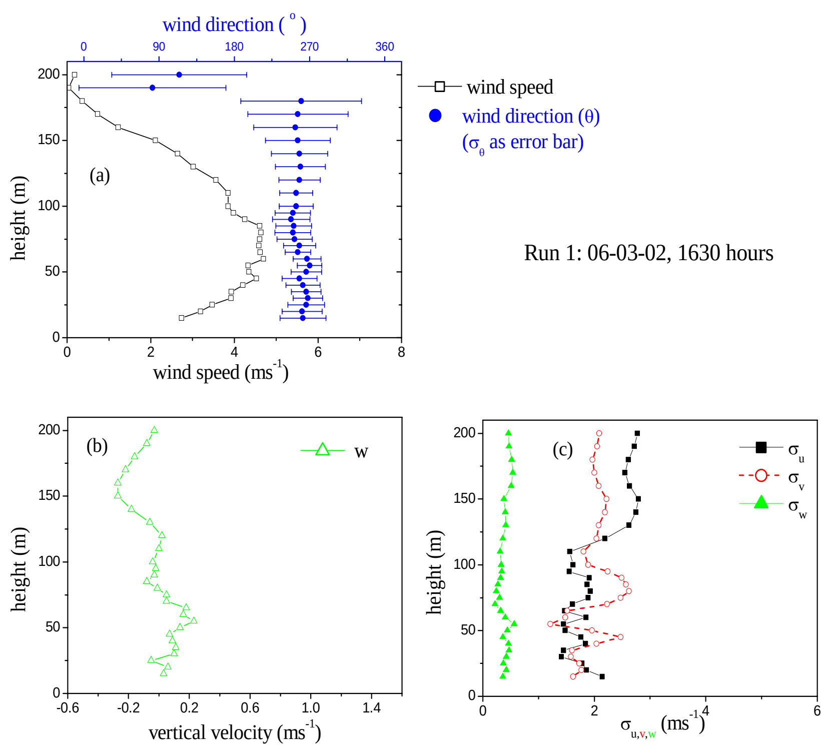

Fig.2 Profiles of observed (a) wind speed and wind direction, (b) vertical velocity and (c) standard deviations of u, v and w components of wind velocity during a 30 minute run in June, 2002 near Claxton, GA. (Courtesy of LeClerc and Karipot, U. of Georgia).

where T is air temperature (°C, note that a different relationship is used below freezing). Thus indicating that RH is a strong function of temperature. The above is taken from Rosenberg (1974) and is accompanied by the statement 'Relative humidity is seldom used in scientific work.'. Despite the strong dependence on temperature and the chagrin of some micro-meteorologists, RH is the measure of humidity almost universally reported in our field.

The transducers most often used in modern humidity sensors are capacitance elements. The capacitance changes with humidity and this effect is calibrated to yield absolute humidity. These are typically collocated with temperature sensors so that RH is calculated directly from processing algorithms in the data logger. (Figure 3.) RH is often the lowest accuracy measurement among those discussed here with accuracies of 5% considered reasonable. As with all these instruments, there are more sophisticated measurement techniques for humidity such as cooled elements but these methods are beyond the technical scope of this paper and typically too expensive for routine measurements.

Many people experienced in meteorological monitoring may be accustomed to other basic techniques that preceded capacitance instruments. An early technique was a horse-hair hygrometer. This mechanical device would deflect a pen on a strip chart as the humidity changed the tension exerted by a strand of hair. Another scheme that is widely used is a wet bulb-dry bulb comparison. Since evaporation is a function of humidity and temperature, the cooling due to evaporation from a surface can be used to indicate humidity. In a sling psychrometer, two thermometers are used, one is left dry and the other is wetted in a cloth sleeve. The pair is slung (spun through the air) and the evaporating water causes the temperature of the wet thermometer to drop. The 'wet bulb depression' is then interpreted as the Relative Humidity, typically using a printed chart. This technique is most often used as a single point measurement, done by hand in such applications as fire danger rating in remote locations.

Figure 3. Shielded RH and Temperature Sensor R.M. Young Company (Courtesy John Campbell, R.M. Young Company, Traverse City, MI).

Temperature and Atmospheric Stability

Pesticide drift only has a minor direct dependence on temperature but temperature plays a major role through its influence on Relative Humidity as discussed above. However, the vertical temperature gradient with height defines atmospheric stability so accurate temperature measurement is critical to understanding dispersion of fine droplets in the atmosphere. Most electronic temperature measurements are made with thermistors. These are individually calibrated transducers that use a change of resistance to indicate temperature. Note that shielding of temperature sensors is necessary to measure air temperature, otherwise the sensor may be heated radiatively, and the sensor will indicate the temperature of the radiatively heated sensor as opposed to air temperature. In situations where the shield is in direct sunshine, especially at lower latitudes, aspiration of the sensor should also be considered as heat may build up in the shield and influence the measured air temperature. Shielding also prevents radiative cooling of the sensor during the night.

Many other thermometers have been designed. The most important to electronic monitoring is the thermocouple. Two junctions of dissimilar metals generate a voltage that is dependent on the temperature difference between the two junctions. This property can be used to create a thermometer. The junction exposed to the environment must have an opposite junction at a known temperature to complete the circuit and be used as a reference junction. All metals will exhibit this effect to some degree, but certain junctions generate larger voltages, and are reasonably linear with temperature in certain temperature ranges. In environmental monitoring, copper-constantan is often the thermocouple junction of choice. Thermocouples have the advantage of generating a signal, so they don't require external power. However, they may have to be associated with amplifiers or the signal amplified by creating multiple junctions in series. The latter creates what is known as a thermopile.

Atmospheric stability is defined by the vertical gradient of temperature in the atmosphere. The challenge to measuring stability on relatively short towers is that an important gradient may be < .1 °C/m . This means that we are looking for differences on the order of .1 °C between thermometers (typically thermistors) that have accuracies typically around +/- .3 °C. When the accuracies of the two thermometers together is considered, the accuracy of the difference is +/- .6 °C. The accuracy constraints of the temperature measurement obscure the gradient. This is known as the ΔT problem.

One approach to this problem is to calibrate the thermometers in the profile so that any systematic error is understood. This is called matching thermometers (see Whiteman (2000) for an example of thermometer calibration for use in a profile). This can reduce the uncertainty in ΔT. For higher value work, there are systems specifically designed to measure ΔT. In this scheme the absolute temperature is not measured but the thermocouple junctions are stationed at two heights and the generated voltage yields ΔT. Other approaches to measuring stability are not discussed in detail here but include the Pasquill-Gifford scheme (Pasquill, 1974) that uses discrete stability categories based on wind speed, cloud cover and time of day; and the σ_ε scheme which utilizes the variation in wind direction (Anonymous, 1987 (EPA Guidance Document)).

Other Instruments

Other meteorological instruments that might be used in drift modeling include rain gauges and solar radiometers. Though only discussed briefly here, rain gauges can be quite useful in evaluating success or failure of an application. Especially in remote sites it is possible that rainfall events that could influence efficacy would go unnoticed. Most modern, electronic rain gauges are of the tipping bucket type. A switch is closed as each increment of rain is collected and the data logger counts closures. An older design is the weighing rain gauge where a scale deflects a pen (this can be configured to yield an analog signal) as the weight changes due to the weight of water in the gauge. Note that these schemes both have problems with frozen precipitation and the instruments need to be handled differently in freezing weather.

The other group of instruments that deserve mention in this limited discussion are solar and net radiometers. Both net radiometers which yield the difference between incoming and outgoing radiation (an indication of total available energy) and direct beam solar radiometers that yield incoming shortwave radiation can be useful. Classic designs utilized thermocouples in various configurations to monitor the surface temperature of a surface exposed to radiation but protected by glass or a plastic bubble from convective heat transfer. More recent technologies use solid state components and can accurately discriminate wavelengths. The trace of solar or net radiation is a useful indicator of the state of the local atmosphere and, beyond measuring the intensity of solar radiation or the net available energy, will indicate cloud passage and changes in atmospheric opacity that will effect surface heating and stability. Note that many types of radiometers are made and it requires some research to match applications. Experience has shown a net radiometer to be particularly useful though it should be noted that the downward looking face of a net radiometer will only see a small patch of ground, if that patch is not representative of the measurement area then the net radiation measurement can be misleading.

Data Loggers the Nature of Instrument Signals and Preconfigured Stations

The data logger itself is a critical component in the data collection system. The logger must be powered. Consider a solar powered logger. If batteries are to be used, understand change out intervals and the recharging schedule. If AC voltage is to be used, a converter to DC may be needed and extension cords should be checked for voltage drop at the logger end. It is necessary to add up the number of channels that will be required and match the input channel capacity of the logger. The logger has a fixed memory capacity. It is possible, since the data is typically stored in very basic formats, to calculate the space your data will require. However, experience has taught that the best approach is to do a trial run with the desired instrument set up, and carefully note how much logger storage capacity is used in a given period of time.

A common source of error in meteorological data collection is incorrect time marking. It is the author's experience that this is the most common source of confusion associated with data logging. The logger time is often input from a PC. If the PC is wrong or the PC time is on a different time zone, this can show up in the data logger. Often bleeder batteries are used to maintain time in systems during storage and these often malfunction. Since much data is processed well after it is collected, incorrect time marks can be a major problem. Another source of confusion is incorrect channel input. In many cases, in a basic configuration you may need multiple variables measured at multiple heights. This can lead to many signal cables that need to be input to the data logger. Some of the signals will be completely incompatible with the signal processing software and will show up immediately when the data is reviewed. Other crossed channels can lead to very subtle errors if calibrations are similar or channels of the same instrument at different heights are crossed. This problem can often be approached with color coding or other labeling.

In the not too distant past, a detailed knowledge of the transducers being used to measure meteorology was needed to configure a data logger. Input channels are either analog or digital. In the case of an analog signal such as a brush generator from a propeller anemometer, processing software multiplies the voltage level on that channel by a multiplier to convert voltage into ms^{-1} . The signal generated by a photochopper type cup anemometer is considered a digital signal (the signal is either high or low) and the number of cycles in a given period is counted. The calibration is used to convert the count into ms^{-1} . The more advanced systems such as the SoDAR and sonic anemometers have their own processors and logging schemes.

Currently, a good option for routine monitoring is to buy a pre-configured meteorological station. These stations come with an array of instruments, data loggers and mounting options (Figure 4.). Many types of preconfigured stations have become available in recent years and the price has come down. The data loggers are configured so all the inputs are keyed and labeled and the channel information is used by the system to create data reports. It is very difficult to cross channels in this scheme and almost no software configuration is necessary. If this approach is chosen as a low cost, turn key option the user is advised to carefully investigate the component instruments and make sure the capabilities meet the needs at hand and that they are physically robust enough to do the job.

A new generation of instrumentation that is impacting aerial application is the use of balloon based meteorology on a site by site basis as well as airborne instrument packages that have the capability of recording detailed meteorology at the point of release.

Figure 4. A Preconfigured Meteorological Station, Onset Computer Corporation. (Courtesy Paul Gannett, Onset Computer Corporation, Bourne,MA).

Site Considerations

It is critical to site the meteorological station at a representative location. For instance, if you are spraying an agricultural field, don't site the meteorological station in a parking lot. For general climate monitoring, the guidance is to site the monitoring station over short grass. However, this guidance can be misleading. As an example, if application is going on over dry sagebrush country, it is not acceptable to put the meteorological station on a watered lawn.

Site and Sampling Considerations

Fetch

It is important not to position the meteorological station near large obstructions since obstructions deflect and alter the wind field. In the past, it was suggested that the tower be ten times the height of the obstruction away from the obstruction. This can be quite limiting if , for example there is a 25m tall tree line nearby. In monitoring pesticide application, the overriding factor is to monitor in a location that is representative of the area being sprayed. This may mean putting up meteorological monitoring in high brush or in a forest. Keep in mind that this type of monitoring is subject to local influences (one big tree or shrub nearby) and may require more sophisticated instrumentation as in and near canopy environments are very low velocity.

Surface Moisture

One of the most common mistakes that is made regarding meteorological monitoring in agricultural settings regards the importance of surface wetness and especially the role of irrigation. As discussed in the previous talk (Thistle, 2004), incident energy evaporates available water instead of heating the environment. This energy is stored in the phase change of the water. Therefore, irrigation can dramatically reduce surface temperatures and alter atmospheric stability. Thunderstorms or brief showers have the same effect. If irrigated land is being sprayed, the met station needs to be at a location with similar surface moisture considerations as the spray block.

Leveling

Instrument leveling is critical to many meteorological measurements. Cup anemometers need to be level so that they are sensing the horizontal wind. If they are out of level, the cups underestimate part of the horizontal component and incorporate part of the vertical. Typically, this will result in an underestimation of the wind speed. Radiometers need to be level or they will underestimate incident radiation, rain gauges need to be level or they will under catch.

How many points?

The number of meteorological stations deployed depends on the uniformity of the spray area and the available resources. It is better to monitor at one point correctly than to monitor multiple points and have data that is not useful. As part of project planning, it is important to decide what is to be done with the generated data. Will it be averaged in space, spatially correlated or will different data sets be used in different parts of the application block? All of these have implications for processing, organization and planning. Does the spray block change from irrigated land to range? Different land use types may require additional monitoring sites. Keep in mind that the area where drift is a concern may extend well beyond the application block. In non-uniform terrain, such as that encountered in many large forestry operations it is difficult to extrapolate wind conditions from one drainage to another and local wind fields will often reflect the orientation of the local terrain. In this case, it may be necessary to instrument each drainage.

Sampling Duration

The duration and frequency of the sampling need to be related to the duration of the application and to the purpose of data collection. If the spray operation will last for 20 minutes, and the wind is blowing at 4 ms^{-1} , in a minute the trailing edge of the material has moved 240 m downwind. If you are worried about drift to 10km, then, thinking linearly, whatever is left in the atmosphere will clear 10km downwind in about 42 minutes. Allowing for meander etc., the monitoring may want to continue for 90 minutes after the application has ended to be conservative. It will typically be desirable to have data available to evaluate application conditions before the applications starts, so you may plan on a 5 hour data collection window. This gives three hours of pre application information to make a go no-go decision, monitoring during the application and sufficient time for primary drift to areas of interest to occur. In some data logging systems, it may be just as easy to begin sampling the day prior and parse out the data of interest in post analysis. It is important to collect data and review it as soon as possible after application. Electronic data is always at risk from physical damage in the field. If data logging is left on continuously at some point files are overwritten and data is lost. If there is a problem with data quality such as time marking errors, it is much easier to correct when the application event is fresh in everyone's mind.

Sampling Frequency

Frequency of sampling in routine monitoring also needs to be related to the event being monitored. The more frequently data are collected, the more data that has to be processed subsequently and the more quickly the data logger resources are exhausted. However, it needs to be remembered that high frequency data cannot be created from low frequency. If you only archive 15 minute data and a short gust moves material in a direction away from the mean direction, you will not see this event in the 15 minute averaged data. For most pesticide application monitoring, it is recommended that 1 to 5 minute meteorological averaged data be saved. This can subsequently be averaged into 15 minute averages if desired. Also, try and synchronize a watch with the data logger so that if a short term event of interest (say a brief shower) does occur, the time can be noted and you will be able to find it in the met records. If one minute averages are saved for five hours, as above, this results in 300 meteorological records which is a manageable quantity.

Post Collection

This section presents some brief notes on meteorological data collection, review and processing. It is critical in a field program to keep a notebook handy and make as many notes as possible. As mentioned above, try to synchronize notes with the data logging equipment. Note when the applicator passes a certain point. In routine agricultural ground sprayer applications, the applicator should keep a log noting accurately the time certain things are done. If positional logging is automated, check to see if external data loggers and the positional system are synchronized. (Note that systems are coming on line that allow the applicator to directly monitor weather conditions and compensate on the fly.) This then allows direct correspondence to the meteorological conditions at that time. If the operation is large enough to require an operational manager, this manager should include weather observations as part of the project log.

QA/QC

An effort should always be made to review and QA/QC electronic records. Certain things can be easily checked. Vane alignment should be double checked in the field but wind direction presents other problems. The engineering and meteorological conventions for direction are opposite. Engineers use the direction a vector is pointing or headed. Meteorologists use the direction the vector is from. This results in a 180º discrepancy. In most meteorological data loggers, the meteorological convention is used but this always needs to be checked.

Meteorological readings are rarely stationary, even one-minute averages. If wind direction is not varying, the vane is suspect. Vanes are known to freeze in position in cold weather. Birds are often a problem with cup and vane sets and can obstruct the instruments with nests thus preventing them from turning. Electrical problems can be subtle, loose wires may only cause a circuit to open when the wind blows, frayed wires may be functional until a fog or morning dew causes a short circuit. Often , stranded signal wire will have a loose strand touching another contact in the data logger where the signal wires are tied into data logger channels, this can manifest itself in ways that are difficult to troubleshoot. Rodents often chew signal wire causing shorts and open circuits. Keep in mind that while some of these errors cause a signal to obviously fail and data loss is apparent, other problems cause the magnitude or variance of the signal to change. The only way to detect these problems is to become familiar with the data, look through it carefully and make sure it is consistent with other readings and manually logged observations.

One of the most common problems that is encountered is misinterpretation of units. Check data for incorrect conversions, mislabeled units, double conversions (where units are converted once and then inadvertently converted again). This remains a common source of mistakes even in sophisticated engineering development programs.

Instrument maintenance is important. Bearings go bad in cup and vane sets and can change calibration. Radiometer windows become opaque and need to be replaced. Thermistor calibrations can vary and should be checked against known standards regularly. It is a good idea to check and verify instrument operation before the beginning of each field season and perform routine maintenance if necessary.

Teaching

Experience indicates that the best technique for teaching meteorological monitoring to technicians and applicators is hands-on. If possible, obtain a complete meteorological tower, erect it and mount instruments. While this process is on-going, discuss such concepts as site implications and make the students level the instruments. For instance, the process of wiring signal leads illustrates the possibility of crossing channels. As each instrument goes on the tower, give a brief description of the instrument, the transducer, and exposure and orientation considerations for the individual instruments. If possible, the class should also then collect data and evaluate it.

Conclusions

It is very difficult to give an overview of meteorological instrumentation in such a brief space. The approach has been to focus on the basic instrumentation that is used most widely and the meteorological parameters that have been identified as important to drift. Generic considerations and common problems encountered in conducting this type of meteorological monitoring are also discussed.

As time goes on, more options for meteorological monitoring are becoming available including turnkey systems. More advanced meteorological monitoring is becoming more widely used in these applications and though discussed only briefly here, likely represents the wave of the future. It is hoped that the information presented here will allow applicators and managers to correctly perform the meteorological monitoring necessary to mitigate pesticide drift.

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