Atmospheric data in *WindTrax*

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This is the second in a series of articles intended to introduce WindTrax to new users. In this article, we will examine the measurements of surface layer properties required by the program, and the ways in which they are added to a simulation.

In order to calculate unknown source emission rates and/or concentrations, WindTrax requires information about the condition of the atmospheric surface layer. In addition to one or more measured concentrations, it must know the average wind speed and direction, the roughness of the surface, and the stability of the atmosphere near the ground when the concentrations were observed. If concentration is measured in units of ppm or ppb, air temperature and pressure are also needed.

The particle models used in WindTrax are time-independent, so the data provided must be values averaged over a period of time, typically fifteen to thirty minutes. This averaging eliminates variability due to turbulence seen in the atmosphere on short time scales. Instantaneous measurements, or those made over too brief a period to average out short-term fluctuations, will not be representative of the atmosphere. Conversely, if the averaging time is too long, you will miss some of the more gradual diurnal variation typical of the surface layer that might be of interest.

In general, measured data is provided to WindTrax by adding sensor icons to the map. If you have made observations of mean wind speed and direction in your field experiment, you will place an anemometer on the map, then set its speed and direction properties, either directly or by connecting them to a column of an input file. Similarly, you will place a thermometer icon on the map to add temperature measurements, a pressure sensor icon to report measured pressures, and one or more concentration sensors to provide WindTrax with your concentration observations. A sonic anemometer will provide all necessary data except air pressure and tracer concentrations.

Every sensor in WindTrax can either provide data to the models as described above or request that their measurements be calculated from the models. Sensors that provide measured data are said to be in *given mode*, while those that request data are in *find mode* or *unknown mode*. If a sensor is in unknown mode, a "?" mark will appear on the map next to its symbol. There are no restrictions on the addition of find-mode sensors to the map, other than those imposed by the physical memory and processor available on your computer. There are, however, constraints on the number and type of given-mode sensors that can be placed. This article will discuss these constraints and the methods available to specify atmospheric measurements in WindTrax simulations.

Wind model parameters

The surface layer wind model used in WindTrax requires that at least four parameters are known: the surface roughness length z_o; the friction velocity u_*; the *Monin-Obukhov length*, L; and the mean horizontal wind direction, θ. The wind statistics σ_u, σ_v, and/or σ_w can be added if they are available, but are not absolutely required; the program will otherwise use well-known empirical relationships to estimate their value.

Wind direction

WindTrax measures wind direction angle θ using the standard definition, for which the reported angle is that between North and the direction the wind is coming from. For example, if the wind is blowing from the North towards the South, the direction angle is 0°; if it is blowing from the East towards the West, θ is 90°; and if it is blowing from the West towards the East, θ is 270°. Any reported values greater than 360° or less than 0° will be converted by WindTrax to an angle between 0° and 360° (using $\theta = \theta_{input}$ mod *360°*).

Atmospheric stability

Stability is the tendency of the surface layer to either overturn or resist upward motion. It is determined by local meteorological conditions such as wind speed, cloud cover, and time of day. On calm, clear nights, the ground surface cools radiatively more quickly than the atmosphere and cools the air just above it. This cold, denser air pools near the surface and resist upward motion, a condition called *stable stratification*. Conversely, sunny afternoons are commonly *unstable* because the Sun heats the ground, which then warms the air in contact with it and encourages overturn or convection. Under cloudy skies and/or strong wind, the surface layer tends to be *neutrally stratified*, meaning that surface air neither pools near the ground nor undergoes strong convection.

The standard micrometeorological measure of stability is called the Monin-Obukhov length, L. It is generally calculated from measurements of wind speed, surface heat flux, and temperature. Although WindTrax uses L internally, it allows you to specify stability in any of eight different ways. If you plan to provide stability information directly to the model, you can report it in one of the following five ways:

- You can use L itself, assuming you have calculated it beforehand from your data;
- You can specify Pasquill-Gifford classes A through G, where A is the most unstable, D is neutral, and G is the most stable;
- You can report the stability in general terms: very unstable (VU), moderately unstable (MU), slightly unstable (SU), neutral (N), slightly stable (SS), moderately stable (MS), and very stable (VS);
- You can provide the gradient Richardson number Ri_g, if you have calculated it;
- You can select from a set of general weather conditions, which WindTrax will use in conjunction with the measured wind speed to estimate stability.

Of course, some of these options will be less accurate than others, with directly specified *L* being the most accurate and the estimation based on local weather conditions the least.

If you intend to enter stability data directly, you can access it through the Surface Layer Model object, whose icon is located in the upper left corner of the map:

Before running a simulation, you will have to set the stability mode of the simulation to one of the five above options by double-clicking on the above icon and selecting the Parameters tab, followed by the Stability tab. If you are using data files, you will attach the appropriate column of your file to the surface layer model's Stability property. You must ensure that the data type matches the mode set for the surface layer model. If alphanumeric data (A, B, C, D, E, F, G, or VU, MU, SU, N, SS, MS, VS) is attached to the stability property but its mode is not compatible, a run-time error will be generated.

The other methods of providing stability information are based on direct entry of your field measurements. If you have used a sonic anemometer, it can provide all of the required model parameters including *L*. Alternatively, if you have measured profiles of temperature and/or wind speed, WindTrax can use the data to calculate *L* as well as u_* (and possibly z_o, if enough speed sensors were used.)

Friction velocity

Friction velocity is a measure of the vertical transport of horizontal momentum near the surface, defined most simply in wind-following coordinates as

$$u_* = \sqrt{-<u'w'>}$$

where $<u'w'>$ is the covariance between the horizontal component of the wind *u* and vertical component *w*. It is associated with wind speed: when the wind is calm near the surface, it is because there is little downward transport of momentum from higher in the atmosphere, where the wind is stronger, so u_* is small. When it is windy near the surface, a lot of horizontal momentum is being carried downward from aloft and u_* is large.

Friction velocity cannot be measured directly, but it can be calculated either from sonic anemometer data or a profile of wind speeds and temperatures; or inferred from standard empirical functions relating it to the wind speed, stability, and surface roughness. Earlier versions of WindTrax used only the latter method to calculate u_*, requiring that you enter a single measured wind speed along with z_o and *L*. The new versions of WindTrax also allow you to enter it directly, if you have already calculated it; or to add your profile or sonic anemometer measurements directly to the map, in which case WindTrax will calculate it for you.

Surface roughness

Surface roughness is expressed in terms of a length, z_o, and is related to (but significantly less than) the height of the plants, soil, or other elements covering the ground. A general rule of thumb is that z_o is about one tenth the heights of the roughness elements covering the surface. This is only a rough approximation; for example, if the surface is covered by plants with a dense canopy, it might appear to be less rough than if the ground cover is sparse.

The surface roughness length is formally defined as the height at which the wind speed in the logarithmic region near the surface reaches zero:

$$u = \frac{u_*}{k_v}\left[\ln\left(\frac{z}{z_o}\right) - \psi\left(\frac{z}{L}\right) + \psi\left(\frac{z_o}{L}\right) \right]$$

where $K_v = 0.4$ is a universal constant. Historically, z_o was calculated by fitting this equation to a profile of measured wind speeds (and generally temperatures as well, using a similar function for temperature). More recently, it is common to derive z_o from sonic anemometer measurements. If neither data is available to you, WindTrax allows you to select from a set of common plant covers such as crops, soil, and snow, and it will use published values of surface roughness length obtained for these surfaces.

Wind statistics

The ratios of the standard deviations σ_u, σ_v, and σ_w of the mean wind components u, v, and w to the friction velocity u_* are important for the particle models used in WindTrax. They determine the lateral and vertical spread of the plume away from the path followed by the mean wind. One of the tenets of micrometeorology is that over flat terrain these ratios are universal functions of stability and height. Field experiments have provided empirical relations that can be used to estimate these ratios, in the absence of their direct measurement by a sonic anemometer. WindTrax uses the following relationships, found in the published literature:

$$\sigma_u / u_* = \begin{cases} 2.5, L > 0 \\ \sqrt{0.35\, w_*^2 + 2.5^2}, L < 0 \end{cases}$$

$$\sigma_v / u_* = \begin{cases} 2.0, L > 0 \\ 0.35 w_*^2 + 2.0^2, L < 0 \end{cases}$$

and

$$\sigma_w / u_* = \begin{cases} 1.25, L > 0 \\ 1.25\,(1.0 - 3.0\, z/L)^{1/3}, L < 0 \end{cases}$$

where w_* is defined as

$$w_* = u_* \left(\frac{-H}{K_v L} \right)^{1/3}$$

with H being the height of the atmospheric boundary layer.

In practice, we have found that using measured values for the statistics generally improves the results over those generated with the preceding empirical relations. If you have calculated σ_u, σ_v, and/or σ_w from measurements, you can provide these to the particle models by adding a wind statistics sensor to the map, and setting the ratios using its property editor (or connecting them to a data file). Alternatively, you can add a sonic anemometer to the map and provide the correct correlations from a data file; WindTrax uses this data to derive the statistics.

Specifying wind model parameters

WindTrax has been designed to accommodate a variety of meteorological data. At present, there are four basic modes in which you can provide this data to WindTrax:

- The values can be entered directly into the Surface Layer Model;
- The mean wind speed U and direction θ can be provided by adding an anemometer (in given mode) to the map, while z_o and L are entered directly;
- A profile of temperature and/or wind speed measurements can be added to the map, from which all the required parameters will be calculated;
- A sonic anemometer (in given mode) can be added to the map, from which all the required parameters and the wind statistics will be calculated.

Hierarchy of data sources

The program automatically selects from the listed options based on the map you have drawn. You should be aware that this selection is based on a hierarchy, so that if conflicting given-mode sensors are present on a map, a single source will be chosen from among them. Highest priority is given to given-mode sonic anemometers; if one is present on the map, then all other data sources will be ignored. Next highest in priority are valid profiles of temperature and/or wind speed, with multi-point profiles given precedence over bulk Richardson profiles (two-point measurements of speed and temperature). Next are single given-mode measurements of wind speed and direction. If more than one speed measurement is present but they do not form a valid profile, the first sensor placed will be used and the rest ignored. Directly entered values have the lowest priority; in fact, WindTrax prevents you from entering data directly if one or more of the other sources of data are present on the map.

Given mode vs. unknown mode for sensors

The hierarchy discussed in the previous section applies only to given-mode sensors. For example, if you place a sonic anemometer in unknown mode on the map and provide measured data using a given-mode standard anemometer, WindTrax will calculate the values of each of the statistics usually measured by the sonic anemometer, based on the standard anemometer's data and the built-in empirical models for wind statistics.

The following sections will describe each of the options for providing wind data in greater detail.

Specifying parameters directly

As mentioned earlier, direct access to the surface layer model parameters u_*, z_o, L, and θ is provided by the Surface Layer Model icon located in the upper left corner of the map. Double-clicking on this icon will open its property editor and allow you to set the parameters; if you are using an input data file, you can connect columns containing the data to the appropriate properties of the Surface Layer Model, which will be listed on the right side of the input file editor form.

It is important to note that it is up to you to ensure that the parameters satisfy Monin-Obukhov similarity theory; WindTrax does not test to see that this condition is met when all parameters are entered directly. If you have calculated the values using a standard technique (e.g. from sonic anemometer data; or fitting a curve through profile measurements using a least-squares fit) then the condition should be satisfied.

Using a single anemometer

The earliest versions of WindTrax required that you provide wind speed and direction measurements through a single standard anemometer, which was automatically placed on the map. The intention was to ensure that the wind model parameters satisfied Monin-Obukhov similarity theory. If you know the surface roughness length and atmospheric stability, this option is still a good one. It is also among the least demanding in terms of instrumentation. In theory, you could provide just a single measurement of wind speed and direction; determine surface roughness by selecting an appropriate ground cover from the list provided when you double-click on the map surface; and estimate stability based on the general conditions in the atmosphere at the time of the observations. It should be expected that the results generated from this approach will not be highly accurate.

Some earlier versions of WindTrax allowed you to set u_* directly using a Standard Anemometer, but this is no longer allowed. Instead, it can be accessed using the Surface Layer Model icon, as discussed in the previous section. Old project files are automatically converted to the new standard.

A minor point, but probably worth mentioning: if you are using the single-speed-measurement method, you can add to the map either a Standard Anemometer, which measures both wind speed and direction:

or a Cup Anemometer to provide wind speed and a Wind Vane to specify measured wind direction. Of course, both sensors can be added to the same tower:
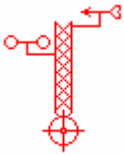
Profile measurements

Traditionally, surface layer properties were determined by measuring profiles of temperature and wind speed, usually on a tower reaching three to ten meters in height. More recently, sonic anemometers seem to have largely replaced this approach; but it is still in use, and historic data of this format might be of interest to you. The new versions of WindTrax allow you to set model parameters indirectly by adding a group of thermometers and/or wind speed measurements to the map, creating a profile.

There are a few constraints on the placement of these sensors. First, they must all be placed on the same platform. Second, all sensors of a given type (i.e. speed or temperature) must be at different heights, with no two sensors at the same height. Third, there is a minimum number of measurements required to form a valid profile. When all of these constraints are met, WindTrax will provide access to a "profile object", which will allow you to adjust the way in which the parameters are calculated.

There are two allowed types of profile, which will be determined by the number of measurements you have provided:

- If you add two wind speed sensors and two temperature sensors to a platform and set their heights to different values, the program will create a *Bulk Richardson profile*, from which it will determine u_* and L. In this case, you will have to add

surface roughness and wind direction separately (or use a standard anemometer to set one of the wind speeds).

- If you add at least four wind speed sensors at different heights to a platform, WindTrax will estimate u_*, z_o, and L by fitting a standard curve through the data using a weighted least-squares method. Adding more data will improve the quality of the estimated parameters. Ideally, a profile should include both wind speed and temperature data, though WindTrax will accept wind speeds alone.

Sonic anemometer measurements

An increasingly common method of providing WindTrax parameters is to feed it data measured by a sonic anemometer; it has the advantage of providing all seven parameters, and has been found to give better results than when the standard statistical relationships are used. It is also probably the most complicated of the available methods. Of course, if you have used a sonic anemometer to measure the wind field, you are always free to do your own calculations to derive the wind model parameters and enter them directly. If you are using a Cerex system and have added a Cerex Data File to the map, the sonic and its data connections will be set up automatically for you. Otherwise, the complications involved require that you either carefully test your setup to ensure that the WindTrax sonic anemometer is set to be compatible, or contact Thunder Beach Scientific to clarify the details.

The complications arise from three sources: the differences between commercially available sonic anemometers; the different averages that might be computed from the instantaneous sonic measurements; and the requirement that you correctly connect the measured values to the WindTrax sonic.

All sonic anemometers measure instantaneous values of wind speed components u, v, and w and temperature T, at some fixed sampling rate (often many times per second). The standard wind components are defined such that u is positive when the wind is blowing toward the East and negative when it is coming from the East; v is positive when the wind is blowing toward the North; and w is positive when the wind is blowing upward from the ground. However, different sonic anemometers use a variety of coordinate systems when they report their instantaneous measurements of u, v, and w. Some report the coordinates in standard format; others have the u and v components reversed, but w the same; and so on.

Yet another complication involving coordinate systems is that various instruments define their standard position in different ways. For example, the Campbell Scientific 3D sonic anemometers are designed so that u, v, and w are reported in the standard sense when the sensor head points due West; while the RM Young 81000 defines u and v in the opposite sense when the arrow on the sensor is aligned to due North.

By default, the WindTrax sonic assumes that the data being reported by your sensor is formatted so that *u*, *v*, and *w* follow the standard definition when the sonic is placed in its standard orientation. If it isn't, you will have to adjust either your data or the WindTrax sonic anemometer's parameters.

Generally, a data logger accumulates these measurements to generate statistical relationships from them. These can be reported as either raw averages or as correlations. Raw averages are calculated using relations such as the following mean product of *u* and *T*:

$$< u \times T >= \sum_{i=1}^{N} u_i T_i$$

or refined to give correlations by subtracting the product of the means, as in the following:

$$< u'T' >=< u \times T > - < u >< T >$$

The WindTrax sonic anemometer allows you to enter data in either format, but you will have to set the appropriate mode using the sensor's property editor.

When using a sonic anemometer, it is almost certain that you will be providing a data file, rather than entering data directly into the property editor. The sensor requires that each of fourteen different mean products be set: $<u>$, $<v>$, $<w>$, $<T>$, $<u \times u>$, $<u \times v>$, $<u \times w>$, $<v \times v>$, $<v \times w>$, $<w \times w>$, $<u \times T>$, $<v \times T>$, $<w \times T>$, and $<T \times T>$. Your data file will have to be set up so that each parameter is placed in a different column. Each line of the file will contain the data from one measurement. Of course, you are free to add concentration and other measurements to the file in different columns, and the data does not have to be in any particular order. The exception to this is Cerex data files, which are set up in a standard format that must not be changed.

Specifying wind direction

Wind direction data can be provided either directly to the Surface Layer Model or using one of three sensors: a wind vane, a standard anemometer, or a sonic anemometer. If a sonic anemometer is present on the map, WindTrax will obtain wind direction from it and ignore any other wind sensors. It is probably best to place only one wind direction sensor on the map.

Temperature and pressure

If your concentration measurements are made in units of ppm or ppb, you will have to provide temperature and pressure measurements; this allows WindTrax to relate the relative concentration data to the standard mass-per-unit-time units of emission rate.

If you do not have any temperature measurements, the program will use a default value called the "station temperature", which can be accessed by double-clicking on the Atmosphere icon found at the upper left corner of the map:

Of course, knowing the actual temperature will improve the accuracy of the units conversion. If you have measured temperature directly, add a thermometer sensor to the map and associate it with your temperature data. If you are using a sonic anemometer, the sensor measures temperature by calculating the speed of sound through air; if a sonic anemometer is added to the simulation, WindTrax will use its temperature data and ignore the station temperature. It is probably best to have just one temperature sensor on the map at a time, though if more are present then WindTrax will use the average value of all, adjusted for height and atmospheric stability.

If you have measured atmospheric pressure, add a pressure sensor icon to the map and associate its pressure property with your observation – taking care as always to ensure that the units agree with your data. If you did not measure pressure directly, you can check weather office records to determine what the local pressure was around the time of your measurements. If that data is unavailable, then WindTrax will estimate pressure based on the elevation you specify for the map, using the hypsometric equation. To set the station elevation, you will double-click anywhere on the map background to open the Map Surface property editor and select the Elevation tab.