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SOME THOUGHTS ON IN-SITU FLUX MEASUREMENT IN THE ATMOSPHERIC SURFACE LAYER

Introduction.

Due to its complexity, the state of a turbulent atmosphere can only be described using statistical quantities such as means, variances, and covariances. Computation of these statistical quantities, particularly those of higher order, must be done with considerable care. This is particularly true if the statistics are used to depict heat and momentum fluxes. This note contains considerations that could help the experimentalist to obtain high quality eddy covariance measurements needed to characterize these fluxes using sonic anemometer/ thermometer (sonic) measurements from a fixed platform mounted within the atmospheric surface layer (ASL).

1. Definition of the Problem.

Eddy covariance flux measurement from a stationary site poses two basic problems. The first problem is that a flux, the turbulent transfer of heat or momentum through one surface or level in the atmosphere to the next, occurs as irregularly spaced coherent events characterized by their duration, intensity, and spatial location. In contrast, the tower-mounted sonic obtains measurements at discrete intervals from a fixed location at some unknown distance downwind of the flux source. The fixed sonic can only measure the flow passing its position, and only time averages of these measurements can be formed. One objective, then, is to come up with a workable procedure that produces a time average that converges towards a flux space-time ensemble average. (Note: Through the ergodic hypothesis we assume that time, space, and ensemble averages are related. Refer to a turbulence textbook such as Lumley and Panofsky (1964) for theoretical details.) Time and space averages can be related with varying degrees of success, depending on the capabilities of the instrument, site conditions and instrument exposure, the care with which the data are handled, and the scales of motions that occur during the measurement period. The second problem with flux measurement arises as a consequence of the intermittent and irregular character of flux events. The averaging needed to approximate an ensemble average obscures the duration, intensity, and spatial location of individual flux events. There are three basic approaches to eddy covariance flux measurement: block averaging and mean removal (MR); block averaging and detrending (DT); and running mean filtering (RMF). Each approach offers advantages and disadvantages. Many of these are described briefly below. Ultimately, the experimentalist must consider the measurement objective and choose between a procedure that provides a reasonable approximation of the average ensemble flux and a procedure that emphasizes the transient characteristics of individual localized flux events. This note ends with some practical flux measurement suggestions.

2. **Instrument and Site Considerations.**

The measurement of heat and momentum flux requires an instrument capable of simultaneous and coincident measurement of the three velocity components and speed of sound (convertible to temperature) with sufficient precision and data rate to sample rapid changes in the temperature and velocity fields. The sonic is a nearly ideal instrument for this purpose. However, sonics come in various designs offering a variety of capabilities, and the experimentalist needs to choose one that is compatible with the measurement requirement. (Note: Refer to ASTM standards D5527 and D6011 for details on sonic operation and performance.) Major considerations include the following:

a. Acceptance Angle. Acceptance angle is the angular distance centered on the array axis of symmetry where wind approaching the sonic transducer array is either free from blockage by structural elements or is compensated by shadow correction algorithms. Some sonics offer an acceptance angle of 360° in the horizontal plane and somewhat greater than ±30º in the vertical plane, while others are constrained to smaller angles. In practice, the presence of mounting and support structures often limit acceptance angles to 270° and ±30º The angle of attack by a steady wind approaching a sonic array usually ranges within ±30º of vertical. However, these angles may be exceeded during very light winds, producing flow distortion that biases the fluxes. If flux measurements are to be made in very light winds (or in other conditions where the vertical wind angle is likely to exceed ±30º it will be very important to choose an array design that accepts a wider vertical angle of attack. Dual instrument mounts may be needed if fluxes are to be measured over all wind directions.

b. Sonic Array Design. Because it is immersed within the flow that it is measuring, the sonic transducer array should be designed to minimize the distortion of that flow while providing velocity component and speed of sound measurements from a common sampling volume. Flow distortion causes undesired flow accelerations and wind direction changes that bias covariance computations. Flow distortion effects are particularly troublesome at very low (< 2 ms^{-1}) wind speeds and most strongly impacts momentum flux computations. Refer to Grelle and Lindroth (1994) for a detailed analysis of these effects. Vertical velocity measurements are particularly susceptible to flow distortion. Many modern sonics use an array geometry that features paths at 60° from the horizontal plane and measurement of the velocity components within a coincident volume. Others offer the advantage of direct vertical velocity measurement and minimum flow distortion at the cost of separating velocity component measurement axes by several tens of centimeters (see Kaimal et al., 1990 for a discussion of the K probe). Array designs featuring a common sampling volume are more suited for near-surface measurements where turbulence scales are small, so long as the angle of attack is not too large. Unobstructed direct vertical velocity measurements using separate axes to minimize flow distortion is more desirable at heights above the surface where turbulence scales greatly exceed the axis separation distance, or where the vertical angle of attack is large.

c. Data Rate. Haugen (1978) offers guidelines suggesting that a data rate of 1 to 5 Hz is sufficient for measurements in daytime convection and 5 to 20 Hz for stable nocturnal flows. Many modern sonics have sampling rates on the order of 100 Hz with user-selected averaging to 10 or 20 Hz. This averaging is used to minimize spectrum aliasing (Kaimal and Finnigan (1994) discuss this subject in detail. Champagne et al (1977) state that the bandwidth required to measure the entire momentum cospectrum is typically on the order of 10^{-3} = fz/U = 10, where f is the frequency in Hertz, z represents height above the surface, and U is the wind speed. Within the range of measurement heights and wind speeds normally encountered within the ABL, a 10 to 20 Hz data rate from a sonic with array path of 10 to 15 cm is sufficient for most flux measurement above the roughness sublayer. Measurements made within the roughness sublayer or in confined settings (an urban street canyon, for example) might contain turbulence scales that are not adequately resolved, thereby causing under-sampling of the true flux.

d. Level and Vertical Velocity. Accurate measurement of vertical velocity w is vital for accurate flux estimation. This requires careful attention to the orientation of array axes measuring vertical velocity. The turbulent component of the vertical wind can be defined as that which makes transient departures from the flow streamline. In the absence of convergence/divergence, the mean of these flow streamline departures should approach zero. Over flat, open terrain, flow is (to within instrument resolution) parallel to the surface, and vertical is easily established perpendicular to the flow streamlines by orientating with respect to gravity. However, most measurement sites feature terrain slopes that deviate from this ideal. Off-streamline vertical velocity measurements produce a vertical velocity bias $ß_w$ equal to the product of the time-mean alongwind velocity component $\underline{\mathbf{U}}$ with the tangent of the angle of inclination to the streamline a:

$$ß_w = \underline{\mathbf{U}} \tan a \, , \qquad (1)$$

where the underbar indicates a time average. Because U >> w, small a can cause substantial $ß_w$. In consequence, high quality flux measurements require orientation of the array axis into a vertical velocity null ($\underline{w}$ ˜ 0). This may require a trial and error process of aligning the axis, taking long term (several hours) vertical velocity averages, and then re-aligning until a consistent null is found (see Oncley et al. 1996 for specific procedures). Alternatively, one can orient the sonic array level with respect to gravity and apply post-measurement bias corrections. Departure of the ambient temperature from the sonic calibration temperature can also contribute a vertical velocity bias. Skibin et al. (1985) describe a procedure designed to minimize vertical velocity biases induced by departures of ambient temperature T (in degrees Kelvin) from temperature T_0 at which the instrument was calibrated. They also consider flow distortion and terrain influences. The time-mean measured (subscript m) temperature flux is related to the true quantity by:

$$\underline{w'T'} = (\underline{T}/T_0)(\underline{w'T'})_m - \{A - [B \cos(\underline{?} - D)]\}\underline{u'T'} + \underline{w}_m/T_0$$

$$+ C(1/T_0^{0.5} - 1/\underline{T}^{0.5})(\underline{T'})^2 \, , \qquad (2)$$

and for the time-mean momentum flux,

$$\underline{w'u'} = (\underline{T}/T_0)(\underline{w'u'})_m - \{A - [B\cos(\underline{?} - D)]\}\underline{u}'^2 + \underline{w}_m/T_0$$

$$+ C(1/T_0^{0.5} - 1/2\underline{T}^{0.5})\underline{u'T'}\ , \tag{3}$$

where A, B, C, and D are coefficients to be determined by analysis of multiple data sets and primed quantities indicate departures from the mean. Coefficient A corrects for flow distortion due to the mounting structure (tower, booms, etc.), B is related to ground slope, C accounts for sensitivity to temperature change, and D is an adjustment for mean wind approach angle $\underline{?}$. Temperature correction effects are typically small, and taking the time to orient with respect to the streamlines is the better approach.

e. Axis Rotations. A sonic properly mounted and oriented with respect to flow streamlines should resolve the approaching flow into its Cartesian components. That is, the flow is decomposed into along-axis u_i, cross-axis v_i, and vertical velocity w_i components. (An additional transformation is needed to convert measurements from non-orthogonal arrays to these components.) For a selected averaging period, coordinate rotations are used to orient the horizontal axis into the flow so that u becomes the along-wind component and v becomes the cross-wind component, with a mean of zero ($\underline{v} = 0$). These rotations are:

$$u = u_i\sin? + v_i\cos? \tag{4}$$

$$v = u_i\cos? - v_i\sin?, \tag{5}$$

where $? = \tan^{-1}(\underline{v_i}/\underline{u_i})$, and the subscript i denotes an unrotated measurement. (Note: $w_i = w$.) An additional rotation is sometimes done to set $\underline{w} = 0$, but Wilczak et al. (2001) caution against this rotation because $\underline{w}$ sampling errors introduce low bias on the stress, particularly during weak winds. Another consideration is that $\underline{w}$ can be non-zero as a consequence of atmospheric convergence/divergence, which makes a real contribution to the overall flux. Instead of forcing $\underline{w}$ to zero, Wilczak et al. (2001) offer a planar fit technique that reduces stress errors, but this has the disadvantage of requiring many data runs before stress can be computed. The simplest and most reliable approach is to: carefully orient the sonic array into a vertical velocity null; perform rotations only on the horizontal axis; determine if the non-zero $\underline{w}$ is a consequence of convergence/divergence and decide whether or not it should be included in the flux measurement; and test for stationarity as described below.

f. Site Roughness and Zero Plane Displacement. Site roughness (z_0) and zero plane displacement (d) must be considered for representative flux measurements. Measurements made close to a complex or rough surface will likely reflect the influences of individual elements rather than an area-average flux. If the purpose of the measurement is to obtain a flux representative of an area rather than of an individual surface feature, the sonic must be mounted at a sufficient height above the area that the flux contributions of individual elements are blended. In an urban environment this blending height, where the measurements are representative of integrated rather than individual elements, is a minimum of 2.5 element heights above the surface (Grimmond and Oke, 1999; Kastner-Klein and Rotach, 2001). Other more subtle effects include transitory changes in surface roughness around the site due to foot or vehicular traffic, and precipitation. Snow, in particular, can dramatically alter site z_0 and d, reducing z_0 while increasing d if it is evenly distributed, or completely transforming the landscape if drifts form. Likewise, people walking or driving around a measurement site can create local roughness changes. Carefully documenting z_0 and d, and their changes are important considerations when analyzing flux data.

f. Fetch and Internal Boundary Layers. Flux source regions lie at distances upwind of the measurement point that vary in proportion to wind speed. In consequence, terrain and vegetation non-uniformities create a problem for experimenters interested in obtaining area-representative flux measurements. These non-uniformities create variations in flux measurements, and on a multi-level tower can lead to disparate results at different measurement heights. Just as wakes form downwind of obstructions, internal boundary layers (IBL) form with each change in surface roughness or albedo. The rate of internal boundary layer growth depends on whether the transition is rough-to-smooth or smooth-to-rough. Garratt (1994) provides the following formula for calculating the fetch distance x required to produce an IBL of depth h downwind of a change in roughness from z_{01} to z_{02} :

$$x = 2z_{02}((h\ z_{02})[\ln(h/ z_{02}) – 1] +1). \quad (6)$$

Not included in the above equation is the effect of stability; Garratt (1994) notes that an IBL tends to grow more quickly with convection and more slowly in the presence of stable stratification.

3. Documentation and Quality Control.

a. Documentation. Collecting data suitable for calculation of heat and momentum fluxes involves a substantial investment in equipment, analysis time, and data storage. The value of the collected data set is directly related to its documentation and quality control. Undocumented data sets are of little value to anyone other than those who collected them, while well documented data sets usually find repeated applications. Documentation includes detailed information about the instruments and procedures used to collect the data, as well as site information. Equipment description, mounting height, orientation, a file time stamp, data sampling rates, and averaging periods are fundamental to the interpretation of any meteorological statistics. Additional information needed for the analysis and interpretation of fluxes includes time-resolved site information. Site information includes documentation of the site and its changes with time. Minimum recommended supplementary equipment for a long term flux measurement program includes precipitation detectors that document the beginning and end of precipitation events, and a pyranometer for measurement of incoming hemispheric short wave solar radiation. Photographic documentation is also needed to record seasonal changes at the site.

b. Data File Management. Care is needed to insure that information is not lost during collection, analysis, and archival. A unique data origin and time stamp is of crucial importance, and the time standard (local standard time, Greenwich mean time, etc.) must be clearly documented. Site information and time is often contained, in abbreviated form, in filenames. Opening and closing files regularly during data collection insures that data will be saved in the event of a power fault or equipment malfunction. Saving files for sampling periods on the order of an hour is a good compromise between the desire to acquire a seamless continuous record versus the need to avoid losing a large data set. (Record lengths on the order of an hour also represent a reasonable compromise between the need for a sample size large enough to contain multiple samples of flux-generating motions, and short enough to be minimally influenced by larger scale motions.) Whether a file's time stamp applies to the beginning or the end of that file must also be known unambiguously. A common convention is for the filename to identify time at the beginning of the data set. It is also useful to establish filename conventions to identify whether a file contains "raw" data or data that has been subjected to quality control.

c. Quality Control. Quality control includes the identification, flagging, and correction of data faults that include spikes, baseline shifts, and missing data. A good quality control plan would include procedures for: (1) archival of the un-altered data as received; (2) data analysis by visual inspection of the time series and/or application of various error detection algorithms to the data set; (3) setting of various flags and detailed examination of portions of the data set receiving these flags; (4) correction of the error (if possible); (5) creation of a new data set that contains an unambiguous marker indicating that it has been through the quality control process; (5) assignment of a quality flag to the data set so that the analyst knows what errors have been or might be present in the data; (6) periodic review of the quality control process and its results. Note also that quality control should be performed as close to the original data as possible (before the fault is obscured by coordinate rotations, conversions, etc.) so that the source and cause of the fault can be expediently identified.

d. Spikes. Spikes appear in data sets from a variety of sources, to include transducer faults, noise induced through electronics or cabling, objects impinging on the transducer, or environmental noise. Spikes appear as unusual sharp peaks or valleys in a data stream that persist for no more than a few data points. Noise appearing in only one channel of data suggests a local transducer or electronics fault, while noise appearing simultaneously on several or all channels indicates the possibility of an environmental source (a gunshot or aircraft flying overhead). Spikes become a major problem when data are averaged into a mean to form a measure of central tendency. One or two spikes averaged with a number of good data samples to form a mean that may depart only slightly from the true mean degrades the data set and are difficult to detect. An alternative is to use a median as a measure of central tendency. In this case, the 50th percentile data point will either represent good data (in the presence of a few spikes) or will represent the readily identifiable spike, but not some average of the two. Spikes of short duration that are sufficiently well spaced can be replaced by estimates taken from valid data immediately before and immediately after the spike. Justification for this is based on the strong autocorrelation present in time series data over periods of a second or less.

e. Baseline Shifts. Baseline shifts appear as an abrupt change in the mean value of a data channel that persists longer than a spike, but has no geophysical explanation. Abrupt shifts in one data channel are most certainly indicators of an internal fault. Simultaneous shifts in all channels suggest the additional possibility of an event external to the equipment. If the signal is preserved on a baseline shift, it is possible through manual editing to correct the problem. Baseline shifts that also include random noise should be marked as missing data.

f. Missing Data. Missing data, where numbers or spaces are missing in the data stream, is often due to data acquisition faults, timing errors, or to blockage of an acoustic path in the sonic array. Nothing can recover lost data, but manual editing can sometimes restore data sets where the numbers or spacing are shifted slightly out of sequence. Note that missing data or data otherwise removed from analysis should not be assigned a value of "0" or any other value that might fall within the operating range of the instrument. Missing or invalid data should be assigned an identifier such as 999.9 that can be easily spotted within an array of valid numbers and programmed out of any further computations performed on the data set.

g. Coordinating Data Sets. Consideration needs to be given to how the flux data set will be used in relation to data sets acquired using other equipment. For example, sonic-derived fluxes may be used in an analysis that includes wind profiler data. A priori coordination of file start and end times with the data acquisition timing used by other equipment greatly reduces post-acquisition analysis efforts and time offset errors.

4. Sampling and Averaging.

The choice of sampling and averaging times used to create a turbulence realization depends on the use to be made of the flux information and the amount of time that the experimenter is willing or able to invest in data analysis. Each chosen realization is one of an ensemble of possible realizations; one measurement objective is the estimation of this flux ensemble. Because fluxes are intermittent in space and time, it would be ideal for the experimentalist to sample over the entire time of interest and carefully analyze each time series and its spectra prior to choosing averaging times. However, equipment, data storage, time limitations, and other criteria make this impossible. The analyst is then left to make the best use of time-averaged turbulence realizations based on the resources at hand. Tools at hand include previously mentioned MR, DT, and RMF flux estimation techniques. Some sampling and averaging considerations are discussed below:

a. Stationarity And The Integral Scale. Early flux sampling and averaging time estimates were based on the tacit assumption of measurement over a homogeneous site during stationary meteorological conditions. The idealized model ABL consists of a turbulent inertial sublayer with an identifiable spectral peak that defines an integral scale. (Note: The existence of an integral scale implies that by averaging over a single independent realization we achieve results similar to averaging over the entire ensemble. Refer to a turbulence text such as Lumley and Panofsky (1964) for theoretical details.) Realistic measurements in the real atmosphere are often deviate greatly from the homogeneous and stationary ideal, and conditions exist where the spectrum produces no readily identifiable integral scale. In this situation each realization is not independent of the next because all are samples of some larger process. Foken and Wichura (1996) offer a simple stationarity test performed by comparing a 30-min averaged flux of quantity c´ with the average of six 5-min averages obtained over the same sampling time. If

$$0.7 < \langle w'c' \rangle_{5min} / \langle w'c' \rangle_{30min} < 1.3 \,, \tag{7}$$

the data set is considered sufficiently stationary for reasonable flux computation. Note that the limits on the test described above may require adjustment for specific sites and applications.

b. Scale Separation. Data sets usually consist of rapidly varying (turbulent) motions superimposed on slowly varying larger amplitude ones. Scale separation between the two is often sufficiently small that they are difficult to isolate. In this situation a systematic under-estimate of the flux occurs due to a failure to capture the largest flux-generating scales, and random errors occur as a consequence of selecting an inadequate record length, which must be balanced against overestimation due to inclusion of larger scale motions. Some of these larger scale motions generate no flux, while other large scale motions contribute to the overall flux as a consequence of localized convergence/divergence. The experimentalist must decide whether or not those motions contribute to the flux measurement objective. Thus, how the flux data are to be used must be carefully considered in the design of a flux measurement program.

c. Defining Mean and Fluctuating Quantities. Flux calculation is based on the selection of appropriate averaging for defining a mean vertical velocity $\underline{\mathbf{w}}$ and the means of the transported quantities ($\underline{\mathbf{U}}$ or $\underline{\mathbf{T}}$). For the vertical flux **F** of a generalized quantity c, the flux is represented by:

$$\mathbf{F} = \langle (w' + \underline{\mathbf{w}})(c' + \underline{\mathbf{c}}) \rangle = \underline{w'c'} \,. \tag{8}$$

Products of mean quantities ($\underline{\mathbf{w}}\,\underline{\mathbf{c}}$) and mixed products ($\underline{\mathbf{w}}\,\underline{c'}$, $\underline{w'}\underline{\mathbf{c}}$) are identically zero if we assume that $\underline{\mathbf{w}}$ and the averages of fluctuating quantities are zero. Unfortunately, the turbulent atmosphere is often not that simple. In some cases $\underline{\mathbf{w}}$ is non-zero, indicating the presence of unresolved flux or some inadequacy in the selected averaging time or method selected for defining the mean. Optimum averaging periods vary with the state of the atmosphere and the quantities to be measured. To ensure the inclusion of all flux-carrying wavelengths, Oncley et al. (1996) used the cumulative integral of the cospectrum to determine the minimum required averaging times. Their results produced averaging times ranging from 5.6 (stable) to 27.8 (unstable) min. for $\underline{w'u'}$, and 2.8 (stable) and 16.6 (unstable) min. for $\underline{w'T'}$. Results may vary at non-uniform or rough sites, but optimum averaging periods will likely range between 3 to 30 min. at most locations. Discussed below are the MR, DT, and RMF flux estimation techniques and how they handle difficulties that arise in real data.

d. Mean Removal (MR). Selecting sequential non-overlapping block averaging times and performing a mean removal on the u and T realizations (recall that u is the alongwind component after rotation into the mean wind direction) is the simplest flux estimation method. The basic premise of this method is that each selected realization is an independent sample of the flux ensemble and that averages of these samples approximate the ensemble. Averaging times that are too short underestimate the flux, while averaging times that are too long include the effects of meanders and trends that over estimate of the flux. Because it is fairly quick and easy to do, simple mean removal can be performed over several averaging times within a measurement period. This allows one to search for an optimum averaging period.

e. Detrending (DT). Detrending the u and T realizations prior to mean removal can overcome some of the limitations of the MR method, and a trend can be quasi-linear if a suitably short averaging time is selected. Linear trend removal can be particularly useful for a temperature record responding monotonically to a diurnal heating/cooling cycle, but most trends in meteorological data are decidedly non-linear and vary with time. Non-linear trend removal can be used with some success against meandering motions, as demonstrated by Caramori et al (1994). However, trend removal can go badly wrong when not adequately adapted to the flow. When the fit is poor, or when DT is performed over inappropriate averaging times, the result can be far worse than no detrending. Detrending techniques should only be used on data that fail a stationarity test (Equation 7) and receive close inspection.

f. Running Mean Filtering(RMF). With running mean filters, the fluctuating components are obtained as deviations from the instantaneous mean from a low-pass filter of user-selected length that moves through the data. This technique can include a variable time interval and averaging window that adapts to the physical properties of the turbulence (Treviño and Andreas, 2000), or the averaging window can be of fixed length (Rannik and Vesala, 1999). The RMF technique offers great advantage when the measurement objective is to study the details of individual flux events. However, fluctuation averages do not necessarily vanish with RMF, thereby violating a Reynolds averaging principle. A comparative analysis performed by Rannik and Vesala (1999) shows that the fixed length RMF technique can produce large systematic errors with the use of short time constants, and large random errors when long time constants are used. The adaptive RMF technique of Treviño and Andreas (2000) probably minimizes these errors, but has not been subjected to independent testing.

5. Practical Engineering Solutions For Automated Flux Measurement.

a. Flux Computation. Kaimal and Gaynor (1991) have shown that the sonic speed of sound measurement, when properly converted to temperature and corrected for crosswind velocity component contamination, produces a sonic temperature that closely approximates the virtual temperature of air. The product of this fluctuating temperature and vertical velocity provides an estimate of the virtual temperature flux. There are three commonly used ways to compute momentum flux, each depending on how the horizontal velocity components are handled. Method A begins with computation of the scalar wind speed s_i from the square root of the sum of the u_i and v_i squares

$$s_i = (u_i^2 + v_i^2)^{0.5}. \tag{9}$$

After subtraction of the mean wind speed, the momentum flux is the product of the fluctuating wind speed component with its corresponding vertical velocity summed over the selected averaging period. Method B involves using Equation 4 to rotate each horizontal velocity component measurement into the mean wind, and computing momentum flux as a product of the rotated u´ with w´. Methods A and B produce equivalent results, $\underline{w'{s_i}'} = \underline{w'u'}$. Method C first calculates the fluctuating unrotated horizontal wind components u_i' and v_i' followed by momentum flux computation using

$$w'u_i{}' + w'v_i{}' = w(u_i'\sin ?_i + v_i'\cos ?_i), \tag{10}$$

with the momentum flux obtained as the sum over the selected averaging period. Method C produces a result that differs somewhat from the other two methods due to the sequence in which the computations are done. This difference appears also in the horizontal velocity means; the average of the square root of the sum of the squares is greater than the square root of the squares of the summed averages. Method A offers the advantage of computing the scalar wind speed, which is likely to be a variable of interest.

b. Estimating The Ensemble Flux. For long term measurements designed to estimate the ensemble flux, time averages must be selected to approximate the (unknown) ensemble average. However, stationarity and averaged vertical velocity tests can be used as guidance with the following steps: (1) collect long sampling records, at least 30 min. in length, but preferably up to 1 hour; (2) perform all quality control steps and minimize site or instrument-induced vertical velocity biases prior to calculating covariances; (3) compute the covariance for each long term record, and also over the same record for non-overlapping block averages of 300 s in length; (4) perform a stationarity test (Equation 7 above), with limits adjusted for one's particular site conditions. If the data set passes the stationarity test and **$\underline{w}$** ˜ 0 for the short sampling record average, use the average of the 300-s records as the best flux estimate. If the test fails, examine the data for meanders or trends. If these are evident, detrend the hourly records, re-compute, and re-do the test. Also try adjusting the short term averaging period to half (if the atmosphere is stable), or three times (if the atmosphere is unstable) its initial 300 s value. The shorter averaging period should minimize contamination by meandering motions in a stable atmosphere, and a longer period will include more of the convective contributions in an unstable atmosphere. If a substantial non-zero **$\underline{w}$** persists due to the large scale convergence/ divergence (prevalent during strong convection), use the covariance computed over the full hour, or whatever average produces the minimum $\underline{w}$, as the best estimate.

c. <u>Investigating Transient Flux Events.</u> If the covariance measurement objective is to study the individual characteristics of transient flux events, apply an adaptive running mean filter of the type described by Treveño and Andreas (2000).

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