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Introduction

Eddy covariance (or eddy correlation-EC) systems have been the subject of detailed research. This past research has provided the framework needed to allow the correct measurement of the turbulent contributions to the surface fluxes of heat, water vapour, momentum and latterly greenhouse gases and other atmospheric scalars. With the arrival of commercial "off-the-shelf" EC measurement systems and largely "black box" software packages [1], these combined EC systems and their measurements have increasingly become an important part of the general measurement portfolio of various environmental and ecological projects. Increasingly, in many projects, they are not necessarily the main component of the project itself.

Their sophistication and generally compact profile have led to many EC systems being deployed as if they were radiation balance instruments, automatic weather stations or even tipping bucket rain gauges. However radiation instruments or rain gauges sample the immediate local conditions - in the case of radiation instruments, a cone immediately above or below the sensor - in contrast, EC systems (hereafter also called flux systems) sample an upwind source area, or fetch that is dynamic in both space and time. This source area, or flux "footprint" not only varies with general weather conditions but also varies with the upwind vegetation and underlying landscape. Here we examine these effects, together with the influence of the supporting structure and the interactions between the various other sensors and the hardware deployed nearby.

This handbook provides a simple source of information for researchers whose expertise is not in EC system deployment, but who wish to apply such systems to collect data pertinent to their overall objectives. The guidance covers the installation of these systems in such a way that the researcher can be confident that the data taken are as accurate as possible. Unlike many other measurement sensors, redundancy is rarely possible and there is generally no replication of EC systems or alternatives against which to check the results. Even adjacent EC systems often fail to fully agree, partly because of different instrument designs but largely because they are looking at different flux source areas whose vegetation cover, soil moisture and soil carbon fluxes are different [2]. Many studies have evaluated the surface energy budget, comparing incoming net radiation, with outgoing soil heat flux and sensible and latent heat fluxes. Although physics requires these terms to balance in practice, this is difficult to achieve.[3,4] There is no such balancing equation in the measurement of the various greenhouse gases (the exception possibly being CO_2 when co-located with the latent heat flux measurement). What you measure is thus the only value you have and trust in these values depends on the correct operation of the sensors and more importantly, the correct relative positioning of the various sensors and instruments that combine to form the entire sensor measurement system.

We start with the researcher arriving at the proposed experimental field site and choosing the location of an EC system for maximum acquisition of accurate data. Continuing with this aim of gaining accurate data, we then look at the errors due to the support structures and power provision. Finally, we give some simple tests that can be run on the initial collected data.

Field Site Considerations

The ideal site for EC measurements is an infinite flat plain. Under this condition the overlying air layer is neither moving consistently towards nor away from the surface - meaning that, over time, the average vertical wind vector is zero. While sites approaching this ideal were used during the initial development of EC sensors and theory, EC systems are now commonly deployed in less than ideal terrain. The EC method calculates the turbulent transport of entities from the deviations, w', of the instantaneous vertical wind velocity, w, from the mean velocity $\overline{W}$. Flux is calculated through the equation $w = \overline{W} + w'$.

Local terrain conditions, such as a slope, hill or substantial surface irregularities can cause deviations from the fundamental requirement of the EC measurement technique: namely, that $\overline{W}=0$. Oblivious to the local conditions, the post-processing EC computation software will attempt to make $\overline{W} = 0$, but in so doing the required measurement of w' will be compromised. A consistent gradient slope can be accommodated by placing the EC system normal to the slope but hill-top placement is generally to be avoided.

Most sites will have surface heterogeneity of some form and these irregularities will have a greater effect upon w and other EC measurements the closer the EC system is to the irregularities. These isolated bluff bodies perturb the over-flowing air mass to a greater extent than in a more homogeneous vegetation cover. This is illustrated in Figure 1 redrawn from Mayaud & Webb [5]. The red lines represent an EC system on top of a support pole. It can be seen that the sparse vegetation can produce pronounced wave type air flows that will compromise the assumption of $\overline{W} = 0$ if the mast is too close to the vegetation. As the vegetation density moves to a more homogeneous cover (bottom illustration), these waves tend to flatten out and while the mast is still not in the unperturbed region above (where it should be), the error in the assumption of $\overline{W} = 0$ is much less and of a more random nature.

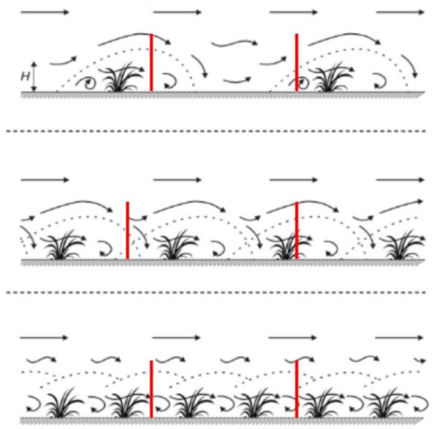

Figure 1: Wind flow over various vegetation densities. Red lines represent an EC system on top of support pole.

Implicit in the above is that there is a height above a surface (of greater or lesser inhomogeneity) where the effect of the surface irregularities on the overpassing turbulence structure have been smoothed out to the point where that turbulent structure is indistinguishable from the layer immediately above. This conceptual height, at or above which the EC system should be placed is known as the "blending height". Meeting this condition is often difficult because of the allied concepts of landscape-scale surface changes and fetch, both of which need to be incorporated into the decision of where to place the EC system and at what height.

Landscape-Scale Surface Changes

When the near-surface atmospheric boundary layer traverses a change in roughness, it takes some time and distance for the air mass to come into equilibrium with the new surface conditions. This distance for the new equilibrium to be achieved is shorter when going from a smooth surface to a rough one (e.g. from a water surface to a vegetated one), than from rough to smooth (e.g. forest to grassland) where the eddies take a greater time and distance to change their turbulent structure to reflect the new underlying terrain. In Figure 2, two EC system masts (in red) are positioned downwind of a change in roughness from Type 1 to Type 2. There is a discontinuity between the air in equilibrium with Type 1 and that within the developing Internal Boundary Layer (IBL) influenced to some degree by Type 2. Below the IBL an Equilibrium Layer (EL) is developing which is representative of the Type 2. The interface between the IBL and the EL is effectively the limit of the constant flux layer, within which measurements at any height are representative of the surface. This interface is not a discontinuity because equilibrium is approached asymptotically. From the diagram, it is evident that the mast close to surface Type 1 will be measuring fluxes that contain a large proportion of information from that surface while the second mast is more likely to be measuring a majority of flux from the layer in better equilibrium with surface Type 2. It is therefore important for an EC system mast to be as far away from a radical change in surface conditions as possible. The vertical placement of the EC system is now between two opposing heights - the lower one of the blending height where surface heterogeneity effects are minimised and the upper one that keeps the system within the EL representative of the underlying surface.

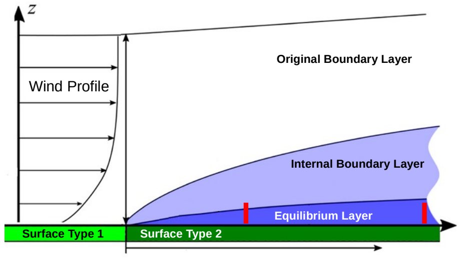

Figure 2: Boundary Transition between two surface types

Within this height range, the higher the sensor is positioned above the land or water surface - the larger the upwind area contributing to the measurement becomes. If there is sufficient upwind area of the type of homogeneous surface under study, then there is no problem in complying with the constraints described above. But often, differing vegetation and soil types (both of which impact moisture and greenhouse gas production) will provide marked differences in upwind terrain, especially in the heavily cultivated areas of Europe where conditions often change markedly across a patchwork of individual fields. This is the problem of "fetch" and what the EC system "sees".

Fetch and Footprints

The fluxes emanating from a very large homogeneous surface will be everywhere the same; under this condition the placement of the EC system wouldn't present too many problems. However the EC sensor measures an accumulation of flux entities whose concentration strength to the overall measurement is a function of their origin in the upwind surface area with those flux entities closer to the mast providing a greater proportion to the overall measurement than those further away. Both experimental and theoretical work has indicated that turbulent mixing of near surface fluxes as measured by flux sensors follows a three dimensional skewed Gaussian distribution.

Figure 3 is a representation of this sample distribution as perceived by an EC system for differing atmospheric stability, sensor to vegetation height and rough to smooth surfaces. The two linear curves are the midline slices of the source strength; the insert shows the three-dimensional distribution of source strength of the combined upwind (u) and crosswind (v) contributions as measured by an elevated sensor located at zero metres distance. The curves are representative of the near extremes of possible Source Area contributions created by large differences in atmospheric stability, height of sensor above the surface and roughness of that surface, whose effect generally follows the same pattern. In reality, inhomogeneity is to be expected, and the upwind location and source strength of individual flux entities will affect their contribution to the overall flux measurement.

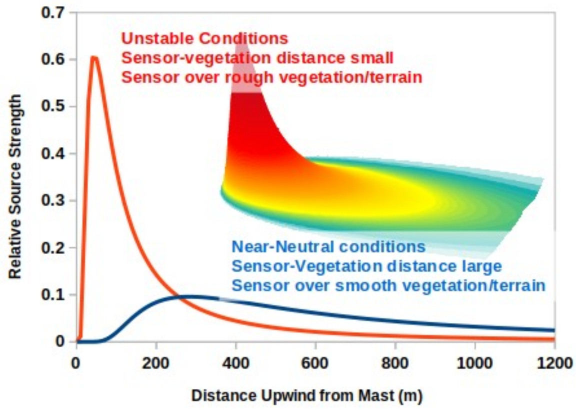

Figure 3: Source area curves upwind of sensor mast

Although source area considerations are more pertinent to sensors measuring water vapour and greenhouse gases, other entities are transported by the atmospheric boundary layer eddies, and their fluxes are modified by the surface and general atmospheric conditions and this is what the sonic anemometer "sees". The difference in the shape of the curves is due to the stability of the local atmosphere, the steep peak during the middle of the day when the air is unstable and the other during, for example, cloudy high wind speed times when the air, lacking bouyancy but being mixed more thoroughly, tends towards neutrality. But these curves are also modified by the roughness of the underlying surface and by the height of the sensor. A smooth lake surface will stretch these curves out to kilometre scales, moving the peak further away from the sensor; on the other hand, rough crops or surfaces will shorten these curves bringing the peak closer. Hence there is generally a compromise in terms of sensor height - high enough to minimise local turbulent and source heterogeneity but low enough to ensure that the measurements are not contaminated by different surface types and conditions beyond the surface terrain under investigation.[6]

Field estimation of Fetch

When initially assessing measurement sites a useful, if rather inexact, rule-of-thumb is to use a fetch:height ratio of 100:1; for every metre the instruments are above the vegetated surface allow 100 metres of uniform upwind vegetation between the instruments and the nearest change in surface roughness or vegetation type. This rule, in another form, was given by Rao et al. [7] who showed from Bradley's field experiments[8] in atmospheric neutral conditions that the thickness of the EL (see above) at a distance (x) downwind of the surface change interface was x/100 for a smooth-to-rough transition and x/200 for a rough-to-smooth transition. The two forms are equivalent if the thickness of the EL is the maximum sensor height for flux measurements. Both forms are inexact because unstable atmospheric conditions will reduce the multiplication factor (shortening the required fetch), and moderately stable conditions will require a much greater multiplication factor thus lengthening the fetch. The rule also underestimates fetch for smooth surfaces or very high measurement heights. Gash[9] provided a diffusion theory based equation for the estimation of effective fetch, again in atmospherically neutral conditions based solely on roughness length, z_o; zero displacement height, d; and z_m (equal to sensor measurement height $z - d$). By incorporating a percentage effective fetch (F/100) factor - this enabled an appreciation of the possible measurement contamination by changes in upwind surface conditions. The effective fetch X_F is given by:

$$X_F = -z_m \frac{[\ln((z_m)/z_0) - 1 + z_0/(z_m)]}{k^2 \ln(F/100)(1 - z_0/(z_m))} \quad (1):$$

Note – the minus sign is just convention indicating distance upwind of mast, and that this equation has the correction identified by Schuepp et al. (1990)

where k is von Kármáns constant (=0.41). Roughness length (z_o) can be approximated as 0.1 of vegetation height h or by appeal to the Revised Davenport roughness classifications given in Appendix 1. The zero plane displacement height, d, is also often approximated as two-thirds of vegetation height (0.67h). Note that as with the fetch-height ratio approach above, the fetch will "concertina", contracting in unstable conditions and expanding in stable conditions. Using the near-neutral calculation will therefore give conservative estimates of the fetch required for the generally more important daytime conditions.

Evaluation of equation (1) at the 90% level (F=90) provides nearly the same answer as the "100" rule given above while indicating that there could be a 10% contamination. Reducing the percentage contamination will markedly lengthen the fetch required. However, note that it is the change in flux beyond the interface that counts: if there is no change in flux beyond X_F then there is no sampling error. Note also that the X_F equation does not contain wind speed; it predicts that fetch is independent of wind speed. Having decided where to put the EC system - we now address other issues that will affect flux measurements accuracy - the effect of multiple sensors and hardware.

Instrument System Considerations

The Sonic Anemometer

The sonic anemometer is the central and most important sensor of an EC system. Incorrect deployment and placement of this sensor will mean that all other measurements that rely on this sensor (energy and greenhouse gas fluxes) will be compromised. The factors necessary for correct deployment comprise both local problems of adjacent instrumentation (disturbance of turbulent airflow), hardware and other measurements. The sonic anemometer, for correct measurements, has to be in a turbulent atmospheric regime that most closely resembles the regime that would exist if no instrumentation were present. While generally difficult to achieve, it is important that effort is put into meeting these criteria as closely as possible.

Disturbance by other sensors and hardware

Good meteorological practice states that incoming solar and net radiation measurements should have complete hemispherical access to the sky. This creates a problem as the sonic anemometer needs to be the highest sensor for correct exposure to the transporting air flow. The solution is either to create a separate mast for all passive instrumentation some distance from the eddy covariance measurements or to accept and compensate for a partial sector of the sky being obscured by the mast. Figure 4 illustrates the deployment of a single mast system in Africa where the radiation instruments are at the far end of the horizontal boom. The small compensation to the radiation measurements is easier, computable and more defensible than attempting to compensate for the unknown effects that sensors above and around the sonic anemometer will introduce to the turbulent air flow.

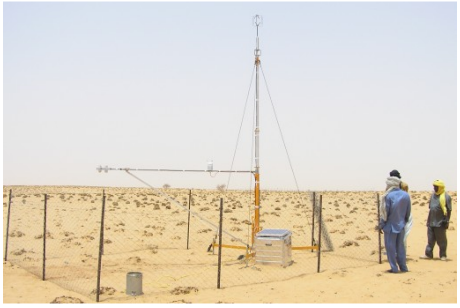

Figure 4: Micrometeorological Site in Northern Mali during the AMMA experiment.

Another factor that needs to be taken into account when considering the height of the mast, especially over smooth surfaces such as lakes, short grass, sand, etc. is the size of the turbulent eddies . As the turbulent eddies propagate away from the surface, they become progressively larger in all three spatial dimensions. But the rate of size increase depends on both the inherent turbulence structure of the approaching air mass and the turbulence created by friction against the surface that the air is moving over. Aside from buoyancy effects from heating of the air, turbulence is created by the underlying roughness of the surface terrain: i.e. turbulence scales with z_0. As a consequence, low wind speeds over an extensive smooth surface such as sand may not produce eddies of a sufficient size to be registered by the sonic anemometer at or below a certain measurement height.

Sonic anemometers cannot resolve eddies whose dimensions are smaller than the sonic anemometer path length and therefore any associated flux contribution by these eddies will be lost. Generally, this is not a huge problem - but should be borne in mind when deploying over very smooth surfaces, e.g. lakes, laterite pans, snow. At the other end of the scale is the production of large eddies whose dimensions may mean that a measurement period ends before the full contribution of that large eddy has been fully included. The dimensions of these large eddies are such that they may also be "contaminated" by unknown terrain sources many kilometres away. The general flux system measurement averaging time period of 30 minutes or 1 hour may not be sufficiently long to accommodate these large eddies but that loss is balanced by minimising their flux contamination effect.

Atmospheric Concentration Sensors

Atmospheric concentration sensors measure the water vapour, carbon dioxide, methane and other gaseous constituents that emanate from terrestrial sources and propagate through turbulent mixing into the boundary layer. These may be carried into the upper atmosphere or deposited further downstream onto another terrestrial surface, e.g. evaporation from a warm wet surface may then condense as dew on a colder surface further downstream.

When conflating measurements from separate sensors, account has to be made for the distances separating them and their own internal characteristics, whether that is measurement path length as mentioned above for the sonic anemometer or the separation distance between the sensors which creates a spatial and timing disparity between the measured vertical wind velocity w and the gaseous concentration c. This could be avoided if both w and c were measured at the same time and in the same spatial volume. In prototype form, this arraignment was achieved in the CEH Mk4 Hydra and is also the configuration provided by the Campbell Scientific Inc. IRGASON system for sensible and latent heat, and CO_2 fluxes, but various operational reasons have meant that most manufacturers have opted to provide separate sonic anemometer and scalar sensor units. In accepting this compromise, various corrections have to be applied to account for path length variations, sensor separation and frequency response differences; corrections which are generally incorporated into the software (Moore)[10] . As Burba[11] points out, it is more difficult to correct for the unknown flow distortion than to correct for sensor separation.

Figure 5: A typical multi-sensor eddy covariance system

However, with the motive of reducing separation errors, many installations place the concentration sensors close to the sonic anemometer. While this will minimise the effects of sensor separation on the overall measurements as shown in Figure 5, the bluff body effect of these CO_2 and CH_4 sensors will reduce the accuracy of the sonic anemometer measurement of *w*. The errors, which will generally be unknown, will vary with wind speed and direction, and thus be difficult to estimate and compensate for.

Another consideration when attempting to co-locate separate sensors is to ensure that the gaseous entities and their concentrations transported by the eddies are being measured at the same height as the sonic anemometer. The gas sensor measures concentration changes and the concentration gradient becomes smaller the further away the sensor is from the source of the gas. The difference in average absolute gas concentration caused by a small height difference between the concentration sensor and the sonic anemometer is minimal if the system height is sufficient. But the eddy covariance system is recording the change in concentration of the gas in the transporting eddies at or near the height of the sonic anemometer. These instantaneous changes in concentration will be much larger than the slight difference in average concentration. Provided the gas sensor is close enough to the sonic anemometer to minimise the time and position corrections associated with sensor separation, the effect of the difference in absolute concentration will be less than any compromising effect that adjacent sensors will create. Therefore a better solution is to place the gas concentration sensor below the sonic anemometer as shown in Figure 6.

Figure 6: Solent R3 Sonic Anemometer-Licor 7500 IRGA System

Location of the Flux System and other factors

Unless the flux system is located in the centre of extensive homogeneous terrain as shown in Figure 4, local differences in the surrounding terrain will play a part in deciding the location and height of the flux system. There is no formal way to estimate the height at which to mount the sonic anemometer and associated gas sensors. Generally, the smoother the surface, the lower the system can be placed - but this minimum should only be accommodated if there is limited fetch in the immediate surrounding. The higher the better - even over "smooth" sand the sonic anemometer in Figure 4 was at 6m to minimise the loss of flux transported by small eddies and to maximise the area from which the various entities emanated to provide a good areal sample. The minimum over the sand surface in Figure 4 was probably 2m. As you move up the vegetation height scale, the height difference between the top of the vegetation and the sonic anemometer increases as the vegetation surface increases its roughness. Homogenous crop fields of 0.5m height will have a minimum sonic height of around 3.5m. When you are measuring above forests the minimum sonic height will be around 10-15m above the canopy. In this case, the flux system is generally on top of a tall tower - so the flux system needs to be placed well above the top of the tower e.g on a mast extending 6m above the top section to minimise the effect of the tower bluff body on the atmospheric stream lines. Even 10 -15m may not be high enough above anything other than plantation forestry, as most natural forests have very heterogeneous canopies in terms of both species and individual tree heights: the lumpiness of the canopy will require a greater measurement height to ensure the flow-lines have been adequately smoothed out. Similarly, hummocks in otherwise low terrain, such as bogs, present a fairly solid bluff body to the air flow, creating local eddies and necessitating a higher instrument height to avoid these local eddy instabilities.

Any substantial support structure near the flux system will also modify, deflect and produce back eddies that may influence the measurements. Flux systems are largely now being located in remote settings where system power is supplied by small wind generators or solar panels. It is important that this power generation infrastructure is sited sufficiently far away from the instruments - and low enough to not significantly compromise the measurements by modifying the surface flow-lines. Figure 7 shows an installation near Abisko, northern Sweden that operated the year round. Solar panels are flat because of the 24-hour daylight at this northern latitude. The brown boxes contain 12 x 12v car batteries to provide power to the flux system during the 24-hour night period - topped up by the wind generators. Ideally, these would have been further away, downwind from the flux system mast - but reindeer roam the area and long cables can get caught in the antlers of browsing reindeer. The cables could have been buried, but many animals, including Reindeer, will investigate disturbed ground, and possibly uncover and damage the cables. There are always elements of compromise in siting micrometeorological instrumentation to deal with such factors. Note also the rest of the micrometeorological sensors are on a support cube some distance away and downwind of the area of tundra under investigation.

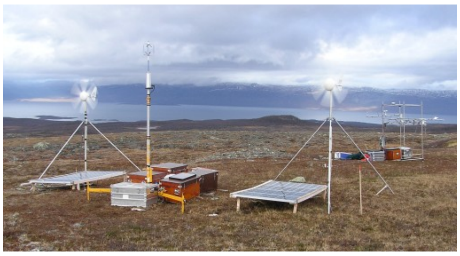

Figure 7: Combined Eddy Covariance and Micrometeorological Station near Abisko, northern Sweden

Instrument System Power Supply

Solar panels are a particular problem especially where sun angles during the measurement period are relatively low as they need to be inclined to maximise solar energy uptake. For annual measurements that do not include adjustment of solar panel angle, this requirement means that solar panel angle should be set to maximise energy capture during the shortest day-sun elevation period. Typically a flux system will require several m^2 of solar panel to supply sufficient wattage to keep the operational batteries charged for 24 hour running of the system. An extensive inclined flat plate will not only massively distort the airflow downwind of the plate but will also modify the streamlines upwind of the plate as shown in Figure 8. It is not always possible to move the solar panel array far enough away from the flux system in order to minimise the upwind flow distortion. This may be due to limited available space to position the solar panels, or as above in Abisko, the necessary long cables may be a problem. And the longer the cables, the thicker they need to be to minimise voltage loss along the cable length. An initial solution would be, having determined the prevailing wind direction, to place the solar panels as far downwind of the flux system as possible. But when space is limited or cable length is a problem, it's probably best to identify the wind direction that is of least concern to the measurements, either because of limited fetch or because winds rarely come from that direction, and place the solar panels in that direction, aware that data from that direction will be compromised and possibly need to be deleted from the dataset.

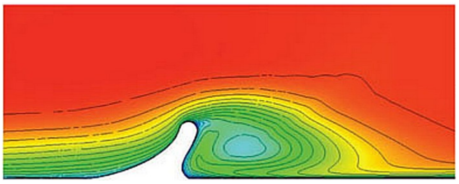

Figure 8: Airflow over an inclined object

There is evidence that there is a weak negative correlation between wind speed and solar energy i.e. that higher winds are correlated with lower solar energy and vice-versa [12] [13]. The fact that wind generators can be actively supplying energy to battery packs over the whole 24 hour cycle, and have a smaller cross-sectional area and effect upon the surface streamlines than inclined solar panels, provides evidence that a combined solar panel (of smaller capacity and dimensions) and wind generator supply is more likely to provide the required system energy while reducing the effects of the infrastructure on the measurements.

Another consideration for long-term deployment of eddy covariance systems is that of power storage for the system. This will generally be provided by 12v batteries. These ideally should be deep-cycle (leisure) batteries, which are constructed differently to car batteries, and able to effectively supply low current over long periods, while also allowing deep discharge-recharge cycling. When working abroad outside the UK and Europe, these are often unavailable or extremely expensive. Buying local 12v car batteries is then the cost effective way. While a single 50Ah 12v battery can power a combined Solent R3 sonic anemometer/Licor 7500 IRGA (combined power requirement 8W) for around 5 days and could be recharged via a combined solar panel-wind generator supply, there has to be sufficient capacity to account for extended periods of overcast windless days. Multiple 12v batteries coupled up in parallel will provide for this possibility as well as for periods with faults in either the solar panel or wind generator systems. The cost of a few extra 12v batteries is nothing compared to the loss of weeks or months of data. The power system in Figure 4 consisted of 2 x 12v batteries and 1 x 50W solar panel, taking into account the guaranteed 12 hours a day overhead sun and a data download/maintenance visit every two weeks. In contrast, the power system shown in Figure 7 comprised 8 x 100W solar panels, 2 x wind generators outputting 100W at 9 ms^{-1} feeding into 12 x 12v car batteries, sufficient to power the system unattended during the long dark cold polar night at these high latitudes. It is important to keep the level of charge similar in each of the batteries and to prevent drainage of charge from good batteries into failing ones. This is achieved by putting a Schottky diode [14] into the instrument system supply cable.

If the power system is located some distance away from the eddy covariance system (as it ideally should be), then consideration has to be given to the size of the supply cable. From both practical and supply considerations normal 2 or

3 core flexible cable (1.5mm^2 cross-section) as used for items such as domestic mains voltage extension leads, will not lose significant voltage over lengths up to 50m at a current of 0.5A - the combined current of a Solent R3 sonic anemometer/Licor 7500 eddy covariance. But with distance, especially on the ground, comes the problem of cable damage, when armoured cable might have to be considered.

Tests for correct installation

Sonic Anemometer Exposure

A simple test for correct exposure of the sonic anemometer, once the first measurements are taken, is to compare the standard deviation of the vertical wind vector (σw) with the friction velocity term (u_*) whose ratio (σw / u_*) will approach a value around 1.3 (Foken et al., 2004) for near neutral conditions.

The equation is given by: $$\frac{\sigma w}{u_*} = c_1\left(\frac{z}{L}\right)^{c_2}$$

where, z/L is the stability parameter (z = measurement height, L is the Obukhov length) and for slightly unstable conditions (typically close to dawn and dusk), c_1 = 1.3 and c_2 = 0 thus negating the need to evaluate z/L. For more unstable conditions during the major part of daytime, the equation still holds but becomes a bit more complicated with c_1 = 2.0 and c_2 = 0.125 for which z/L has to be computed - although many eddy covariance software programs will compute and output L. Any value of (σw / u_*) markedly different to 1.3 close to dawn or dusk, especially if there appears to be a wind direction dependency, will indicate that the flow through the sonic anemometer is being distorted by some local bluff body effect, whether instrumental or surface derived.

An Energy Balance check on CO_2 fluxes

While there are ways to check on the quality of acquired eddy covariance data, many of which are described by Lee *et al.*[15] these are generally complicated, are mainly post-processed data techniques, and best for studied examination rather than in-field evaluation at the start of the experiment. While there is no simple way to check the veracity of greenhouse gas fluxes if there are no independent similar measurements at the same site, most CO_2 Infra-red Gas analysers (e.g. Li-Cor 7500) also measure the evaporative flux (LE) within the same sensor measurement space and largely by the same measurement technique. In this case, an appeal to the Energy Balance equation (Rn-G=H+LE) where Rn is net radiation, G is soil heat flux and H is sensible heat flux may help. Although theoretically required, very few field experiments manage to routinely close this budget for various reasons [2]. Net radiation and soil heat flux are generally measured near to the flux measurements - and the static small area measurements may not represent the varying and dynamic radiation and soil conditions producing the measured flux from the surface some way upwind of the sensors. Soil heat flux is even more of a local measurement than net radiation, taking account of the few vertical centimetres above and below the sensor. But by looking at daily totals, G can be effectively neglected as it follows a diurnal zero-sum positive-negative path with only a slight seasonal change. Nevertheless, even if the net radiometer has been correctly sited to provide a sample measurement of the assumed surface energy regime upwind of the flux system, the attenuated daily energy balance (ΣRn=ΣH+ΣLE) may still show an apparent 20 - 30% reduction in the total eddy flux summation. A review of the energy balance closure problem by Mauder *et* al.[3] ruled out instrumental errors as a major contributor to the missing flux and the effects of post-processing software was also ruled out with (sub-)mesoscale transport being the main cause of the non-closure. Any balance disparity greater than this may indicate sensor instrumental error (calibration or faulty instrument) or incorrect deployment of the sensor(s). However, if the energy (in)balance is better than the figures quoted above, it can generally be assumed that the CO_2 measurements are being measured adequately. No such equivalent test is however available for eddy covariance methane sensors.

Summary

The overarching message of this handbook is that eddy covariance instrumentation cannot be treated in the same way as other micrometeorological sensors. The latter are predominantly passive and record data local to their position, often directly below or above them. In that respect, they are easier to site, it is easier to appreciate what they are measuring and their position can be adjusted accordingly. Sensors such as cup anemometers and wind-vanes that do interact with the passing airflow do require an appreciation of their positioning for correct measurements but of an order below that of more sensitive eddy covariance systems.

If the primary measurement provided by the sonic anemometer (w'), is compromised by poor placement and exposure, then all the sensor measurements and results that depend on this one parameter will be compromised. With the exception of the evaporation flux, where the energy balance can provide some insight into the veracity of the final data, there is little in the way of corroborating evidence to provide confidence in the production of greenhouse gas flux data. It is therefore imperative that all steps taken are considered with adequate care and attention to ensure that the eddy covariance system sensors are placed to maximise their correct operation. With many policy decisions being placed on the results from these sophisticated instrument systems, it is imperative that correct deployment is achieved to provide the best possible underlying data. The time and effort invested in gaining the acquisition of the best data possible is repaid by the subsequent ease of data analysis and formation of experimental results.

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Further Reading

The papers, books listed here are to provide more detailed information on the reasoning behind the various aspects to be considered when deploying eddy covariance systems in the field.

Overall Consideration

Burba,G. 2021. Eddy Covariance Method - for Scientific, Regulatory, and Commercial Applications. LI-COR Biosciences, LI-COR Biosciences, Lincoln, Nebraska. ISBN 978-0-578-97714-0. 702 pp. *A comprehensive expansion of the considerations in this document and detailed description of the full eddy covariance system from theory to field deployment to post-processing analysis.*

The Sonic Anemometer

Burba,G. 2021. Section 2.2 Instrument Principles Helpful in Designing the Station. in *Eddy Covariance Method - For Scientific, Regulatory, and Commercial Applications*. LI-COR Biosciences, Lincoln, Nebraska. ISBN 978-0-578-97714-0. 702pp

Fetch - Source Area Footprints

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Bluff body distortion

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Appendix 1. The Revised Davenport roughness classification - Wieringa [16]

Class	**Roughness length (z_0) metres**	**Landscape Description**
1. Sea	0.0002	Open water, tidal flat, snow, with free fetch ≥ 3 km
2. Smooth	0.005	Featureless land with negligible cover, or ice
3. Open	0.03	Flat terrain with grass or very low vegetation, and widely separated low obstacles, airport runway
4. Roughly Open	0.10	Cultivated area, low crops, occasional obstacles separated by more than 20 obstacle heights H
5. Rough	0.25	Open landscape, crops of varying height, scattered shelter belts, etc., separation distance of 15 H.
6. Very Rough	0.5	Heavily used landscape with open spaces = 10 H; bushes, low orchards, young dense forest.
7. Closed	1.0	Full obstacle coverage with open spaces = H, e.g. mature forests, low-rise built-up areas
8. Chaotic	≥ 2.0	Irregular distribution of very large elements; city centre, big forest with large clearings