A Brief Practical Guide to

Eddy Covariance Flux Measurements

Principles and Workflow Examples for Scientific and Industrial Applications

CH_4
CO_2
H_2O
Heat
Wind
Biology
Ecology
Hydrology
Agronomy
Horticulture
Entomology
Global Carbon
Climate Change
Landfill Emissions
Fugitive Emissions
Greenhouse Gases
Oil and Gas Industry
Carbon Sequestration
Environmental Monitoring

G. Burba and D. Anderson

This version 1.0.1 is a first partial revision of the original 2005-07 field manual entitled "Introduction to the Eddy Covariance Method: General Guidelines and Conventional Workflow". Several new sub-sections have been added to the Instrumentation Section, and the detailed Section on Open-Path Instrument Surface Heating was also added. Other text went through editorial revisions and updates in a number of places.

Please continue to send us your suggestions. We intend to keep the content of this work dynamic and current, and we will be happy to incorporate any additional information and literature references. Please address correspondence to george.burba@licor.com with the subject "EC Guide".

This introduction has been created to familiarize a beginner with general theoretical principles, requirements, applications, and processing steps of the Eddy Covariance method. It is intended to assist readers to further their understanding of the method, and provide references such as textbooks, network guidelines and journal papers. It is also intended to help students and researchers in the field deployment of the Eddy Covariance method, and to promote its use beyond micrometeorology.

Each page is divided into the top portion, with key points and summaries, and the bottom portion, with explanations, details, and recommended readings.

The exclamation point icon and red text indicate warnings, and describe potential pitfalls related to the topic on a specific page.

Blue text indicates scientific references, web-links and other information sources related to the topic on a specific page.

"A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications"
by
G. Burba and D. Anderson of LI-COR Biosciences

Version 1.0.1

LI-COR Biosciences
4647 Superior Street
P.O. Box 4425
Lincoln, Nebraska 68504 USA
www.licor.com
Email: george.burba@licor.com

Phone: 402.467.3576
Toll Free (USA): 800.447.3576

CONTENT

INTRODUCTION

- The Eddy Covariance method is one of the most accurate, direct and defensible approaches available to date for measurements of gas fluxes and monitoring of gas emissions from areas with sizes ranging from a few hundred to millions of square meters

- The method relies on direct and very fast measurements of actual gas transport by a 3-D wind speed in real time *in situ*, resulting in calculations of turbulent fluxes within the atmospheric boundary layer

- Modern instruments and software make this method easily available and potentially widely-used in studies beyond micrometeorology, such as in ecology, hydrology, environmental and industrial monitoring, *etc.*

- Main challenge of the method for a non-expert is the shear complexity of system design, implementation and processing the large volume of data

The Eddy Covariance method provides measurements of gas emission and consumption, and also allows measurements of fluxes of sensible heat, latent heat and momentum, integrated over an area.

This method was widely used in micrometeorology for over 30 years, but now, with firmer methodology and more advanced instrumentation, it can be available to any discipline, including science, industry, environmental monitoring and inventory.

Below are a few examples of the sources of information on the various methods of flux measurements, and specifically on the Eddy Covariance method:

Micrometeorology, 2009. By T. Foken. Springer-Verlag.

Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, 2008. By X. Lee; W. Massman; B. Law (Eds.). Springer-Verlag.

Principles of Environmental Physics, 2007. By J. Monteith and M. Unsworth. Academic Press.

Microclimate: The Biological Environment. 1983. By N. Rosenberg, B. Blad, S. Verma. Wiley Publishers.

Baldocchi, D.D., B.B. Hicks and T.P. Meyers. 1988. 'Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods', Ecology, 69, 1331-1340

Verma, S.B., 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. Remote Sensing Reviews, 5: 99-115.

Wesely, M.L., D.H. Lenschow and O.T. 1989. Flux measurement techniques. In: Global Tropospheric Chemistry, Chemical Fluxes in the Global Atmosphere. NCAR Report. Eds. DH Lenschow and BB Hicks. pp 31-46

PURPOSE

- To help a non-expert gain a basic understanding of the Eddy Covariance method and to point out valuable references
- To provide explanations in a simplified manner first, and then elaborate with specific details
- To promote a further understanding of the method via more advanced sources (textbooks, papers)
- To help design experiments for the specific needs of a new Eddy Covariance user for scientific, environmental and industrial applications

Here we try to help a non-expert to understand the general principles, requirements, applications, and processing steps of the Eddy Covariance method.

Explanations are given in a simplified manner first, and then elaborated with some specific examples. Alternatives to the traditionally used approaches are also mentioned.

The basic information presented here is intended to provide a foundational understanding of the Eddy Covariance method, and to help new Eddy Covariance users design experiments for their specific needs. A deeper understanding of the method can be obtained via more advanced sources, such as textbooks, network guidelines, and journal papers.

The specific applications of the Eddy Covariance method are numerous, and may require specific mathematical approaches and processing workflows.

This is why there is no one single recipe and it is important to further study all aspects of the method in relation to a specific measurement site and a specific scientific purpose.

ACKNOWLEDGMENTS

We would like to acknowledge a number of scientists who have contributed to this review directly via valuable advice and indirectly via scientific papers, textbooks, data sets, and personal communications.

Particularly we thank Drs. Dennis Baldocchi, Dave Billesbach, Robert Clement, Tanvir Demetriades-Shah, Thomas Foken, Beverly Law, Hank Loescher, William Massman, Dayle McDermitt, William Munger, Andrew Suyker, Shashi Verma, Jon Welles and many others for their expertise in this area of flux studies

We thank Fluxnet, Fluxnet-Canada, AsiaFlux, CarboEurope and AmeriFlux networks for providing access to the field data, to setup, collection and processing instructions and formats for their Eddy Covariance stations

We also thank a large number of people who provided valuable feedback, suggestions and additions to the first 2007 edition of the guide.

And we also would like to thank numerous other researchers, technicians and students who, through years of use in the field, have developed the Eddy Covariance method to its present level and have proven its effectiveness with studies and scientific publications.

MAIN PARTS

PART I.	Overview of Eddy Covariance Principles
PART II.	Typical Eddy Covariance Workflow
PART III.	Alternative Flux Methods
PART IV.	Future Developments
PART V.	Eddy Covariance Review Summary
PART VI.	Useful Resources
PART VII.	References

There are seven main parts to this guide: explanations of the basics of Eddy Covariance Theory; examples of Eddy Covariance Workflow; description of Alternative Flux Methods; discussion of Future Developments; Summary; list of Useful Resources; and References

PART I. OVERVIEW OF EDDY COVARIANCE PRINCIPLES

EDDY COVARIANCE THEORY

- Flux measurements
- State of methodology
- Air flow in ecosystems
- How to measure flux
- Derivation of main equation
- Major assumptions
- Major sources of errors
- Error treatment overview
- Use in non-traditional terrains
- Summary of EC theory

The first part of the seven-part guideline is dedicated to the basics of Eddy Covariance Theory.

The following topics are discussed: Flux Measurements; State of Methodology; Air flow in ecosystems; How to measure flux; Derivation of main equations; Major assumptions; Major sources of errors; Error treatment overview; Use in non-traditional terrains; and a summary.

Swinbank, WC, 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology. 8, 135-145

Verma, S.B., 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. Remote Sensing Reviews, 5: 99-115.

Wyngaard , J.C. 1990. Scalar fluxes in the planetary boundary layer-theory, modeling and measurement. Boundary Layer Meteorology. 50: 49-75

Micrometeorology,2009. By T. Foken. Springer-Verlag.

Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, 2008. By X. Lee; W. Massman; B. Law (Eds.). Springer-Verlag.

Principles of Environmental Physics, 2007. By J. Monteith and M. Unsworth. Academic Press.

Microclimate: The Biological Environment. 1983. By N. Rosenberg, B. Blad, S. Verma. Wiley Publishers.
Introduction to Micrometeorology (International Geophysics Series). 2001. By S. Pal Arya. Academic Press.

Field Measurements for Forest Carbon Monitoring: A Landscape-Scale Approach, 2008. By C.M. Hoover (Ed.). Springer-Verlag.

FLUX MEASUREMENTS

- Flux measurements are widely used to estimate heat, water, and CO_2 exchange, as well as methane and other trace gases
- Eddy Covariance is one of the most direct and defensible ways to measure such fluxes
- The method is mathematically complex, and requires a lot of care setting up and processing data - but it is worth it!

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Acad. Publ., Dordrecht, Boston, London, 666 pp.

Verma, S.B., 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. Remote Sensing Reviews, 5: 99-115.

Wesely, M.L. 1970. Eddy correlation measurements in the atmospheric surface layer over agricultural crops. Dissertation. University of Wisconsin. Madison, WI.

Advanced topics in Biometeorology and Microclimatology, 2006. By D. Baldocchi, Department of Environmental Science, UC-Berkeley http://nature.berkeley.edu/biometlab/espm228

AmeriFlux Guidelines For Making Eddy Covariance Flux Measurements, by Munger and HW Loescher, AmeriFlux http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

Fluxnet-Canada Measurement Protocols, by Fluxnet-Canada Network Management Office http://www.fluxnet-canada.ca/pages/protocols_en/measurement protocols_v.1.3_background.pdf

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

STATE OF METHODOLOGY

- There is currently no uniform terminology or a single methodology for EC method
- A lot of effort is being placed by networks (e.g., Fluxnet) to unify various approaches
- Here we present one of the conventional ways of implementing the Eddy Covariance method

In the past several years, efforts of the flux networks have led to noticeable progress in unification of the terminology and general standardization of processing steps. The methodology itself, however, is difficult to unify. Various experimental sites and different purposes of studies dictate different treatments. For example, if turbulence is the focus of the studies, the density corrections may not be necessary. Meanwhile, if physiology of methane-producing bacteria is the focus, then computing momentum fluxes and wind components spectra may not be crucial.

Here we will describe the conventional ways of implementing the Eddy Covariance method and give some information on newer, less established venues.

Micrometeorology, 2009. By T. Foken. Springer-Verlag.
http://nature.berkeley.edu/biometlab/espm228

Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

WHAT IS FLUX?

- Flux – how much of something moves through a unit area per unit time

- Flux is dependent on: (1) number of things crossing the area; (2) size of the area being crossed, and (3) the time it takes to cross this area

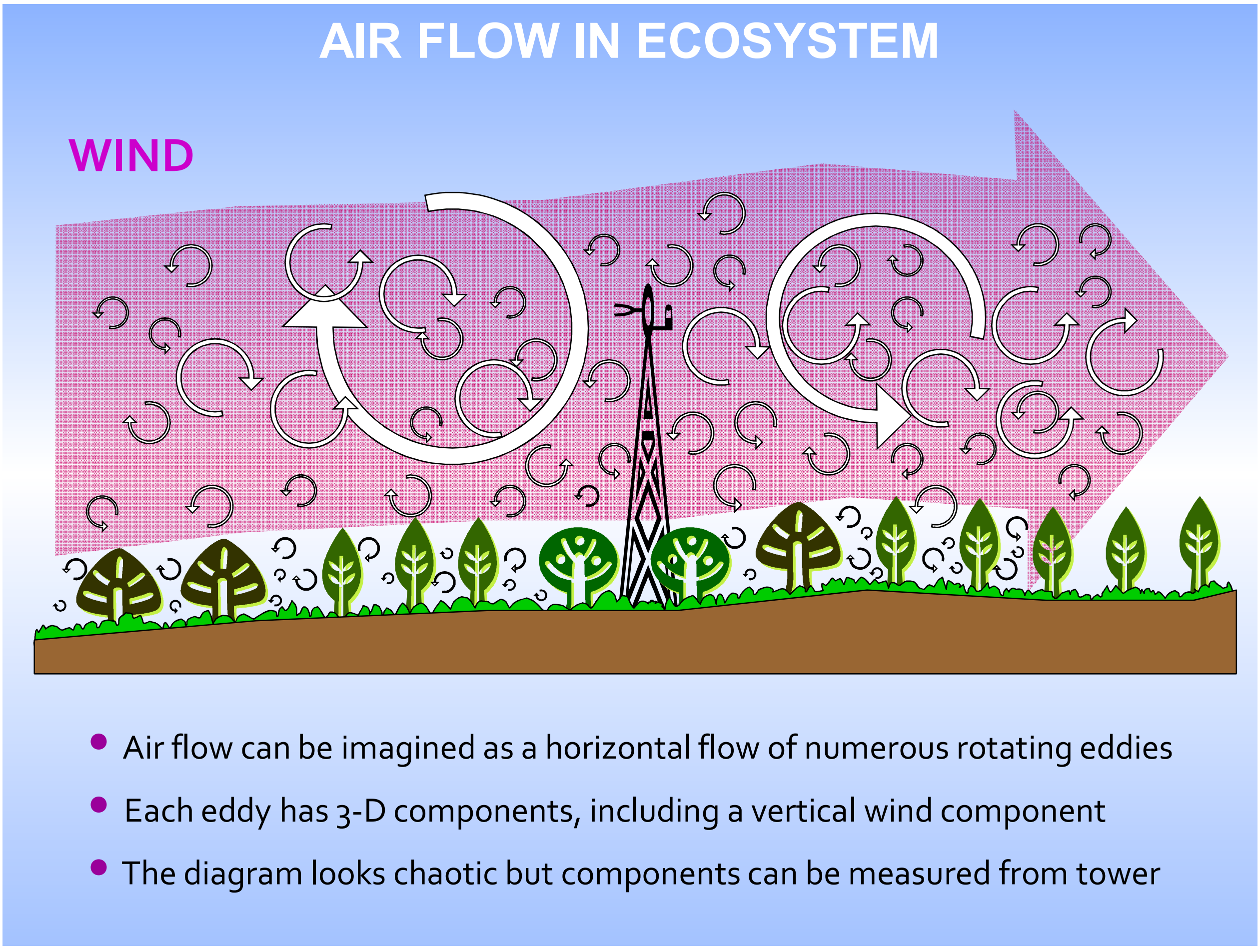
In very simple terms, flux describes how much of something moves through a unit area per unit time.

For example, if 100 birds fly through a 1x1' window each minute - the flux of birds is 100 birds per 1 square foot per 1 minute (100 B ft^{-2} min^{-1}). If the window were 10x10', the flux would be 1 bird per 1 square foot per 1 minute (because 100 birds/100 sq. feet = 1), so now the flux is 1 B ft^{-2} min^{-1}.

Flux is dependent on: (1) number of things crossing an area, (2) size of an area being crossed, and (3) the time it takes to cross this area.

In more scientific terms, flux can be defined as an amount of an entity that passes through a closed (i.e., a Gaussian) surface per unit of time.

If net flux is away from the surface, the surface may be called a source. For example, a lake surface is a source of water released into the atmosphere in the process of evaporation. If the opposite is true, the surface is called a sink. For example, a green canopy may be a sink of CO_2 during daytime, because green leaves would uptake CO_2 from the atmosphere during the process of photosynthesis.



Air flow can be imagined as a horizontal flow of numerous rotating eddies. Each eddy has 3-D components, including vertical movement of the air. The situation looks chaotic at first, but these components can be easily measured from the tower.

On this picture, the air flow is represented by the large pink arrow that passes through the tower and consists of different size of eddies. Conceptually, this is the framework for atmospheric eddy transport.

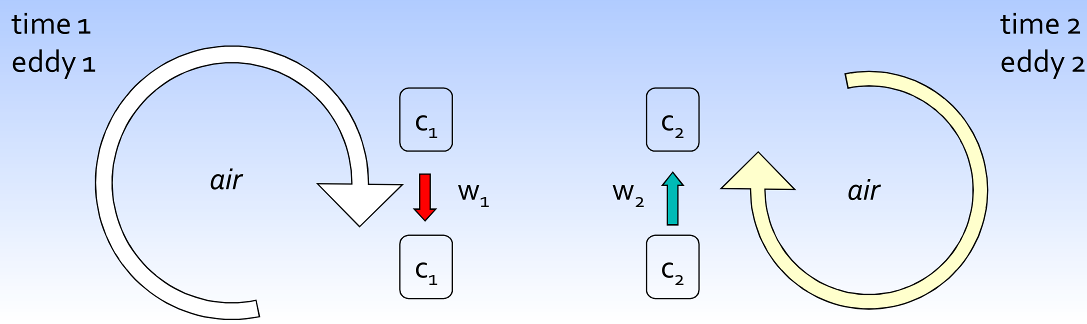
Kaimal, J.C. and J.J. Finnigan. 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, UK. 289 pp.

Swinbank, WC, 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology. 8, 135-145.

Wyngaard , J.C. 1990. Scalar fluxes in the planetary boundary layer-theory, modeling and measurement. Boundary Layer Meteorology. 50: 49-75.

Micrometeorology, 2009. By T. Foken. Springer-Verlag.

EDDIES AT A SINGLE POINT



At a single point on the tower:

Eddy 1 moves parcel of air c_1 down with the speed w_1 then Eddy 2 moves parcel c_2 up with the speed w_2

Each parcel has concentration, temperature, humidity; if we know these and the speed – we know the flux

On the previous page, the air flow was shown to consist of numerous eddies. Here, let's look closely at the eddies at a single point on the tower.

At one moment (time 1), eddy number 1 moves air parcel c_1 downward with the speed w_1. At the next moment (time 2) at the same point, eddy number 2 moves air parcel c_2 upward with speed w_2. Each air parcel has its own characteristics, such as gas concentration, temperature, humidity, etc.

If we could measure these characteristics and the speed of the vertical air movement, we would know the vertical upward or downward fluxes of gas concentration, temperature, and humidity.

For example, if at one moment we know that three molecules of CO_2 went up, and in the next moment only two molecules of CO_2 went down, then we know that the net flux over this time was upward, and equal to one molecule of CO_2.

This is the general principle of Eddy Covariance measurements: covariance between the concentration of interest and vertical wind speed in the eddies.

HOW TO MEASURE FLUX

The general principle:

If we know how many molecules went up with eddies at time 1, and how many molecules went down with eddies at time 2 at the same point – we can calculate vertical flux at that point and over that time period

Essence of method:

Vertical flux can be represented as a covariance of the vertical velocity and concentration of the entity of interest

Instrument challenge:

Turbulent fluctuations occur very rapidly, so measurements of up-and-down movements and of the number of molecules should be done with very fast

The general principle for flux measurement is to measure how many molecules are moving up and down over time, and how fast they travel.

The essence of the method, then, is that vertical flux can be represented as a covariance between measurements of vertical velocity, the up and down movements, and concentration of the entity of interest.

Such measurements require very sophisticated instrumentation, because turbulent fluctuations happen very quickly; changes in concentration, density or temperature are small, and need to be measured very fast and with great accuracy.

The traditional Eddy Covariance method (aka, Eddy Correlation, EC) calculates only turbulent vertical flux, involves a lot of assumptions, and requires high-end instruments. On the other hand, it provides nearly direct flux measurements if the assumptions are satisfied.

In the next few pages, we will discuss the math behind the method, and its major assumptions.

Strictly speaking, there is a difference between the terms "Eddy Covariance" and "Eddy Correlation", and "Eddy Covariance" is a proper term for the commonly used method of flux measurements described in this guide. Please refer to the textbook entitled 'Micrometeorology' by T. Foken (2009) for detailed explanations of the differences between these two terminologies.

BASIC DERIVATIONS

In turbulent flow, vertical flux can be presented as:
($s=\rho_c/\rho_a$ is the mixing ratio of substance 'c' in air)

$$F = \overline{\rho_a w s}$$

Reynolds decomposition is used then to break into means and deviations:

$$F = \overline{(\overline{\rho_a} + \rho'_a)(\overline{w} + w')(\overline{s} + s')}$$

Opening the parentheses:

$$F = \overline{(\overline{\rho_a}\,\overline{w}\,\overline{s} + \cancel{\overline{\rho_a}\,\overline{w}s'} + \cancel{\overline{\rho_a}w'\overline{s}} + \overline{\rho_a}w's' + \cancel{\rho'_a\overline{w}\,\overline{s}} + \rho'_a\overline{w}s' + \rho'_a w'\overline{s} + \rho'_a w's')}$$

Averaged deviation from the average is zero

Equation is simplified: $$F = (\overline{\rho_a}\,\overline{w}\,\overline{s} + \overline{\rho_a}\,\overline{w's'} + \overline{w}\,\overline{\rho'_a s'} + \overline{s}\,\overline{\rho'_a w'} + \overline{\rho_a' w's'})$$

In very simple terms, when we have turbulent flow, vertical flux can be presented by the equation at the top of this page: flux is equal to a mean product of air density, vertical wind speed and the mixing ratio of the gas of interest. Reynolds decomposition can be used to break the right hand side of the top equation into means and deviations. Air density is presented now as a sum of a mean over some time (a half-hour, for example) and an instantaneous deviation from this mean for every time unit, for example, 0.05 or 0.1 seconds (denoted by a prime). A similar procedure is done with vertical wind speed and mixing ratio of the substance of interest.

In the third equation the parentheses are opened, and averaged deviations from the average are removed (because averaged deviation from an average is zero). So, the flux equation is simplified into the form at the bottom of the page.

Please see lecture number two, specifically pages three and four from the 2005 lecture series by Dennis Baldocchi, entitled 'Advanced Topics by Bio Meteorology and Micro Meteorology'. You will find he has very detailed and thorough calculations of this portion of the deviation. The link for Lecture 2, pages 3-4 is given below:

http://nature.berkeley.edu/biometlab/espm228 Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

DERIVATIONS (cont.)

Now an important assumption is made (for conventional Eddy Covariance) – i.e. air density fluctuations are assumed negligible:

$$F = (\overline{\rho_a}\,\overline{w}\,\overline{s} + \overline{\rho_a}\,\overline{w's'} + \cancel{\overline{w}\,\overline{\rho'_a s'}} + \cancel{\overline{s}\,\overline{\rho'_a w'}} + \cancel{\overline{\rho'_a w' s'}}) = \cancel{\overline{\rho_a}\,\overline{w}\,\overline{s}} + \overline{\rho_a}\,\overline{w's'}$$

Then another important assumption is made – mean vertical flow is assumed negligible for horizontal homogeneous terrain (no divergence/convergence):

$$\boxed{F \approx \overline{\rho_a}\,\overline{w's'}}$$

'Eddy flux'

In this page we see two important assumptions that are made in the conventional Eddy Covariance method. First, the density fluctuations are assumed negligible. But, that may not always work. For example, with strong winds over a mountain ridge, density fluctuations ρ'w' may be large, and shouldn't be ignored. But in most cases when Eddy Covariance is used conventionally over flat and vast spaces, such as fields or plains, the density fluctuations can be safely assumed negligible.

Secondly, the mean vertical flow is assumed negligible for horizontal homogeneous terrain, so that no flow diversions or conversions occur.

There is more and more evidence, however, that if the experimental site is located even on a small slope, then the second assumption might not work. So one needs to examine the specific experimental site in terms of diversions or conversions and decide how to correct for their effects.

For an ideal terrain, diversion and conversions are negligible, so we have the classical equation for the eddy flux. Flux is equal to the product of the mean air density and the mean covariance between instantaneous deviations in vertical wind speed and mixing ratio.

pp. 147-150 in Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp

http://nature.berkeley.edu/biometlab/espm228Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

PRACTICAL FORMULAS

General equation: $F \approx \overline{\rho_a}\,\overline{w's'}$

Sensible heat flux: $H = \rho_a C_p \overline{w'T'}$

Latent heat flux: $LE = \lambda \frac{M_w / M_a}{P} \rho_a \overline{w'e'}$

Carbon dioxide flux: $F_c = \overline{w'\rho_c'}$

NOTE: Instruments usually do not measure mixing ratio *s*, so there is yet another assumption in the practical formulas (such as: $\overline{\rho_a}\,\overline{w's'} = \overline{w'\rho'_c}$

As we saw on the previous page, the eddy flux is approximately equal to mean air density multiplied by the mean covariance between deviations in instantaneous vertical wind speed and mixing ratio.

By analogy, sensible heat flux is equal to the mean air density multiplied by the covariance between deviations in instantaneous vertical wind speed and temperature; conversion to energy units is accomplished by including the specific heat term.

Latent heat flux is computed in a similar manner using water vapor and later converted to energy units. Carbon dioxide flux is presented as the mean covariance between deviations in instantaneous vertical wind speed and density of CO_2 in the air.

Please note that older instruments usually do not measure mixing ratios. So yet another assumption is made in the practical formulas. That is that the product of mean air density and mean covariance between deviations in the instantaneous vertical wind speed and mixing ratio is equal to the mean covariance between deviations in instantaneous vertical wind speed and gas density.

This assumption is not required for instruments capable of outputting true mixing ratio, or dry mole fraction, at high speed. One example of such an instrument is the enclosed LI-7200 CO_2/H_2O gas analyzer.

More details on practical formula and references are given in Rosenberg, N.J., B.L. Blad & S.B. Verma. 1983. Microclimate. The biological environment. A Wiley-interscience publication. New York. 255-257.

MAJOR ASSUMPTIONS

- Measurements at a point can represent an upwind area
- Measurements are done inside the boundary layer of interest
- Fetch/footprint is adequate – fluxes are measured only at the area of interest
- Flux is fully turbulent – most of the net vertical transfer is done by eddies
- Terrain is horizontal and uniform: average of fluctuations is zero; air density fluctuations , flow convergence & divergence are negligible
- Instruments can detect very small changes at very high frequency

In addition to the assumptions listed on the previous three pages, there are other important assumptions in the Eddy Covariance method:

Measurements at a point are assumed to represent an upwind area

Measurements are assumed to be done inside the boundary layer of interest, and inside the constant flux layer

Fetch and footprint are assumed adequate, so flux is measured only from the area of interest

Flux is fully turbulent
Terrain is horizontal and uniform
Density fluctuations are negligible
Flow divergences and convergences are negligible
The instruments used can detect very small changes with very high frequency

The degree to which some of these assumptions hold true depends on proper site selection and experiment setup. For others, it will largely depend on atmospheric conditions and weather. Later we'll go into the details of these assumptions.

http://nature.berkeley.edu/biometlab/espm228 Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

http://www.cdas.ucar.edu/may02_workshop/presentations/C-DAS-Lawf.pdf - B. Law, 2006. Flux Networks – Measurement and Analysis

Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

MAJOR SOURCES OF ERRORS

Measurements are not perfect: due to assumptions, physical phenomena, instrument problems, and specificities of terrain and setup

There could be a number of flux errors introduced if not corrected:

Frequency response errors due to:

System time response
Sensor separation
Scalar path averaging
Tube attenuation
High pass filtering
Low pass filtering
Sensor response mismatch
Digital sampling
etc.

Other key error sources:

Sensors time delay
Spikes and noise
Unleveled instrumentation
Density fluctuations (WPL)
Sonic heat flux errors
Band-broadening for NDIR
Spectroscopic effect for LASERs
Oxygen in the 'krypton' path
Data filling

Measurements are of course never perfect, because of assumptions, physical phenomena, instrumental problems, and specifics of the particular terrain or setup. As a result, there are a number of potential flux errors, but they can be corrected.

First, there is a family of errors called frequency response errors. They include errors due to instrumental time response, sensor separation, scalar path averaging, tube attenuation, high and low pass filtering, sensor response mismatch and digital sampling.

Time response errors occur because instruments may not be fast enough to catch all the rapid changes that result from the eddy transport. Sensor separation error happens because of physical separation between the places where wind speed and concentration are measured, so covariance is computed for parameters that were not measured at the same point. Path averaging error is caused by the fact that the sensor path is not a point measurement, but rather integration over some distance; therefore it can average out some of the changes caused by the eddy transport. Tube attenuation error is observed in closed-path analyzers, and is caused by attenuation of the instantaneous fluctuation of the concentration in the sampling tube. There can also be frequency response errors caused by sensor response mismatch, and by filtering and digital sampling.

In addition to frequency response errors, other key sources of errors include sensor time delay (especially important in closed-path analyzers with long intake tubes), spikes and noise in the measurements, unleveled instrumentation, the Webb-Pearman-Leuning density term, sonic heat flux errors, band-broadening (for NDIR measurements), spectroscopic effect (for LASER-based measurements), oxygen sensitivity, and data filling errors. Later, in the Data Processing Section, we will go through each of these terms and errors in greater detail.

Foken, T. and Oncley, S.P., 1995. Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'. Bulletin of the American Meteorological Society, 76: 1191-1193.

Fuehrer, P.L. and Friehe, C.A., 2002. Flux corrections revisited. Boundary Layer Meteorology, 102: 415-457

Massman, W.J. and Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agricultural and Forest Meteorology, 113(1-4): 121-144.

Moncrieff, J.B., Y. Mahli and R. Leuning. 1996. 'The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water', Global Change Biology, 2, 231-240

Twine, T.E. et al., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology, 103(3): 279-300.

ERROR TREATMENT

- These errors are not trivial - they may combine to over 100% of the flux
- To minimize or avoid such errors a number of procedures could be performed

Errors due to	Affected fluxes	Approximate Range
Frequency response	all	5-30%
Time delay	all	5-15%
Spikes, noise	all	0-15%
Unleveled instrument/flow	all	0-25%
Density fluctuation	H_2O, CO_2, CH_4	0-50%
Sonic heat error	sensible heat	0-10%
Band Broadening for NDIR	mostly CO_2	0-5%
Spectroscopic effect for LASER	any gas	0-30%
Oxygen in the path	some H_2O	0-10%
Missing data filling	all	0-20%

None of these errors are trivial. Combined, they may sum to over one hundred percent of the initial measured flux value. To minimize such errors, a number of procedures exist within the Eddy Covariance technique. Here we show the relative size of errors on a typical summer day over a green vegetative canopy, and then we provide a brief overview of the remedies. Step-by-step instructions on how to apply these corrections are given in the Data Processing Section of this guide.

Frequency response errors affect all the fluxes. Usually they range between five and thirty percent of the flux, and can be partially remedied by proper experimental set up, and corrected by applying frequency response corrections during data processing.

Time delay errors can affect all fluxes, but errors are most severe in closed path systems with long intake tubes, especially for water vapor and other "sticky" gases (e.g., ammonia). They range between five and fifteen percent, and can be fixed by adjusting the time delay during data processing. One can fix these by shifting the two time series in such a way that the covariance between them is maximized, or one can compute a time delay from the known flow rate and tube diameter.

Spikes and noise may affect all fluxes but usually are not more than fifteen percent of the flux. Proper instrument maintenance, along with a spike removal routine and filtering help to minimize the effect of such errors.

An unleveled sonic anemometer will affect all fluxes because of contamination of the vertical wind speed with a horizontal component. The error can be twenty-five percent or more, but is relatively easily fixed using a procedure called coordinate rotation.

Webb-Pearman-Leuning density fluctuations mostly affect gas and water fluxes, and can be corrected by using a Webb-Pearman-Leuning correction term. Size and direction of this added correction varies greatly. It can be three hundred percent of the small flux in winter, or it could be only a few percent in summer.

ERROR TREATMENT (cont.)

Errors	Remedy
Frequency response	frequency response corrections
Time delay	adjusting for delay
Spikes, noise	spike removal
Unleveled instrument/flow	coordinate rotation
Density fluctuation	Webb-Pearman-Leuning correction
Sonic heat error	sonic temperature correction
Band Broadening for NDIR	band-broadening correction
Spectroscopic effect for LASER	no uniform widely used correction
Oxygen in the path	oxygen correction
Missing data filling	Methodology/tests: Monte-Carlo etc.

Sonic temperature errors affect sensible heat flux, but usually by not more than ten percent, and they are fixed by applying a fairly straightforward sonic heat correction.

Band-broadening errors affect gas fluxes measured by NDIR technique, and greatly depend on the instrument used. The error is usually on the order of zero to five percent, and corrections are either applied in the instrument's software, or described by the manufacturer of the instrument.

Spectroscopic effects for recent laser-based technologies may affect fast concentrations and fluxes. The extent is generally specific to the technology, little studied in Eddy Covariance applications, and should be treated with caution.

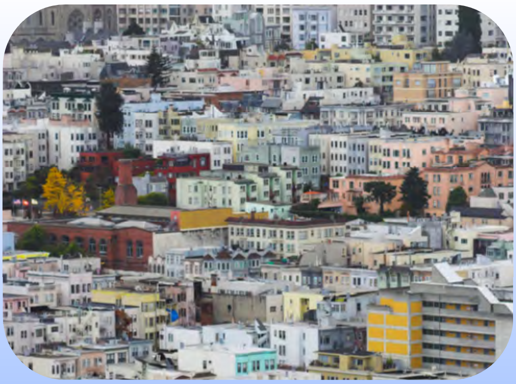
Oxygen in the path affects krypton hygrometer readings, but usually not more than ten percent, and the error is fixed with an oxygen correction.

Missing data will affect all the fluxes, especially if they are integrated over long periods of time. There are a number of different mathematical methods to test and compute what the error is for a specific set of data. One good example is the Monte Carlo Method. Other methods are described in the gap filling section of this guide.

Also, please note how large the potential is for a cumulative effect of all of these errors, especially for small fluxes and for yearly integrations. You can see how important it is to minimize these errors during experiment set up, when possible, and correct the remaining errors during data processing.

USE IN NON-TRADITIONAL TERRAINS

- All principles described previously were developed and tested for traditional settings: horizontal, uniformed terrain, with negligible density fluctuations, negligible flow convergence & divergence, and with prevailing turbulent flux transport
- Later developments of the method have revisited these assumptions in order to use method in complex terrains, such as hills or cities
- Success of these later applications is intermittent, but progress in this direction, though slow, is promising



All of the principles described above were developed and tested for traditional settings, over horizontal uniform terrain with negligible density fluctuation, negligible flow convergence and divergence, and with prevailing turbulence.

The latest developments of the method have revisited many of these assumptions, and used Eddy Covariance in complex terrains (on hills, in cities, and under conditions of various flow obstructions). Success of these applications has been intermittent, but progress in this direction is very promising.

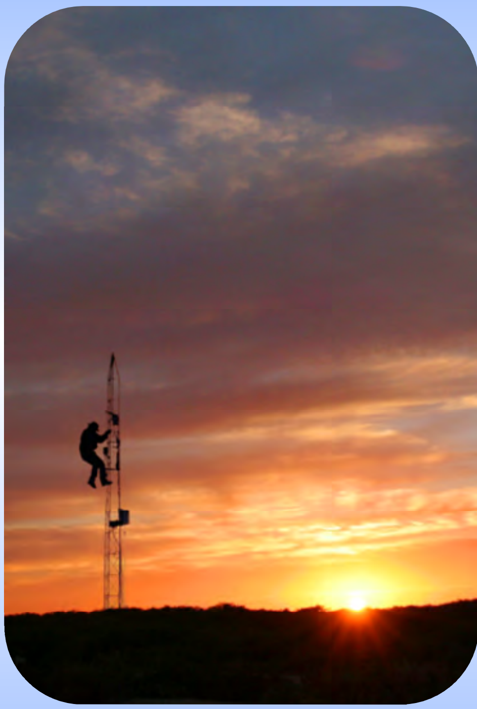
There are several groups in the FluxNet and other networks who work specifically in complex terrains, and have became experts in this area of the Eddy Covariance method.

McMillen, R.T. 1988. 'An eddy correlation technique with extended applicability to non-simple terrain', Boundary Layer Meteorology, 43, 231-245.

Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

Raupach, MR, Finnigan, JJ. 1997. The influence of topography on meteorological variables sand surface-atmosphere interactions. Journal of Hydrology, 190:182-213

SUMMARY OF EDDY COVARIANCE THEORY



- Measures fluxes transported by eddies
- Requires turbulent flow
- Requires state-of-the-art instruments
- Calculated as covariance of w' and c'
- Many assumptions to satisfy
- Complex calculations
- Most direct way to measure flux
- Continuous new developments

Eddy Covariance is a method to measure vertical flux of heat, water or gases. Flux is calculated as a covariance of instantaneous deviations in vertical wind speed and instantaneous deviations in the entity of interest.

The method relies on the prevalence of the turbulent transport, and requires state-of-the-art instruments. It uses complex calculations, and utilizes many assumptions. However, it is the most direct approach for measuring fluxes. It is rapidly developing its scope and standards, and has promising perspectives for future use in various natural sciences, carbon sequestration studies, industrial and monitoring applications, *etc.*

This page is the end of the section on the Eddy Covariance Theory Overview. The practical workflow for the Eddy Covariance method follows.

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 1. Experimental Design

EDDY COVARIANCE WORKFLOW

- Eddy Covariance method workflow is a challenge
- Mistakes in experimental design and implementation may render data worthless, or lead to large gaps
- Mistakes during data processing are not as bad, but require re-calculations

Proper execution of the workflow is perhaps the second biggest challenge for a novice, after mastering the theoretical part of the Eddy Covariance method.

Oversights in experimental design and implementation may lead to collecting bad data for a prolonged period of time, or could result in large data gaps. These are especially undesirable for the integration of the long-term data sets, which is the prime goal for measuring fluxes of carbon dioxide, methane or other greenhouse gases.

Errors in data processing may not be as bad, as long as there is a back-up of the original raw data files, but they also can lead to time-consuming re-calculations, or to wrong data interpretation.

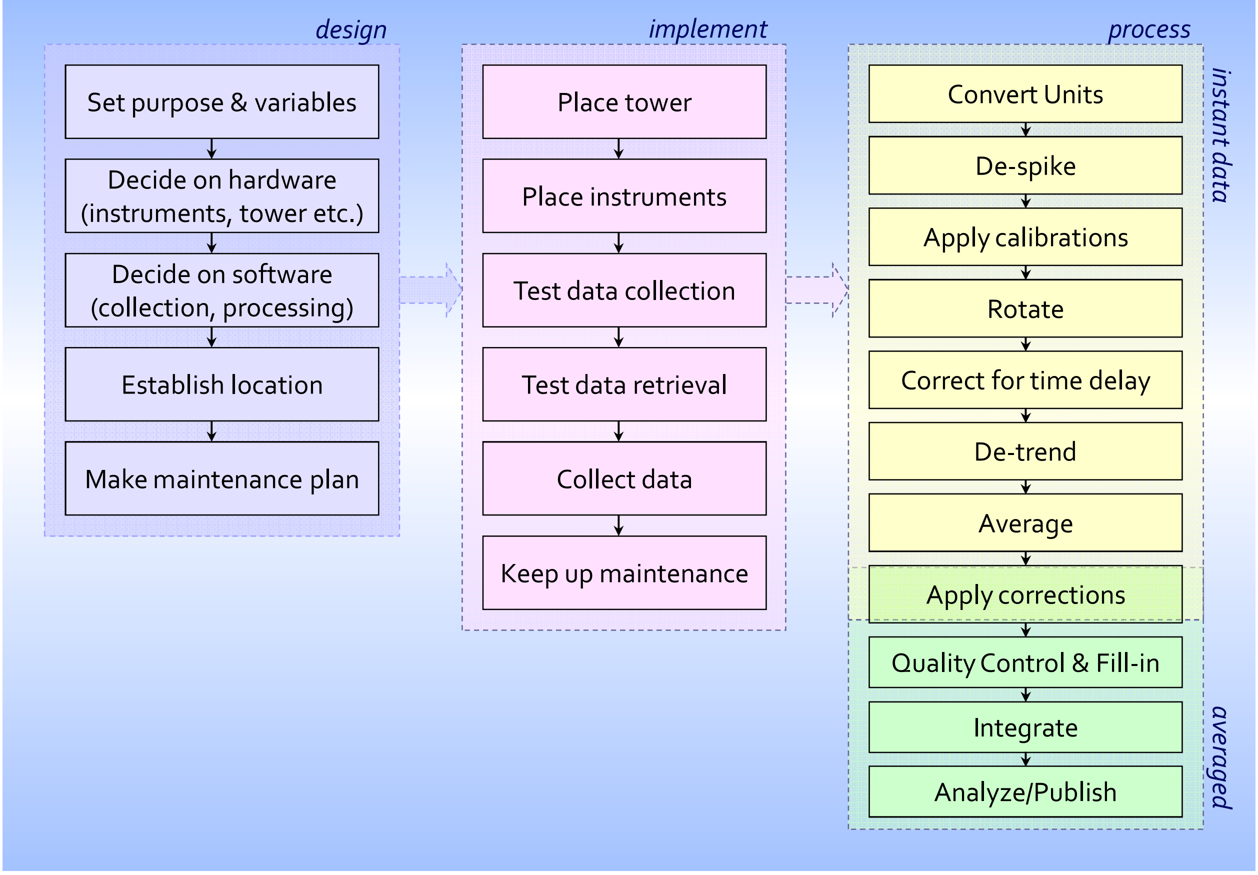
There are several different ways to execute the Eddy Covariance method and get substantially the same result. Here we will give an example of one traditional sequence of actions needed for successful experimental setup, data collection, and processing.

This sequence may not fit your specific scientific goal, but it will provide a general understanding of what is involved in Eddy Covariance study, and will points out the most difficult parts.

The Eddy Covariance workflow is the largest portion of this guide.

It is extremely important to always keep and store original 10Hz or 20Hz data, collected using Eddy Covariance method. This way data can be reprocessed at any time using, for example, new frequency response correction methods, or correct calibration coefficients. Some of the processing steps cannot be confidently recalculated without the original high-frequency data.

TYPICAL WORKFLOW EXAMPLE



There are several different ways to execute the Eddy Covariance method and get substantially the same result. Here we give an example of one traditional sequence of actions needed for successful experimental setup, data collection, and processing. One can break the workflow into three major parts: design of the experiment, implementation, and data processing.

The key elements of the design portion of Eddy Covariance experiments are: setting the purpose and variables for the study, deciding on the instruments and hardware to be used, creating new or adjusting existing software to collect and process data, establishing appropriate experiment location and a feasible maintenance plan.

The major elements of the implementation portion are: placing the tower, placing the instruments on the tower, testing data collection and retrieval, collecting data, and keeping up the maintenance schedule.

The processing portion includes: processing the real time, "instant" data (usually at a 10-20 Hz sample rate), processing averaged data (usually from one half to two hours), quality control, and long-term integration and analysis.

The main elements of data processing include: converting voltages into units, de-spiking, applying calibrations, rotating the coordinates, correcting for time delay, de-trending if needed, averaging, applying corrections, quality control, filling in the gaps, integrating, and finally, data analysis and publication.

pp.8-18 in http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf - Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003.

http://www.geos.ed.ac.uk/homes/rclement/PHD Clement R. 2004. Mass and Energy Exchange of a Plantation Forest in Scotland Using Micrometeorological Methods.

EXPERIMENTAL DESIGN

- Purpose and Variables
- Hardware
  - Instrument Requirements
  - Overall Instrumentation
  - LI-7500A
  - LI-7200
  - LI-7000
  - LI-7700
  - Auxiliary Measurements
- Software
- Location
- Maintenance plan

Setting the scientific purpose for the experiment will help to determine the list of variables needed to satisfy that purpose. Variables, in turn, will help to determine what instruments should be used, and what measurements should be conducted and how.

The scientific purpose may also help to determine the requirements for the specific site, location of the tower within the site, and instrument placement at the tower.

Once the scientific purpose is adequately defined, data collection and processing programs can be written or adjusted to accommodate the previously outlined steps, and to process the data.

PURPOSE AND VARIABLES

- Eddy Covariance is a statistical way to compute turbulent fluxes, and can be used for number of different purposes
- Each experimental purpose may require particular settings and a list of variables for computing and correcting fluxes of interest
- Researchers should be aware of the particular requirements, make a list of required variables, and plan accordingly for each project

Eddy Covariance is a statistical method to compute turbulent fluxes, and it can be used for many different purposes. Each experimental purpose will require unique settings and a different list of variables that will be needed for computing and correcting the fluxes of interest. The researcher should be keenly aware of the particular requirements for their experiment, make a list of the variables required, and plan accordingly to insure sufficient accuracy and resolution required for the data analysis.

For example, if the main interest of the experiment is in turbulence characteristics of the flow above the wind-shaken canopy, one may not need to collect water and trace gas data, but may need to collect higher frequency (20+ Hz) wind components and temperature data. Instruments may need to be placed on several different levels, including those very close to the canopy.

On the other hand, if one is interested in the response of the evaporation from an alfalfa field to the nitrogen regime, there may not be a need for profiles of atmospheric turbulence, and 10 Hz data may be good enough for sampling. However, such a study would definitely require instantaneous measurements of water vapor along with sonic measurements well above the canopy, but within the fetch for the studied field.

Another example is computing CO_2 net ecosystem exchange. This may require not only instantaneous wind speed and CO_2 concentration measurements, but also latent and sensible heat flux measurements (for Webb-Pearman-Leuning term), mean temperature, mean humidity and mean pressure (for unit conversions and other corrections).

Mean CO_2 concentration profiles would also be highly desirable for computing the CO_2 storage term.

INSTRUMENT REQUIREMENTS

Air flow can be imagined as a horizontal flow of numerous rotating eddies of different sizes distributed by measurement height:

Lower to the ground – small eddies prevail and transfer most of the flux
Higher above the ground – large eddies prevail and transfer most of the flux

Small eddies rotate at high frequencies, and larger ones rotate slowly

Good instruments should be made universal:

- Sample fast enough to cover all required frequency ranges
- Be very sensitive to small changes in quantities
- Not break large eddies with bulky structure for accurate measurement
- Not create many small eddies with set-up structure
- Not average small eddies by large sensing volume
- Be practical in terms of maintenance, power consumption and weight

Tower should not be too bulky to obstruct the flow or shadow the sensors

Air flow can be imagined as a horizontal flow of numerous rotating eddies of different sizes roughly distributed over the measurement height. Lower to the ground small eddies usually prevail, and they transfer most of the flux. Higher above the ground large eddies transfer most of the flux. Small eddies rotate at very high frequencies, and large eddies rotate slowly.

For these reasons, good instruments to use for Eddy Covariance need to be "universal". They need to sample fast enough to cover all required frequency ranges, but at the same time they need to be very sensitive to small changes in quantities. Instruments should not break large eddies with a bulky structure so they can measure accurately at great heights, and they should be aerodynamic enough to minimize the creation of many small eddies from the instrument structure so they can measure accurately at low heights.

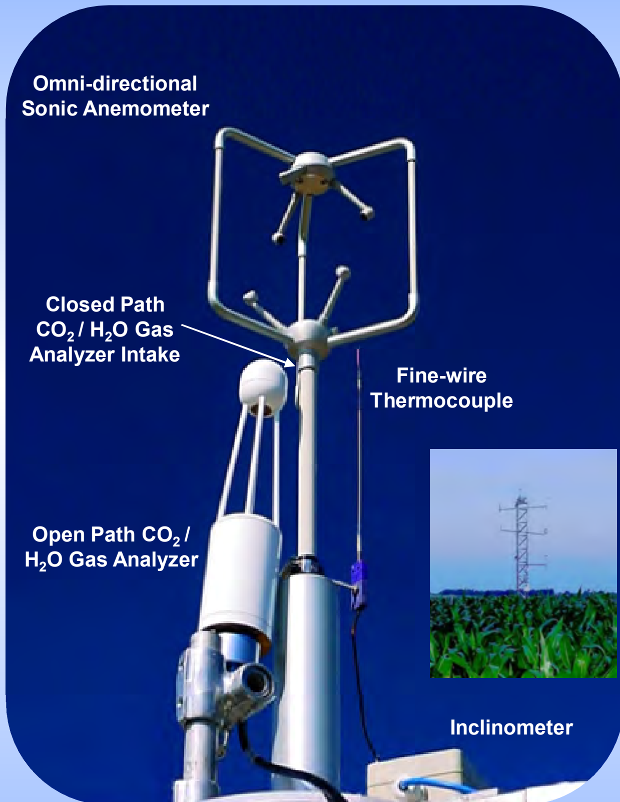
They should not average small eddies by using large sensing volumes, and should be practical in terms of maintenance, power consumption and weight.

The tower and instrument installation should not be too bulky, so as to avoid obstructing the flow or shadowing the sensors from the wind.

Foken, T. and Oncley, S.P., 1995. Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'. Bulletin of the American Meteorological Society, 76:1191-1193

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute
http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

EDDY COVARIANCE INSTRUMENTATION



The instrumentation shown in this image is a typical example of an Eddy Covariance installation, with a 3-dimensional sonic anemometer, an open-path gas analyzer, sample inlet for a closed-path gas analyzer, and a fine-wire thermocouple.

The gas and temperature sensors should be positioned at or below the sonic anemometer. The horizontal separation between the sonic and other sensors should be kept to a minimum, preferably not exceeding 10 to 15 cm. Instrument arrangement should also minimize distortion of the flow going into the sonic anemometer. In the case of the open path gas analyzer, the sensor head can be slightly tilted to minimize the amount of precipitation accumulating on the windows.

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute
http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

MEASUREMENT PRINCIPLES

$$F_c = \overline{w'\rho_c'}$$

where w is in (m s^{-1}), and ρ_c is in (mg m^{-3})

$$F_c = (\text{m s}^{-1}) \times (\text{mg m}^{-3}) = \text{mg m}^{-2}\,\text{s}^{-1}$$

Sonic Anemometer

- Uses difference in time it takes for an acoustic signal to travel the same path in opposite directions
- Gill Instruments, ATI, CSI, Metek, Koshin-Denki, R.M. Young, *etc.*

Gas Analyzer

- Non-dispersive infrared (NDIR) sensor
  - broadband infrared beam transmitted through cell, with absorption band of 4.26 µm for CO_2 & 2.59 µm for H_2O
  - beam is modulated to distinguish it from the background using a chopper wheel
- Narrow-band or single line LASER analyzer

A sonic anemometer measures the speed of sound in air using a short burst of ultrasound transmitted via a transducer. Another transducer then picks up the reflections of the sound. The delay between the transmitted burst time and the received time can be converted to the speed of sound if the distance between transducers is known. Such perceived speed of sound is actually the speed of sound in static air plus or minus the speed of the wind. In other words, the wind speed causes the difference between the measured speed of sound and the actual speed of sound. The speed of sound in static air is well-known, and depends mostly on the temperature, and to a lesser extent, on humidity and gas mixture. Sonic temperature can also be calculated from the speed of sound measured by the anemometer.

Modern fast-response instruments measuring carbon dioxide and water vapor densities utilize absorption of radiation in the infrared region of the electromagnetic spectrum.

Also, laser analyzers are becoming available to measure CH_4 and other gases at the sampling rates and with resolution sufficient for Eddy Covariance application.

Examples of CO_2 and H_2O NDIR gas analyzers include the LI-COR LI-7200, LI-7500A, and LI-7000. An example of a fast CH_4 laser analyzer is the LI-7700.

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute
http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

SONIC ANEMOMETERS

- Proper installation, leveling and maintenance are important
- Should be installed on firm base facing prevailing wind direction
- Each instrument reacts differently to light rain events, but none of the instruments produce accurate readings in heavy precipitation
- Rain, dew, snow and frost on the sonic transducer may change path length to estimate speed of sound and lead to small errors

Proper installation, leveling and maintenance are important for sonic anemometers. This includes maintaining a constant orientation to minimize angle of attack errors and keeping the transducers clean to minimize sonic errors. Each instrument model reacts differently to light rain events, but none of the instruments produce accurate readings in heavy precipitation.

Rain, dew, snow and frost on the sonic transducer may change path length to estimate speed of sound and lead to small errors. The instrument should also be installed on a firm support facing the mean wind direction to minimize vibration and flow distortion.

The key producers of sonic anemometers are:

Gill Instruments - http://www.gill.co.uk/
ATI - http://www.apptech.com
CSI - http://www.campbellsci.com
Metek - http://www.metek.de/
Koshin-Denki - http://www.koshindenki.com
R.M. Young - http://www.youngusa.com

An example of instructions for sonic anemometer setup and operation can be found here: http://www.campbellsci.com/documents/manuals/opecsystem.pdf CSI, Inc. 2004-2006. Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH_2O.

OPEN PATH VS. CLOSED PATH

	Open Path LI-7500A LI-7700 (CH_4)	Enclosed LI-7200	Closed Path LI-7000
Flux losses are due to	spatial separation	very small frequency dampening	frequency dampening
Cell cleaning	easy, user and/or auto cleanable	easy, user cleanable	moderately easy, user cleanable
Loss during precipitation	often limited by anemometer and analyzer design, may be high	limited by anemometer	limited by anemometer
Power	8-15 W	27 W	50 W (10W + 40 W pump)
Calibration	weeks to months, manual	weeks to months, manual or automated	24-48 hours, can be automated

The choice of an open-path versus an enclosed design versus a closed-path sensor is largely a function of power availability and frequency of precipitation events.

Closed-path gas analyzers require the sample air to be mechanically drawn to the sample cell by means of a high flow rate air pump, thus increasing system power requirements. The limiting factors in closed-path installation are the capability of the sonic anemometer to operate during precipitation events, and loss of flux due to tube attenuation.

Enclosed analyzers (such as LI-7200) may be treated as a specific case of a closed-path approach, but are designed to be used with short intake tubes, thus minimizing tube attenuation, WPL correction, and power consumption, without incurring susceptibility to precipitation-related data loss.

The open-path analyzer measures *in situ* gas. No external air pump is required, thus reducing power consumption. Open path analyzers' flux losses are largely due to spatial separation between the sonic and the open path analyzer and due to rain events. Flux calculations based on *in situ* density measurement require significant density corrections.

In the next pages we will go through all major instrument types using LI-COR gas analyzer models as examples.

OPEN-PATH LI-7500A CO_2/H_2O ANALYZER

- New 2010 model for CO_2 and H_2O fluxes
- Based on widely used LI-7500 design
- Modified to produce substantially less heat and to consume less power during extremely cold conditions
- Includes fast logger for sonic anemometer data and gas analyzer data collection
- Optimized for remote and mobile flux measurements: extremely low power and light

The LI-7500A is a high speed, high precision, non-dispersive infrared gas analyzer that accurately measures densities of carbon dioxide and water vapor *in situ*. With the eddy covariance technique, these data are used in conjunction with sonic anemometer wind speed to determine the fluxes of CO_2 and H_2O into and out of ecosystems, and other areas.

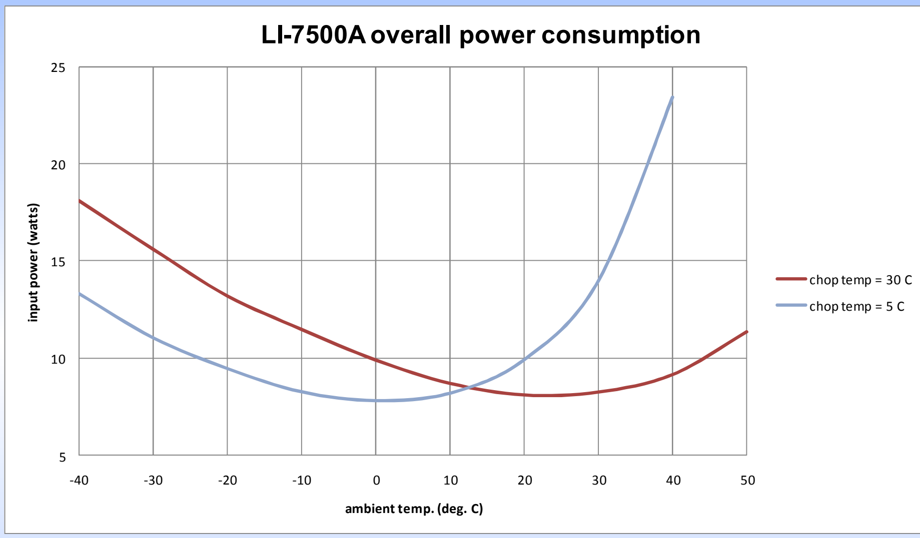
The LI-7500A is a new model of open-path CO_2/H_2O gas analyzer, based on the older LI-7500 model which was modified to produce substantially less heat and reduce power consumption during extremely cold conditions.

The new LI-7500A also includes a stand-alone logging system, the LI-7550, to collect sonic anemometer data alongside the CO_2 and H_2O data. The LI-7550 accepts high-speed analog data (±5V) from a 3-D sonic anemometer and logs complete data sets to a removable USB storage device.

The LI-7550 is a part of the LI-7500A instrument, and has a weatherproof enclosure to house the control unit's high speed Digital Signal Processing (DSP) electronics.

Ethernet and Serial data are output at selectable speeds of up to 20 Hz, and linearized user-configurable Digital-to-Analog Converters (DACs) output analog signals at up to 20 Hz bandwidth. The LI-7550 also offers SDM communication for use with CSI data loggers. Direct PC logging of LI-7550A and sonic data is also available.

LI-7500A 5°C TEMPERATURE CONTROL



- Two user selectable chopper housing settings help to keep power dissipation from the instrument in single Watts
- Electronics heating of the window surfaces is a small fraction of total power coming to the instrument

The LI-7500A software allows users to manually set the chopper housing temperature at two settings: a low temperature setting of +5 °C, and regular setting of +30 °C. The low temperature setting was added for studies in cold climates to reduced energy usage and heat dissipation in extremely cold environments.

Field tests showed that both external heat dissipation and the system power demand were significantly reduced when +5 °C setting was activated under extremely cold conditions. Please see section on Surface Heating Correction for details on the advantages of the 5 °C setting.

LI-COR recommends changing to the +5 °C setting only when the average ambient temperature drops below +5 °C; you can change the setting again to +30 °C when the average ambient temperature is above +5 °C.

Note, however, that the instrument will still function properly when the chopper motor housing temperature is set to +30 °C, even when temperatures are below +5 °C.

When changing between winter and summer settings, you will need to perform a zero and dual span user calibration.

Do not set the chopper housing temperature to +5 °C when ambient temperatures are above +5 °C, as the instrument may not function properly.

LI-7500A SPECIFICATIONS

Type: Absolute, open-path, non-dispersive infrared analyzer

Detector: Thermo-electrically cooled lead selenide

Bandwidth: 5, 10, or 20 Hz, software selectable

Path Length: 12.5 cm (4.72")

Operating Temperature Range: -25 to +50 C (-40 to 50 C by request)

Outputs: Ethernet, RS-232, SDM, (6) DAC (0 to +5V DC)

Inputs: Ethernet, 4 general purpose 5 V high speed analog inputs

Power Requirements: +10.5 to +30 VDC

Power Consumption: 30 W during warm-up, 12 W in steady state

Power Saving Mode: +5 C (winter) & +30 C (summer) software selectable

Head: 6.5 x 30 cm; designed for minimal flow disturbance; 0.75 kg (1.65 lb.)

Control Box: 35 x 30 x 15 cm; 4.4 kg (10 lbs.)

IRGA cable: 5 m standard, 10 m available

Power, Serial, DAC, Auxiliary Input and SDM cables: 5 m

The specifications for the LI-7500A are similar to the widely-used LI-7500 analyzer, and are shown at the top of this page. Designed specifically for Eddy Covariance applications, this instrument makes sensitive open-path high speed measurements of *in situ* densities of CO_2 and H_2O vapor. A wide operating temperature range allows for deployment in any of the world's ecosystems, or other areas, and data collection interfaces have been optimized for computers and rugged data loggers (e.g., LI-7550).

Key Features

- Software Selectable Power Saving Modes: +5 $^{\circ}$C (winter) +30 $^{\circ}$C (summer)
- Low power consumption: 15 W during normal operation
- High speed: up to 20Hz bandwidth
- High precision: 0.11 ppm CO_2, 0.0047 ppt H_2O
- Absence of tubing eliminates delays and sorption effects
- No signal attenuation for CO_2/H_2O
- Suitable for harsh environments

Further details on the specifications of LI-7500A, additional information, updates and downloadable software can be found at the LI-COR LI-7500A website:

http://www.licor.com/env/Products/GasAnalyzers/li7500A/7500A.jsp

LI-7500A PERFORMANCE

CO_2		µmol mol^{-1}	mmol m^{-3}†	mg m^{-3}†
Calibration range		0 - 3000	0 - 117	0 - 5148
RMS noise at ambient (370 ppm) PSD* = 35 ppb/$\sqrt{Hz}$ typical 70 ppb/$\sqrt{Hz}$ max.	Bandwidth: 5 Hz 10 Hz 20 Hz	 0.08 0.11 0.16	 0.0031 0.0043 0.0061	 0.13 0.19 0.27
Zero drift with temperature (per C)	Maximum± Typical±	0.3 0.1	0.012 0.004	0.5 0.2
Gain drift with temperature at 370 ppm (% of reading per C)	Maximum± Typical±		0.1% 0.02%	
Direct sensitivity to H_2O (mol CO_2/mol H_2O)	Maximum± Typical±		4.00E-05 2.00E-05	
H_2O		**mmol mol^{-1}**	**mmol m^{-3}†**	**g m^{-3}†**
Calibration range		0 - 60	0 - 2340	0 - 42
RMS noise in moist air (10 mmol mol^{-1}) PSD* = 1.5 ppm/$\sqrt{Hz}$ typical 2.5 ppm/$\sqrt{Hz}$ max.	Bandwidth: 5 Hz 10 Hz 20 Hz	 0.0034 0.0047 0.0067	 0.13 0.18 0.26	 0.0024 0.0033 0.0047
Zero drift with temperature (per C)	Maximum± Typical±	0.05 0.03	2 1	0.04 0.02
Gain drift with temperature at 20 mmol mol^{-1} (% of reading per C)	Maximum± Typical±		0.3% 0.15%	
Direct sensitivity to CO_2 (mol H_2O/mol CO_2)	Maximum± Typical±		0.05 0.02	

The resolution and performance of the LI-7500A has been optimized for Eddy Covariance applications.

The LI-7500A is a single beam tri waveband gas analyzer. It has a single optical path, and continuously alternates between absorbing and non-absorbing wavelengths passing through the sample path using a chopper wheel rotating at 150 times per second to modulate the IR source. Digital signal processing techniques demodulate the signal and convert the raw values into number density.

Overall details on the performance of the LI-7500A can be found at the LI-COR LI-7500A web-site:

http://www.licor.com/env/Products/GasAnalyzers/li7500A/7500A.jsp

LI-7500A FLUX APPLICATIONS

TERRESTRIAL	AIRBORNE	OCEANOGRAPHIC
98% of applications	<1% of applications	< 1% of applications
Designed for stationary use	May need customized reinforcement	May need customized coating, LPS3
Limited by precipitation, fog, & dew	May be affected by extreme temperatures and vibrations	May be affected by precipitation, dew, & gyroscopic effects

A majority of the LI-7500A applications are focused around terrestrial flux applications and widely used by flux networks. Though such applications are usually not associated with vibration issues, airborne and oceanographic installations can experience severe vibration.

It is important to know that the LI-7500A is vibration sensitive at frequencies of 152 Hz ± the bandwidth. Thus, if the bandwidth is 10Hz, the problematic frequency range will be 142 to 162 Hz (and upper harmonics). The instrument is nearly completely insensitive to vibrations slower than this, and only very slightly sensitive to vibrations higher than this.

In land-based installations, a potential source of vibrations can be a lightweight, tall tower with tight guy wires attached at the top. Vibration can be minimized by a larger number of guy wires including ones attached at the middle of the tower. In other settings (aircraft, ships, etc.) vibration can be minimized through appropriate compensating and mounting attachments.

Additional information, updates and downloadable software can be found at the LI-COR LI-7500A website:

http://www.licor.com/env/Products/GasAnalyzers/li7500A/7500A.jsp

Details on the specific topic related to use of LI-7500 can also be found in the LI-7500 manual:

ftp://ftp.licor.com/perm/env/LI-7500A/LI-7500A_Manual.pdf

LI-7500A CALIBRATION

- Factory determined calibration coefficients are good for years
- The zero and span settings make the analyzer's response agree with its previously determined factory response at a minimum of two points
- Calibration requires manual interaction because shroud must be inserted into optical path

Factory determined polynomial calibration coefficients are usually good for several years. However, periodic setting of zero and span is recommended to make sure the instrument performs correctly.

The zero and span settings make the analyzer's response agree with its previously determined factory response at a minimum of two points. The calibration requires manual interaction because a shroud must be inserted into the optical path.

Calibration gases of 1% accuracy can often be obtained without too much difficulty; for higher accuracy the user should obtain WMO standards that are within the range of concentrations to be encountered during experimental measurements. It is recommended that the user keep these WMO gases as primary standards for checking less expensive working gas calibration tanks.

For H_2O, you are constrained by the temperature of the air. You would normally choose a very low dew point, such as 5 °C, and something close to (just below) ambient. If the air temperature is 15 °C or less, you should probably avoid doing a secondary span.

Further details on calibration of the LI-7500A can be found in the LI-7500A manual:

http://www.licor.com/env/Products/GasAnalyzers/li7500A/7500A.jsp

LI-7500A SAMPLING FREQUENCY

- Sample at a rate twice the frequency of physical significance of data to avoid aliasing
- LI-7500A signals are available at 300 Hz for DAC, >50 Hz for SDM and 20 Hz for RS-232 and Ethernet
- Bandwidth setting of 5, 10 or 20 Hz means minimum sampling rate of 10, 20 and 40 Hz respectively

It is generally recommended to sample at a rate twice the frequency of physical significance of the data to avoid aliasing. Sampling at a rate of 10 or 20 Hz is usually adequate for most land applications, while higher frequencies may be required for airborne applications and in special circumstances (e.g., at very low heights, understory, etc.).

Bandwidth (5, 10 or 20 Hz) determines the signal averaging done by the digital filter. Since one should sample the LI-7500A at a frequency greater than or equal to 2 times the bandwidth, if you are sampling at 10 Hz, set Bandwidth to 5 Hz.

Bandwidth is the frequency at which the indicated amplitude is 0.707 of the real amplitude. Bandwidth is a useful indicator for characterizing real-world behavior in which there are fluctuating gas concentrations. Given a sinusoidal oscillation of concentration, the instrument's ability to measure the full oscillation amplitude diminishes as the oscillation frequency increases.

The bandwidth selection has no impact on the system delay. The filters were designed so they have exactly the same delay whether a 5, 10, or 20 Hz signal bandwidth is selected.

To accommodate a wide range of potential uses, The LI-7500A signals are available at 300 Hz for DAC, >50 Hz for SDM, and 20 Hz for RS-232 and Ethernet connections.

Bandwidth setting of 5, 10 or 20 Hz indicates a minimum sampling rate of 10, 20 and 40 Hz respectively.

OPEN PATH LI-7700 CH_4 GAS ANALYZER

- New 2010 model for CH_4 flux measurements
- Break-through technology to reduce power demands 40-150 times below present technologies
- Ethernet output to any Ethernet device
- Compatible with fast logger for sonic anemometer and gas analyzer data collection
- Optimized for remote and mobile flux measurements: extremely low power and lightweight

Methane is considered the most important greenhouse gas after H_2O and CO_2, and has a global warming potential (GWP) about 23 times that of CO_2 over 100-year cycle (Houghton et al., 2001).

Prior measurements of CH_4 fluxes have mostly been made with chambers, and with Eddy Covariance approach via closed-path analyzers.

Both chambers and closed-path analyzers have their advantages. However, chamber measurements are discrete in time and space, may disturb soil surface integrity and atmospheric pressure, and often are labor-intensive.

Present closed-path analyzers work under significantly reduced pressures, and require powerful pumps and commercial grid power. Long intake tubes lead to frequency losses.

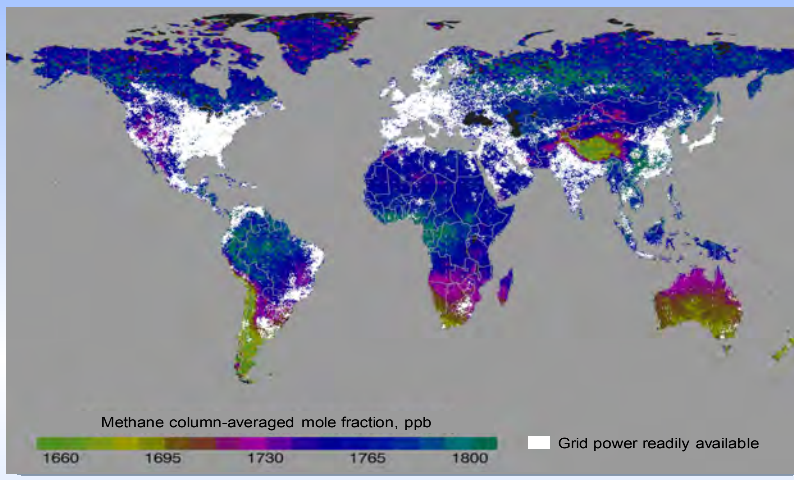
Power and labor demands may be reasons why CH_4 flux is often measured at locations with good infrastructure and grid power, and not with high CH_4 production.

The LI-7700 is an open-path CH_4 gas analyzer which allows Eddy Covariance measurements of CH_4 flux with power consumption 40-150 times below presently available technologies. This design gives the following key advantages for CH_4 flux studies:

- remote solar-powered deployment due to low power demand
- portable or mobile deployments due to light weight
- undisturbed *in situ* spatially integrated flux measurements
- zero frequency response errors from tube attenuation
- measurements at any location of interest regardless of available infrastructure

http://www.licor.com/env/Products/GasAnalyzers/li7700/7700.jsp

IMPORTANT IMPLICATIONS OF LI-7700 DESIGN



NASA and SCHIAMACHY

- Most of natural CH4 production happens in remote areas with little infrastructure and no grid power
- Design, low power consumption, and light weight of LI-7700 make it simple to measure Eddy Covariance fluxes of CH4 in the middle of the area of interest, without the need for power lines or roads

Low-power and lightweight configurations of the LI-7700 provide a new and unique opportunity for measuring natural, agricultural, and other CH_4 production where it actually occurs, rather than measuring it where power grid and roads are available

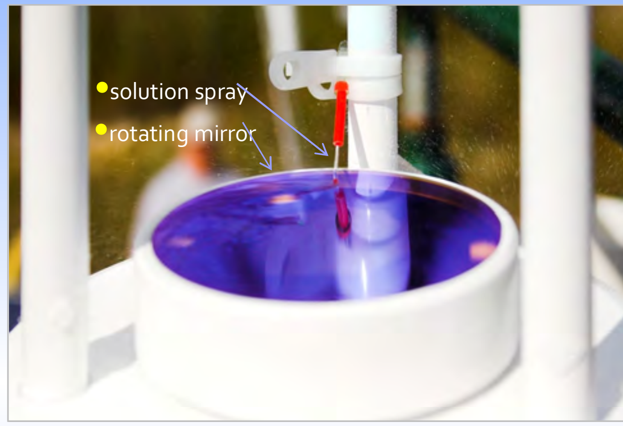
The LI-7700 CH_4 fast open-path analyzer uses 8 Watts of power, and can easily be run on solar panels, or with small portable generator, while present technologies require 300-1500Watts of the grid power.

This extremely low-power technology will allow the placement of methane Eddy Covariance stations in the middle of the source (wetland, rice paddy, forest, landfill, *etc.*) in the absence of grid power.
This can significantly expand the Eddy Covariance CH_4 flux measurements coverage, and possibly, significantly improve the budget estimates of world CH_4 emissions and budget.

For example, the consumption by entire open-path Eddy Covariance station in Florida Everglades was <30 Watts, including LI-7700 for CH_4, LI-7500 for CO_2/H_2O, sonic anemometer, and air temperature/relative humidity sensors and barometer.

The 12 lb. (5.5 kg) open-path methane analyzer was carried into the wetland by one person in a backpack, along with tools, other sensors, and a laptop.

OPEN-PATH LI-7700 FEATURES



- Field maintenance is minimized by a self-cleaning lower mirror to help keep it contamination-free

The LI-7700 uses WMS (Wavelength Modulation Spectroscopy) technology that employs a VCSEL (vertical-cavity surface-emitting laser) and an open multi-pass cell design.

CH_4 is measured with a RMS noise below 5 ppb at 10 Hz sampling in controlled laboratory conditions.

LI-7700 provides CH_4 outputs with frequencies up to 40 Hz. The air temperature in the sampling path and fast atmospheric pressure are also measured.

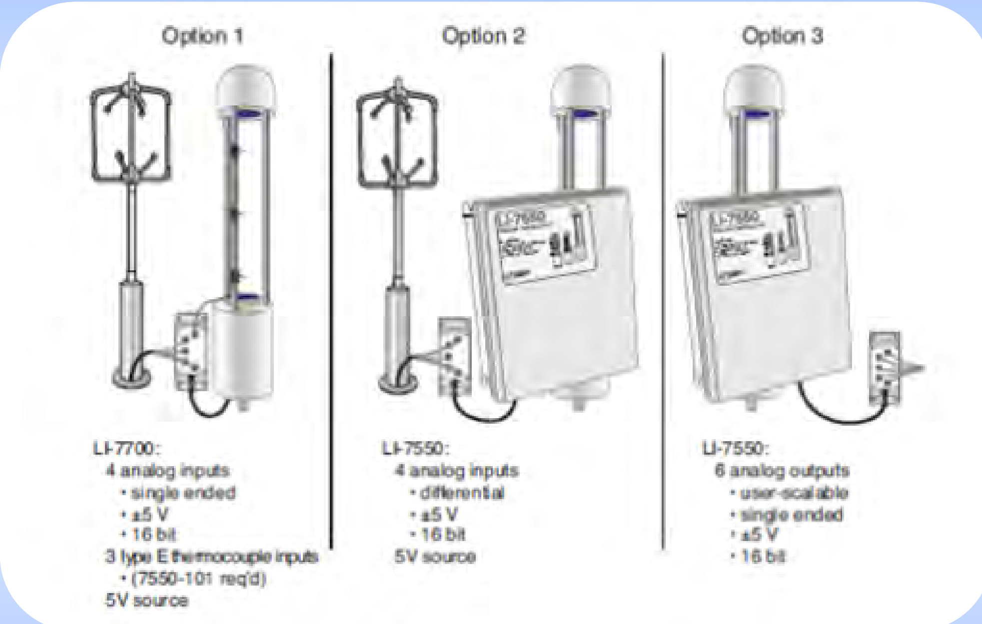
Four fast auxiliary input channels are available for sonic anemometer outputs or for any desired fast or slow data. Seven additional fast channels and USB data logging are available with an optional LI-7550 Analyzer Interface Unit.

Field maintenance is minimized by a fully-programmable self-cleaning mechanism for the lower mirror. Dew formation on both mirrors is solved by fully programmable heaters. Also, a radiation shield is provided to minimize condensation and power demands.

The stand-alone power consumption of LI-7700 is about 8 Watts in steady-state and 12 Watts during warm-up.

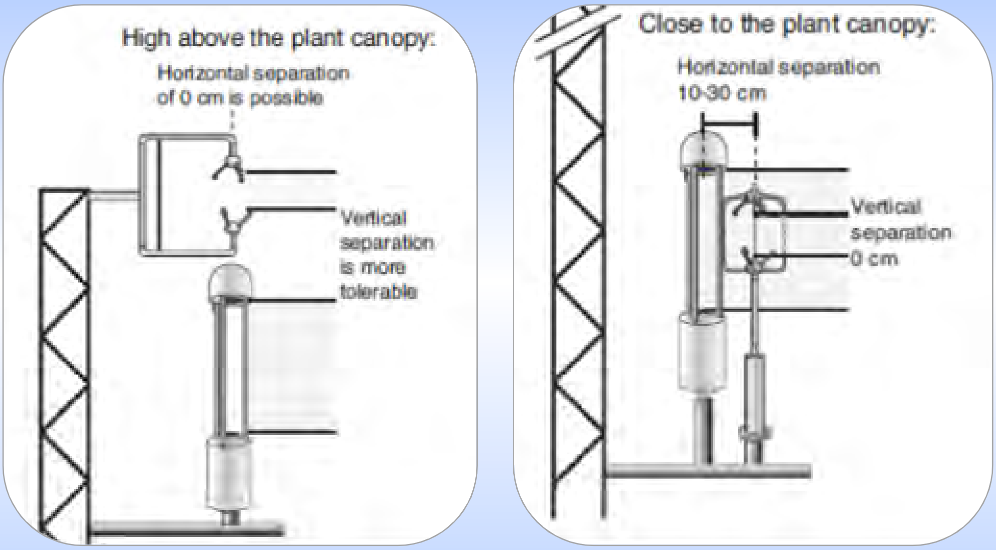
http://www.licor.com/env/Products/GasAnalyzers/li7700/7700.jsp

OPEN-PATH LI-7700 SPECIFICATIONS



- Resolution (RMS noise): 5 ppb at 10 Hz and 2000 ppb CH_4
- Measurement Range: 0 to 50 ppm
- Data Communication: Ethernet (up to 40 Hz)
- Operating Temperature Range: -25 °C to 50 °C
- Operating Pressure Range: 50 to 110 kPa
- Detection method: Wavelength Modulation Spectroscopy, 2f Detection
- Accuracy: <1% of reading nominal; dependent upon calibration standards
- Power Requirements: 10.5 to 30 VDC
- Power Consumption: 8 W nominal, 16 W during cleaning cycle
- Dimensions: Sensor: 14.33 cm dia (5.64 in), 82.8 cm height (32.6 in.)
- Optical Path: 0.5 m physical path (1.65 ft), 30 m measurement path (98.4 ft)
- Weight: 5.2 kg (11.5 lbs)
- Calibration Range: 0-40 ppm @ 25 °C 0-25 ppm @ -25 °C
- Linearity: Within 1% of reading across full calibration range

OPEN-PATH LI-7700 INSTALLATION



The LI-7700 is designed to fit easily into existing or new eddy covariance flux stations. As such, there are numerous factors to take into account when deploying the LI-7700. Addressing these concerns appropriately is critical to minimizing required frequency response corrections. The two key items are: instrument height above the canopy and proximity to the sonic anemometer.

For most applications, the LI-7700 and other sensors should never be within the canopy roughness sublayer, as that may violate the assumptions of the eddy covariance flux method. The minimum recommended height above the canopy is 1.0-1.5 m or more, but this will vary.

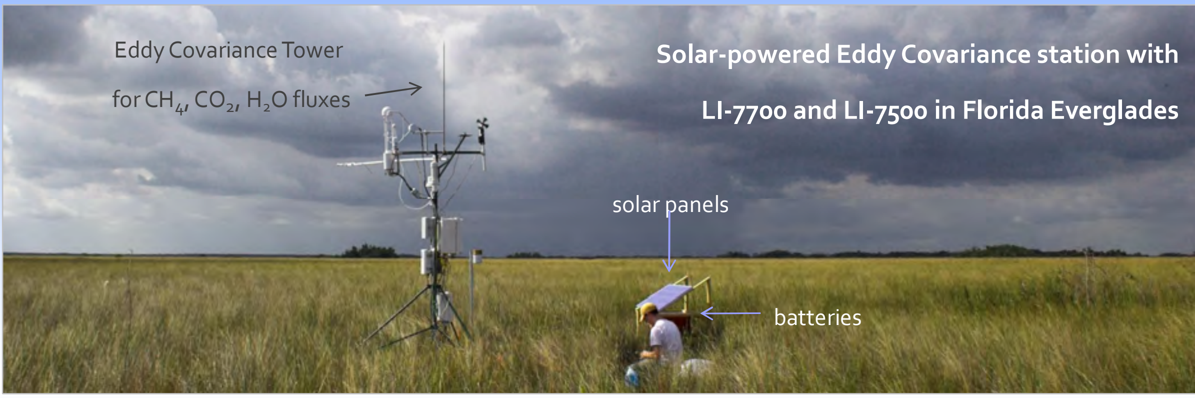
As with all instrumentation in an eddy covariance flux system, the closer to the canopy they are, the closer the instruments must be to each other to minimize frequency response corrections for sensor separation.

For deployments high above the canopy, the LI-7700 should still be as close as is practical to the sonic anemometer, however larger vertical separations are now suitable (with the sonic anemometer above the LI-7700). For example, at heights of 40 meters above the canopy, the anemometer sample path could be above the LI-7700 entirely.

For near surface deployments, the LI-7700 should be 10-30 cm horizontally from the anemometer, and they should have a minimal vertical separation depending on surface roughness and other factors.

It is not recommended putting fast scalar measurements (e.g., gas concentration, thermocouple temperature, humidity) above the vector measurements (e.g., wind from sonic anemometer), as it may lead to errors and may require difficult to predict corrections.

OPEN-PATH LI-7700 CALIBRATION



- The power consumption by the entire Eddy Covariance station in the Florida Everglades was <30 Watts, including LI-7700 for CH_4, LI-7500 for CO_2/H_2O, sonic anemometer, and air temperature/relative humidity sensors and barometer
- The 12 lb. (5.5 kg) open-path methane analyzer was carried into the wetland by one person in the backpack, along with tools, other sensors, and a laptop
- In such remote places occasional calibration checks can be done using small hand-carried gas tanks with known CH_4 concentration and CH_4-free air

The overall accuracy of the LI-7700 depends upon its calibration. Always use quality zero and span gases with CH4 accuracy greater than 1% and 0 ppm Volatile Organic Compounds (VOC free). Check the readings every 6 months.

Zero setting:

1. Connect the LI-7700 to a power supply and a computer running the LI-7700 software. Launch the LI-7700 software and connect to the instrument.

2. Install the calibration shroud. Ensure that it seals around the top and bottom openings.

3. Connect the "zero gas" to the shroud fittings.

4. Flow the desired gas through the shroud. Allow from 10 to 30 minutes for equilibration, depending on flow rate.

5. Click the Zero CH_4 button in the calibration frame. The Zero CH_4 button will change to "Abort". Clicking Abort terminates the zero procedure. It usually takes about 10 seconds to zero.

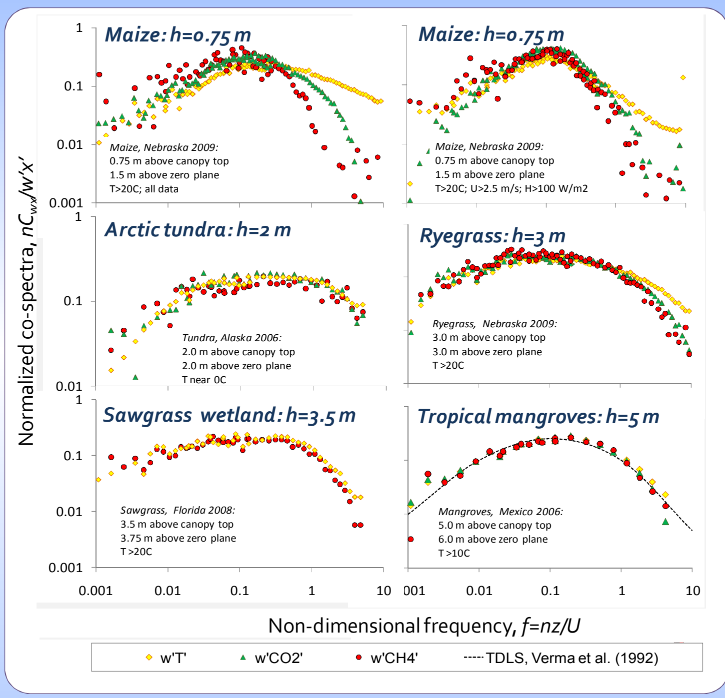
6. When the instrument completes the zero operation, a dialog box will open. You must choose either to apply the new calibration value or revert to the previous calibration value.

Span setting:

Span setting is essentially the same as a zero, except that you must flow the span gas through the optical path and enter the span gas concentration in parts per million (ppm). Once that is done and the span gas concentration is stable, click the Span CH_4 button. The instrument response will be similar to that for setting the zero.

The Factory Reset button in the main view will restore the original factory zero and span settings. Use this only if you attempt to set the zero and span, but are unable to complete the procedure for some reason or another, or if you complete an attempted calibration, but prefer to use the factory zero and span settings.

OPEN-PATH LI-7700 FREQUENCY RESPONSE



As with any new fast instrument, open-path or closed-path, it is important to validate its frequency response, using actual field data, especially if the sampling path is relatively large.

Ensemble averages of normalized midday co-spectra are plotted above versus non-dimensional frequency for 5 contrasting ecosystems and setups.

First, as an ultimate "fidelity" test, we have purposefully put the LI-7700 way too low in relation to the canopy, at 0.75 m above the canopy top.

At such an extremely low measurement height, there was a noticeable high frequency loss as expected. However, with strong turbulence (U>2.5 m s^{-1} and H >100 W m^{-2}), CH_4 flux co-spectra became comparable to that of CO_2 and H_2O flux co-spectra from LI-7500 even at such a low height.

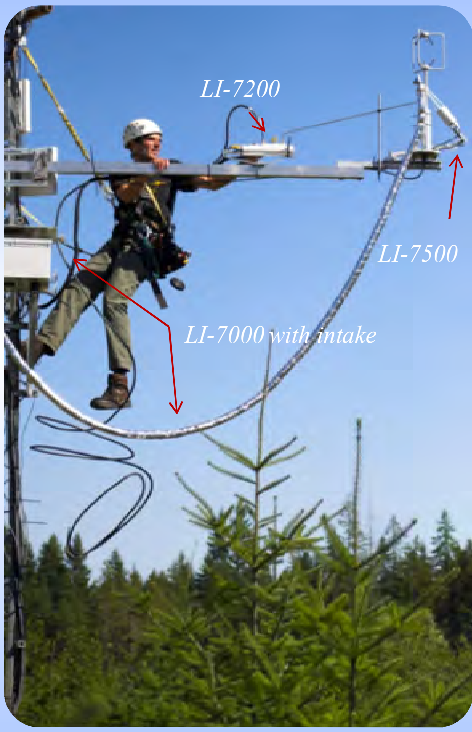
Co-spectral corrections for LI-7700 were still viable at this height, but such low heights are not recommended for Eddy Covariance measurements for any sensor.

In all other experiments with heights exceeding 0.75 m, CH_4 flux co-spectra behaved similar to CO_2 co-spectra from LI-7500, and were close to that of sonic temperature.

The co-spectra from the LI-7700 measurements closely followed the Kaimal model (Kaimal et al., 1972), and also were in good agreement with another cospectrum from TDLS (Unisearch Associates, Inc.) over peat land (Verma et. al., 1992).

At examined measurement heights above 0.75 m, the LI-7700 adequately measured CH_4 fluctuations across the whole spectrum of frequencies which contributed to turbulent transport at different surface roughness and atmospheric stabilities.

ENCLOSED LI-7200 GAS ANALYZER



- New 2010 model for CO_2/H_2O fluxes
- Combines advantages of open-path and closed-path designs
- Eliminates CO_2 and H_2O losses during rain, and any surface heating effects
- Includes fast logger for sonic anemometer and gas analyzer data collection
- Optimized for remote and mobile flux measurements: low power and light

The enclosed concept of a gas analyzer was developed for and is introduced by the LI-7200 analyzer. When used with a long intake tube, the analyzer behaves identically to traditional closed-path analyzers. Yet when used with very short intake tube, the analyzer has some features of open-path gas analyzers. In the next few pages a detailed description and advantages of this new approach is discussed in more detail.

The LI-7200 is a compact closed path CO_2/H_2O analyzer enabled for operation with very short intake tubes. The intake tube can be as short as few centimeters or as long as many meters (similar to LI-7000 and LI-6262), but the optimal length is 0.5m to 1m.

The LI-7200 is specifically designed for Eddy Covariance measurements, intended to maximize strengths and to minimize weaknesses of both traditional open-path and closed-path designs, but it also can be used with any other flux measurement techniques.

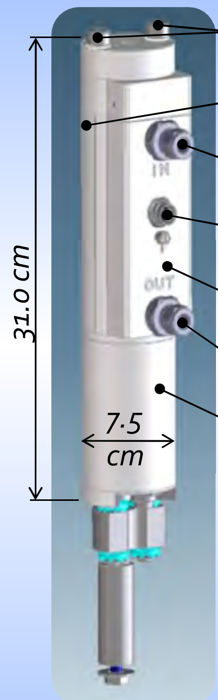
The LI-7200 is based on the absolute NDIR design of the LI-7500; however, it uses a closed-path sampling cell, similar to the LI-7000 and LI-6262. Unlike any previous closed-path instrument, the LI-7200 can be used with a short intake tube because the analyzer is weatherproof and can be mounted on the tower, not on the ground.

Fast temperature and fast pressure of the gas stream are measured at the sampling cell. Fast temperature is measured in two places; just before gas entry into the cell and just after the gas exits from the cell. Fast pressure is measured in the middle of the sampling cell.

Burba, G., D. McDermitt, D. Anderson, M. Furtaw, and R. Eckles, 2010. Novel design of an enclosed CO_2/H_2O gas analyzer for Eddy Covariance flux measurements. Tellus B: Chemical and Physical Meteorology. *Accepted*

http://www.licor.com/env/Products/GasAnalyzers/li7200/7200.jsp

ENCLOSED LI-7200 KEY FEATURES



Lock screws: holds sample cell in place when sampling

Removable cell: no tools required for easy on-tower field cleaning

Cell inlet: can be used with short or long intake tube

IGRA Connector: weather-proof, 5 m or 10 m cable to LI-7550

In-cell fast T and P measurement block

Cell outlet: connects to pump or fan with or w/o buffer

Coupled metal body: keeps sample cell warm and stable

Inside the cell:

- fast T is on inlet and outlet, fast P is in the middle
- cell walls are made of PVC to minimize T gradient
- cell has low sensitivity to dirt; same as LI-7500

The use of a short intake tube and fast temperature and pressure measurements made inside of the cell allow the LI-7200 to use the strengths of both open-path and closed-path designs at the same time. Here are a few key advantages from such a design:

Similar to closed-path analyzers:

(1) minimal data loss due to precipitation and icing (similar to LI-7000 and LI-6262)
(2) no surface heating issues (similar to LI-7000 and LI-6262), as fast cell temperature is measured
(3) possibility of automated calibrations on tower (similar to LI-7000 and LI-6262) with additional hardware
(4) minimal-to-negligible WPL H correction
(5)system can be heated to prevent icing in extremely cold environments

Similar to open-path analyzers:

(1) good frequency response for both CO_2 and H_2O fluxes
(2) small and easily correctable flux attenuation in short intake tube
(3) infrequent calibration requirements (similar to LI-7500A)
(4) minimum maintenance requirements (similar to LI-7500A)
(5) tool-free one-hand cell cleaning on the tower (similar to LI-7500A)
(6) low power configuration when used with a short intake tube
(7) system simplicity, small size, light weight, and weather-proof design

ENCLOSED LI-7200 SPECIFICATIONS

	CO_2	H_2O
Calibration Range	0-3000 ppm	0-60 ppt
Accuracy	1% of reading nominal	Within 2% of reading nominal
Zero drift (per °C)	±.0.1 ppm typical ±0.3 ppm max.	
5 Hz **10 Hz** **20Hz** **RMS noise:** **(typical @370 ppm CO_2 and 10 mmol mol^{-1} H_2O)**	0.08 ppm 0.11 ppm 0.16 ppm	0.0034 ppt 0.0047 ppt 0.0067 ppt
Gain drift **(% of reading per °C)**	±0.02% typical ±0.1% max. @ 370 ppm	±0.15% typical ±0.30% max. @ 20 ppt
Direct sensitivity to H_2O **(mol CO_2/mol H_2O)**	±2.00E-05 typical ±4.00E-05 max.	--- ---
Direct sensitivity to CO_2 **(mol H_2O/mol CO_2)**	--- ---	±0.02 typical ±0.05 max.

The LI-7200 is a single beam multi-waveband gas analyzer. It has a single optical path, and continuously alternates between absorbing and non-absorbing wavelengths passing through the sample path by using a chopper wheel rotating at 150 times per second to modulate the IR source. Digital signal processing techniques demodulate the signal and convert the raw values into number density.

The technical specifications for the LI-7200 are generally similar to the widely-used open-path LI-7500 and the new, improved LI-7500A analyzer.

Designed specifically for Eddy Covariance applications, this instrument makes sensitive high speed measurements of *in situ* densities of CO_2 and H_2O vapor. A wide operating temperature range, insusceptibility to rain, snow and icing, and low power consumption allow for deployment in virtually any location.

Additional specifications are as follows:

Type: Absolute, non-dispersive infrared
Detector: Thermoelectrically cooled lead selenide
Operating Temperature: -25 to 50° C (-40° C on request)
Power Requirements: 10.5 to 30 VDC
Power Consumption: 12 W nominal (w/LI-7550)
Data Storage: USB flash storage device
Outputs: Ethernet, SDM, RS-232, 6 DACs
Inputs: Ethernet, 4 analog input channels
Bandwidth: 5, 10, or 20 Hz, user-selectable
Dimensions: 7.5 cm (3”) diameter, 31 cm (12.2”) length ;1.8 kg (3.95 lbs)
Flow Module (optional): 15 W nominal @ 15 LPM; 15 LPM nominal (10 to 18 LPM)

Overall details on the performance of the LI-7200 can be found at the LI-COR LI-7200 web-site:

http://www.licor.com/env/Products/GasAnalyzers/li7200/7200.jsp

ENCLOSED LI-7200 APPLICATIONS

Even though LI-7200 was designed for Eddy Covariance flux measurements, it can also be used for flux storage profile measurements, Relaxed Eddy Accumulation, gradient flux techniques, canopy and soil chamber measurements, airborne and shipborne measurements, pCO_2, and any other application requiring fast, or slow, accurate measurements of CO_2 and H_2O.

Since the enclosed nature of LI-7200 allows it to operate equally well in all environmental conditions, from extremely cold to extremely hot, and from extremely humid to extremely dry, it can be placed in virtually any place over land or ocean.

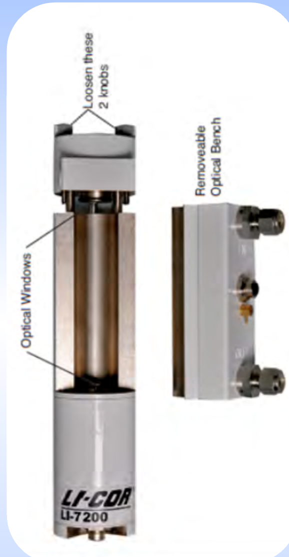
The LI-7200 integrates and stores data from any fast sonic anemometer with analog output (*e.g.*, Gill, ATI, CSI, Kaijo, Metek, RM Young) and includes the LI-7550 Analyzer Interface Unit for data logging.

Another important feature of the LI-7200 is that it can be used in a solar-powered or small generator-powered arrangement with the use of the 7200-101 Flow Module. The latter provides an efficient, integrated air-flow solution for the enclosed analyzer, and consumes about 15 Watts of power for 15 lpm of flow.

This way, fast Eddy Covariance closed-path measurements are made using solar panels, and the station can be placed in the middle of the area of interest without the need for power or infra-structure. At the same time, tube attenuation, WPL correction, and precipitation data losses are greatly reduced or eliminated.

The LI-7200 is also capable of outputting true mixing ratio, or dry mole fraction, at high speed. When these output units are used for computing Eddy Covariance flux, no density corrections are required, because thermal expansion and water dilution of the sampled air have already been accounted for.

ENCLOSED LI-7200 CALIBRATION AND CLEANING



The LI-7200 does not need to be calibrated more often than the LI-7500 or LI-7500A. However, as with any closed-path instrument, if desired, an automated calibration system can be used for monthly, weekly, daily or even hourly calibration at the tower, depending on measurement technique and user preferences.

If needed, the cell can be removed from the head while on the tower, and without disconnecting the tubing or cables. Cell windows can easily be cleaned with nearly any cloth or soft brush, as they are made of sapphire, and are very hard. Cell walls are made of PVC and should be cleaned by a non-abrasive method (paper towel, cotton swab, etc.). The cell is water-proof, and can withstand large positive and negative pressure fluctuations.

Use of untested chemicals for cleaning the cell should be avoided. Some chemicals may form a microfilm on the windows preventing the correct computation of CO_2 and H_2O concentrations. Windex and RainX can be used for cleaning the cell, while "CLR" brand and other household cleaners cannot.

After the cell is opened, cleaned and closed again, re-setting zero for CO_2 and H_2O is recommended, which can also be done on the tower. Resetting or not resetting the zero after cell cleaning usually is not essential for Eddy Covariance flux measurements, but it may cause an offset in mean concentration measurements, because cell conditions may have been modified by the user.

ENCLOSED LI-7200 INTAKE INSTALLATION

The LI-7200 gas analyzer comes with a standard 1 meter long 3/8" ID intake tube, with removable insulation under a white plastic sleeve.

We provide these for convenience, but any desired intake tube suitable for Eddy Covariance measurements can be used instead of the factory-provided default.

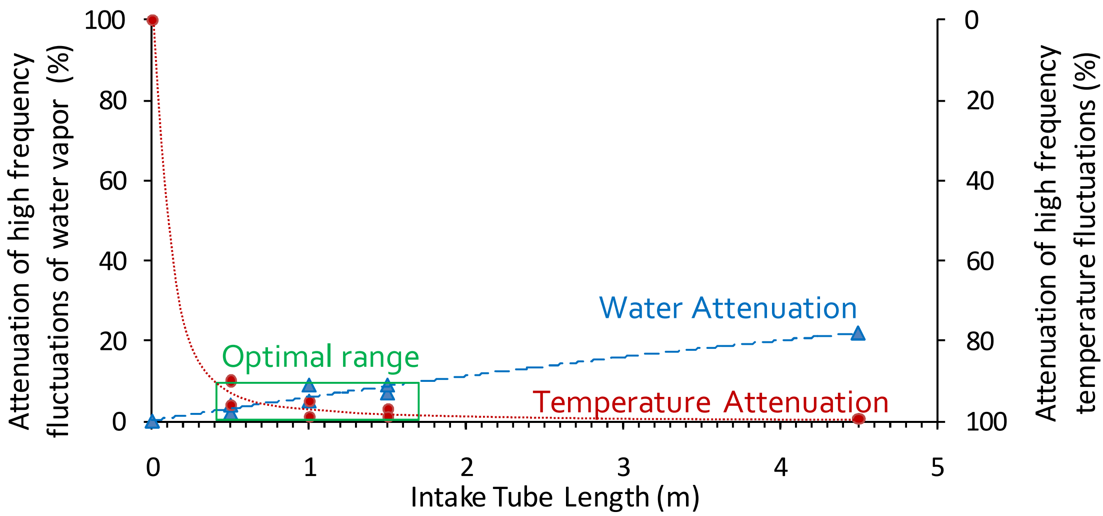
The optimum tube length for most applications is between 0.5 and 1 m (Clement *et al.*, 2008). The shorter intakes may lead to lesser temperature attenuation and may be difficult to mount near the sonic without flow obstruction.

The longer intakes may lead to higher water flux attenuation, and require more power for the pump; however, depending on the site setup, longer or shorter intakes may be required. The LI-7200 will work with intake lengths ranging from a few centimeters to many meters long.

The LI-7200 can be mounted in any position, and standard mounting hardware does not have to be used if different specific arrangements are desired; however, we describe a default setup configuration in the next section that will work for most cases.

Avoid putting long objects (e.g., narrow tubing, screw driver, etc.) into inlet and outlet ports of the analyzer. Fine-wire thermocouples are stretched across the inlet and the outlet ports of the sampling cell. Inserting long objects into the inlet and outlet ports may damage the thermocouples.

TUBE OPTIMIZATION



- The crossing of two fitted lines suggests the best length of about 0.7 m
- H_2O-only studies may benefit from shorter intakes (0.4-1.0 m)
- CO_2-only studies may benefit from longer intakes (1.0-1.7 m).

For the LI-7200, the default intake was designed to maximize the attenuation of instantaneous fluctuations of temperature, and to minimize the attenuation of instantaneous fluctuations of water at the same time.

This helps to significantly reduce WPL term and associated uncertainties, without requiring excessive frequency response corrections for water vapor flux and its uncertainties.

The optimal intake length for LI-7200 suggested by experimental data ranges from about 0.4 m, attenuating 90% of high frequency temperature fluctuations and less than 5% of the water fluctuations, to about 1.7 m, attenuating 99% of the temperature fluctuations and less than 10% of the water fluctuations.

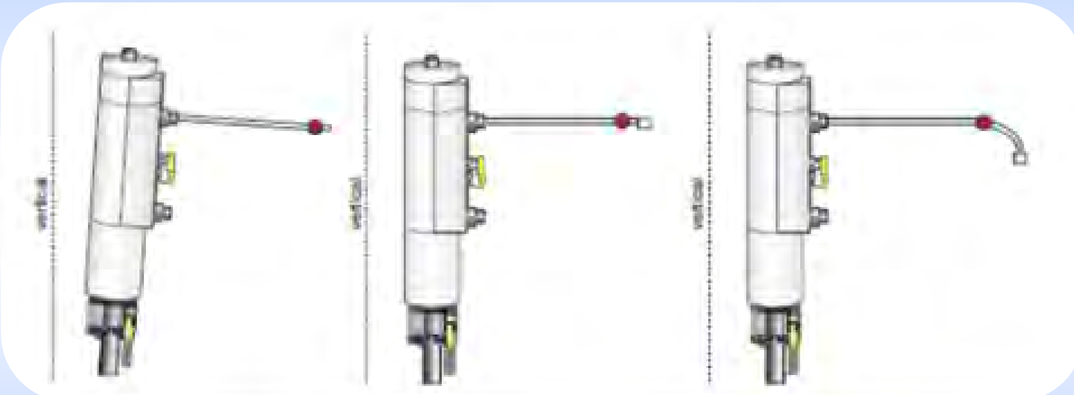
The crossing of the two fitted lines in the above figure suggests the best intake length of about 0.7 m. However, the single length is too restrictive to apply to all studies because a specific study may require a specific tube length. For example, hydrological studies may benefit from shorter tubes (e.g., 0.4-1.0 m, or less) to reduce uncertainties associated with the effects of long intakes on water vapor fluctuations.

Meanwhile, research groups focused solely on ecosystem CO_2 exchange would benefit from using longer tubes (e.g., 1.0-1.7 m, or more) to further reduce or eliminate temperature fluctuations and associated uncertainties.

In the latter case, especially with intake tubes longer than 1.7 m, the water attenuation can still be corrected by frequency response corrections, so no actual water vapor flux would be lost, but uncertainty will increase.

This uncertainty is also expected to increase with tube wall contaminations, relative humidity, and sharp turns or uneven joints in the intake tube (Massman and Ibrom, 2008).

ENCLOSED LI-7200 MOUNTING



The standard 1 meter intake tube can be cut to 0.5 cm or shorter or a custom tube can be used. When the LI-7200 is used with an intake tube longer than 50 cm, we recommend installing and securing the intake tube on the tower first, before attaching the analyzer head. This is to prevent potential excessive stress on the joint where the intake tube is attached to the LI-7200 head.

When the intake tube is 50 cm or shorter, the tube can be attached to the LI-7200 head first, and then secured on the tower. Even with an intake tube of 50 cm or shorter, we recommend securing the outer end of the tube to the sonic anemometer or any other rigid element of the tower setup. This is to make sure that strong winds do not cause intake tube vibrations and translate into stress on the head.

In most cases, the best positioning of the LI-7200 head is vertical, so that water that may have gotten into the cell during heavy rains does not pool inside the cell.

The sampling cell is water-proof and will not get damaged if water is present, but it will affect H_2O and CO_2 concentrations and flux measurements, and may result in salt deposits on walls and windows.

As for the intake filter, in extremely dusty environments one may benefit from using a low-restriction open-face intake filter (e.g., 50+ micron NuPro), but usually such a filter is not needed for the LI-7200. The LI-7200 has low sensitivity to cell contamination, similar to the LI-7500 and LI-7500A, and can easily be cleaned on a tower with one hand and without tools.

We recommend using a bug screen on the intake tube in all environments to prevent insects from getting pulled into the cell. When a longer intake tube is used instead of the standard intake, avoid sharp bends and tube pinches. It is important to keep the flow undisturbed, and to minimize flow restrictions.

ENCLOSED LI-7200 INSULATION

- Insulating the intake tube prevents nighttime condensation inside the intake tube in humid environments, for any tube or any closed-path or enclosed analyzer

- Insulation is installed by default, but can be removed if desired

- In extremely cold environments (*e.g.*, winter measurements in arctic and alpine ecosystems etc.) a heated wire may be placed under the tube's insulation to prevent icing up on the inside of the intake tube

- If flow disturbance is a concern, part of the insulation can be removed or replaced with a heating wire or a heating tape

The head generally does not need to be insulated or shielded, as energy from the head's electronics is always larger than energy that can be radiated away at night by a "black" sky or convected away by wind.

There are two cases, however, when the analyzer head may benefit from insulation/shielding:

- Environments with extremely rapid advection of much warmer air, such as some locations inside cities, warm ocean shore in the autumn, etc. In such environments the advection of much warmer air may happen very rapidly, and sampled air may be considerably warmer than the cell walls for one or two hours after the advection due to the thermal inertia of analyzer head. Some minor condensation can theoretically occur, but it can be avoided if the head is insulated.

- In extremely hot environments, such as tropical deserts, it is theoretically possible for the head to get warmed above 50 ^{o}C, even though we did not encounter this problem with the LI-7500 head during the many years of its use. Shielding the LI-7200 head in such cases may help. Also, a slightly longer tube may be used, and the analyzer head may be placed under the tower mounting plate, thus, naturally shielding the head from sunlight.

Heating of the head should not be needed in any circumstances, however, artificial heating (below 50 ^{o}C) will not adversely affect the measurements, since the air temperature in the cell is measured at a fast rate.

CLOSED PATH LI-7000 GAS ANALYZER

	 LI-7000
Gas Sample Path	Closed
Analyzer Type	Differential NDIR
Detector	Lead Selenide
Optical Bench	0.95 cm D × 15.2 cm L, 10.86 cm^3
Operating Temperature	0 to 50 °C
Power Consumption	15-40 W
Pump	Yes
Max. Cell Pressure	Capable of 10 liters/min. with minimal pressure drop
Pressure Sensor	Yes
Heat Exchangers	Yes
Tubing	External only
Weatherproof	No
Cleanable Optics	Yes
Windows® Interface	Yes
DACs	Four, updated at 600 Hz
Digital Output	RS-232, USB up to 50 Hz
Bandwidth	0.025 to 20 Hz
CO_2 Range	0-3,000 ppm
Zero Drift - max	±0.3 ppm/°C
Span Drift - max	±0.2% of reading/°C
Signal Noise	78 ppb at 5 Hz typical
H_2O Range	0-60 mmol/mol
Zero Drift - max	±0.02 mmol/mol/°C
Span Drift - max	±0.4% of reading/°C
Signal Noise	0.004 mmol/mol at 5 Hz typical

The specifications for a closed-path LI-7000 analyzer are shown on this page. This instrument is a high performance, dual cell, differential gas analyzer. It uses a dichroic beam splitter and two separate detectors to measure infrared absorption by CO_2 and H_2O in the same gas stream. The optical bench can be dismantled and cleaned by the user without the need for factory recalibration.

Further details on the specifications of LI-7000 can be found in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

LI-7000 GEOGRAPHIC USE

TERRESTRIAL

Continuous use in flux networks

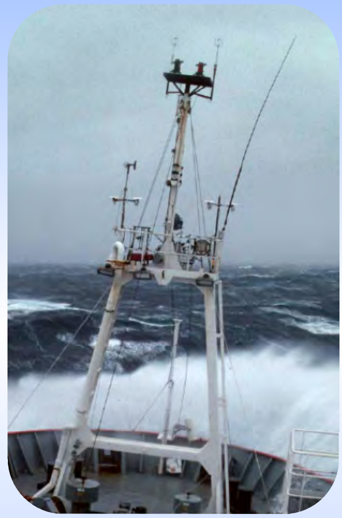
Limited by sonic data during precipitation

AIRBORNE

Housed in aircraft, air pulled into sample cell

Measurements taken for short time periods

OCEANOGRAPHIC



Sea-air water and CO_2 flux

Interference from gyroscopic effects

Many of the LI-7000 applications are in terrestrial flux applications in flux networks. Airborne and oceanographic installations are also common.

In land-based installations, the performance is usually limited by sonic anemometer performance during rain and snow events. Airborne and oceanographic applications may require special mounting attachments to compensate for gyroscopic effects, such as wake and heave.

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:
http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

Further details on the deployment and use of LI-7000 in the field are in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

LI-7000 INSTALLATION

- An environmental enclosure is required for the LI-7000 to shelter the instrument from precipitation and dust
- Temperature control is highly advisable to minimize potential span drift with temperature and to avoid overheating of the instrument which is designed for temperatures from 0 to +55°C
- All connections should be tested for leaks after instrument installation and before data collection

An environmental enclosure is required for the LI-7000 to shelter the instrument from precipitation and dust. Temperature control is also highly advisable to minimize potential span drift with temperature and to avoid overheating of the instrument. It is designed for temperatures from 0 to +55 °C.

Leak tests should be provided for all instrument connections after the instrument is installed and before data collection. The simplest leak test can be done by breathing around the instrument connections and away from the intake, and making sure that the CO_2 signal does not increase.

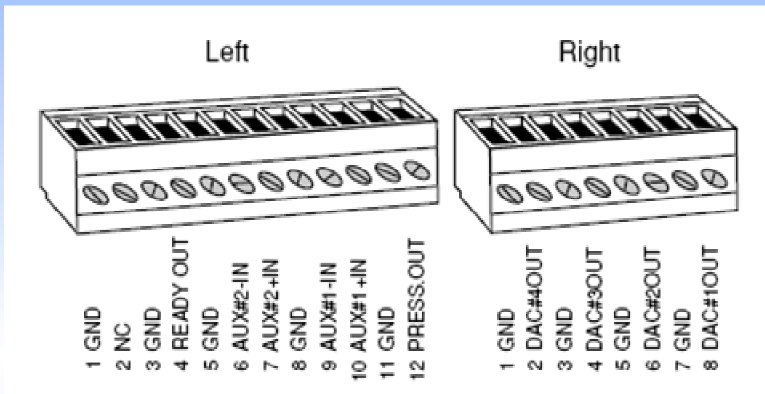
Further details on the installation of LI-7000 in the field are in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

LI-7000 ANALOG WIRING



- Analog: 4 user-scalable 14 bit DACs, 600 Hz update frequency; feed into high speed data logger or sonic anemometer

- Auxiliary input channels: 2, ±2.5V, 10 Hz bandwidth; could feed w signal from sonic anemometer into this input

Details on analog wiring of an LI-7000 in the field can be found in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

LI-7000 DIGITAL WIRING

- RS-232: 9600-115200 baud, 8, N, 1; supports XON/XOFF & trigger input
- USB: 2.0 compliant; PC must run Windows2000/XP/Vista/7 to support USB
- Serial data rates to 50 Hz; instrument grammar is published

Details on digital wiring for an LI-7000 in the field can be found in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

LI-7000 CALIBRATION

- Polynomial calibration coefficients determined at the factory are typically valid for several years
- The zero and span settings make the analyzer's response agree with its previously determined factory response at a minimum of two points
- Closed-path instruments can be configured for automatic routine calibrations

Factory determined polynomial calibration coefficients are usually good for several years. However, periodic setting of zero and span is recommended to make sure the instrument performs correctly. The zero and span settings make the analyzer's response agree with its previously determined factory response at a minimum of two points. The system can be configured for automatic hourly, daily or weekly calibrations.

Further details on the calibration of LI-7000 in the field can be found in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

LI-7000 SAMPLING

- Sample at a rate twice the frequency of significance to avoid aliasing
- User programmable bandwidth setting of 5, 10 or 20 Hz means minimum sampling rate of 10, 20 and 40 Hz respectively
- Selectable update rates for DAC output are up to 600 Hz, and for RS-232 and USB outputs are up to 50 Hz

It is generally recommended to sample at a rate twice the frequency of the physical significance of the data to avoid aliasing. Sampling at the rate of 10 or 20 Hz is usually adequate for most land applications, while higher frequencies may be required for airborne applications and in special circumstances (e.g., at very low heights, understory, etc.).

To accommodate a wide range of potential uses, LI-7000 signals are available at 600 Hz for DAC, 50 Hz for USB and RS-232 outputs. Bandwidth setting of 5, 10 or 20 Hz would indicate a minimum sampling rate of 10, 20 and 40 Hz respectively.

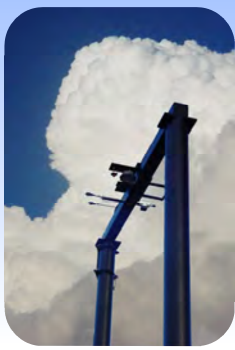
Further details on the sampling by LI-7000 in the field can be found in the LI-7000 manual:

http://www.licor.com/env/Products/GasAnalyzers/7000/documents/LI7000_Manual_V2.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website:

http://www.licor.com/env/Products/GasAnalyzers/7000/7000.jsp

AUXILIARY MEASUREMENTS



- Net radiation - net radiometers based on thermopile sensor
- Shortwave radiation and PAR: LI-200, LI-190SA
- Soil heat flux - soil heat flux plates and thermometers

- Photosynthesis: LI-6400/XT
- Soil CO_2 Flux: LI-8100/A, LI-8150
- Leaf Area: LI-3000C, LAI-2200

In addition to a sonic anemometer and gas analyzer, the Eddy Covariance technique may benefit from other meteorological, soil and canopy parameters to help validate and interpret Eddy flux data.

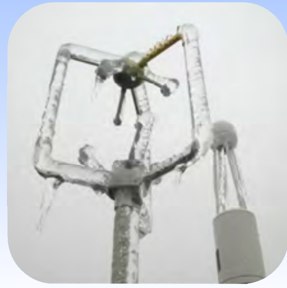
The main variables include net radiation and soil heat flux to construct a full energy budget, shortwave radiation and PAR to quantify the incoming light, leaf-level photosynthesis measurements to help interpret Eddy flux patterns, soil flux measurements and green and total leaf area measurements.

Above are some examples of such variables and instruments to measure them.

Also important are soil moisture, soil temperature, relative humidity, air temperature, precipitation, etc.

HARDWARE: SUMMARY





- Sample fast to cover all required frequency ranges
- Be very sensitive to small changes in quantities
- Should not break large eddies by their bulky structure
- Should not create many small eddies with rough structure
- Should not average small eddies by large path or volume
- Be practical in terms of maintenance, size, power and weight

In summary, the minimum essential requirements for Eddy Covariance instruments include the following: instruments need to sample fast enough to cover all required frequency ranges, while at the same time they need to be very sensitive to small changes in the quantities of interest; instruments should not break large eddies by having a bulky structure, and should be smooth enough to measure well at low heights; they also should not average small eddies using large sensing volumes; and should be practical in terms of maintenance, size, power and weight

Foken, T. and Oncley, S.P., 1995. Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'. Bulletin of the American Meteorological Society, 76: 1191-1193

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute
http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

SOFTWARE

- Data collection
- Data processing
- Collection & processing

- It is imperative to keep and archive original high frequency raw data files

The majority of scientific groups use their own software that has been customized to their specific needs. There are generally three types of software: data collection (without processing), data processing (after collection), and data collection with on-the-fly processing (simultaneously or within a few seconds behind the data collection).

Depending on the calibration schedule and expected failure rate of some instruments, data processed on-the-fly may need to be reprocessed after new calibration coefficients or other relevant new information has been incorporated into the old data, and after failed variables have been filled.

Throughout the entire procedure of data collection and processing it is imperative to keep the original raw data files. These may be needed for multiple reasons, for example, time delay re-calculation using circular correlation technique, flux re-calculation with new calibration polynomial, recalculation using different averaging times or with different criteria of spiking, etc. Original raw data files are large in volume due to 10 or 20 Hz data collection, and may easily occupy 500 KB of memory for every half-hour. Provisions should be made to accommodate and archive these data.

It is extremely important to always keep and store original 10Hz or 20Hz data, collected using Eddy Covariance method. This way, data can be reprocessed at any time using, for example, new frequency response correction methods, or correct calibration coefficients. Some of the processing steps cannot be confidently recalculated without the original high-frequency data.

SOFTWARE (CONTINUED)

- Researchers often write their own software to process their specific data sets
- Recently, comprehensive packages have became available from flux networks, research groups, and manufacturers; some examples are:

  Eddysol and EdiRe from University of Edinburg
  HuskerFlux and HuskerProc from University of Nebraska
  EC_Processor from University of Toledo
  EddyMeas & EddySoft from MPI-BGC, Germany
  TK2.0 from University of Bayreuth
  MASE from Marine Stratus Experiment
  ETH from Swiss Federal Institute of Technology
  CSI flux software for data loggers
  WinFlux from UCSD

- Software and programming can be tested by processing the "GOLD" data file on the Ameriflux web-site and making sure that results match the "GOLD" standard output

Even though researchers often write their own software to process specific data, recently, comprehensive data processing packages have became available from flux networks, research groups and instrument manufacturers.

One example of such a package is EdiRe – a set of comprehensive, flexible, user-definable modulated programs developed by Dr. Robert Clement at the University of Edinburgh. It's freeware, and can be downloaded from the link given in the notes section.

There are also several other programs including ones from University of Toledo, CSI and the University of Bayreuth in Germany.

Software outputs can be tested by processing the GOLD data file (located on the Ameriflux network website), and making sure that results of your data processing code match the GOLD standards.

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O., 2008. Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software, Biogeosciences, 5, 451-462

http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/ - EdiRe information and downloads.

http://public.ornl.gov/ameriflux/sop.shtml - GOLD files location and downloads.

http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf - Mauder, M. and T. Foken. 2004.

Documentation and Instruction Manual of the Eddy Covariance Software Package. Pages 260-261 in Micrometeorology by T. Foken (2009)

LOCATION REQUIREMENTS

- Represent the ecosystem/area of interest
- Large enough: sufficient fetch/footprint
- Assumptions hold or are correctable
- Terrain is reasonably flat and uniform

Many of the location requirements follow directly from the Eddy Covariance equations described earlier in this guide, and are intended to satisfy the assumptions made during derivations of these equations.

Most of all, the location should represent the ecosystem or area of interest, and the plot size should be large enough to provide sufficient fetch/footprint. Ideally the surface will be flat and uniform, or and least manageable, so the assumptions will hold or be correctable. Also, the site should be reasonably accessible for maintenance in accordance with the maintenance plan.

We will explain many of these points in detail, in the sections on Experiment Implementation and Flux Footprint.

http://www.cdas.ucar.edu/may02_workshop/presentations/C-DAS-Lawf.pdf - B. Law, 2006. Flux Networks – Measurement and Analysis

http://nature.berkeley.edu/biometlab/espm228/Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

POSITIONING WITHIN ECOSYSTEM

- The Eddy Covariance station in the middle of the wetland in Florida Everglades measured fluxes of CO_2, H_2O and CH_4 over 3 years

- The flux tower consumed less than 30 Watts of power (LI-7700, LI-7500, sonic anemometer, weather data) and was hand-carried into the center of the wetland

Over the last decades flux studies have covered a number of major ecosystems and few gas species.

In recent years, these studies are moving further into less studied ecosystems, or other areas, and gas species. For example, methane flux measurements in remote Arctic wetlands, or isotope flux measurements at high elevations, leak monitoring over carbon capture and sequestration sites, or constructing a greenhouse budget of a landfill.

The flux studies have also become longer in duration, and with less on-site presence for maintenance and data retrieval.

These tendencies make it especially important to consider the positioning of the tower within the ecosystem, or other area of interest. Many past studies were located close to roads and commercial power lines, and selection of the tower placement was determined by both scope of the study and practicality of the installation.

Recent low power and lightweight instrument development allows placing remote unattended solar-powered flux towers in the middle of the study area without any consideration for the road infrastructure and grid power availability.

This reduces data losses due to bad wind directions, and enables novel experiments in little studied areas, but also has increased demands on the experiment planning, instrument selection, site access and data retrieval.

MAINTENANCE PLAN

- Sensor cleaning
- Sensor replacement
- Sensor calibrations
- Cable replacements
- System repair

- Maintenance plan is very important to avoid unnecessary data loss
- Each maintenance item may be trivial, while interaction of all items gets complex: example, 20 sensors to calibrate every year
- One or two spare sensors are desirable for each measurement

After defining the experiment scope and purposes, creating a list of variables and instruments, and selecting the experiment location, but before the actual setup, it is a good idea to create a long-term maintenance plan.

At minimum, a maintenance plan includes: periodic sensor cleaning and replacement, a calibration schedule, planned replacement of damaged cables, and other anticipated repairs of the instrument system.

A well designed maintenance plan is very important to avoid unnecessary loss of data in the future, during the data collection process. Each of the maintenance items may seem trivial, however, interaction of all these items gets complex fairly quickly.

For example, a yearly or 6-month recommended factory calibration of 20 different instruments becomes a serious logistical task, and requires optimization of the number of required back-up instruments, trips to the experimental site, and introduces a risk of data loss.

If a sensor requires factory service, it may take several weeks, so plans should be made beforehand for a replacement instrument.

In addition to routine maintenance, unforeseen circumstances may complicate the schedule further (fires, lightening strikes, storm damage, rodent damage, power failure, *etc.*). This is why one or two spare sensors per each variable, and a portable power backup for a few essential measurements are very desirable, especially for remote sites.

The maintenance plan is one of the most overlooked items in the Eddy Covariance setup, especially for first-time users. Proper planning here will help to avoid large potential data losses in the future.

CARBON FOOTPRINT CONSIDERATIONS

- The measurements of CO_2 and other greenhouse gases can have a substantial carbon footprint themselves - this aspect may be good to consider during experimental design
- Depending on the scope and focus of a particular study, some gas sensing technologies can lead to large CO_2 emissions, or equivalents, while other studies can stay nearly carbon-neutral
- For example, the carbon footprint of a study measuring fluxes of 3 gases (CO_2, H_2O and CH_4) over one year could differ over 30 times depending on the gas sensing technology the measurements are based upon

Gas sensing technology	WMS/NDIR (*e.g.*, LI-7500, LI-7700)	WMS/NDIR (*e.g.*, LI-7200, LI-7700)	CRDS	ICOS
Power Demand	≈ 20 W	≈ 35 W	≈ 600W	≈ 600W
Carbon Footprint	≈ 107 kg/yr	≈ 187 kg/yr	≈ 3200 kg/yr	≈ 3200 kg/yr
Power Cost	$19/yr	$34/yr	$574/yr	$574/yr

In recent years, more and more attention is being paid to a carbon footprint, defined as the total set of greenhouse gas emissions "caused by an organization, event or product" (UK Carbon Trust).

Carbon footprint is usually measured in the CO_2 equivalent and describes how much of the greenhouse gas was emitted into the atmosphere as a result of direct emission (for example, using a power generator) or indirectly (as a result of general power consumption, travel, *etc.*). A number of organizations and individual researchers have adopted a carbon-neutral approach by optimizing the electrical demands, travel, and lifestyle.

Similarly, the flux studies and projects may consider the carbon footprint resulting from how fluxes are being measured. This will depend on the scope and focus of the particular study, but also on the gas sensing technology being used.

Four leading gas sensing technologies presently employed in fast greenhouse gas measurements are Non-Dispersive Infrared (NDIR), Wavelength Modulation Spectroscopy (WMS), Integrated Cavity Output Spectroscopy (ICOS), and Cavity Ringdown Spectroscopy (CRDS). While being quite good in their respective applications and instruments, these are quite different in power consumption during long-term field deployments, resulting in substantial differences in their carbon footprint.

For example, combination of NDIR and WMS gas sensing with pump-free instrument design allows fast simultaneous measurements of CO_2, H_2O and CH_4 species using about 20 Watts of power and causing 107 kg of CO_2 emissions per year of continuous studies. Ability to use solar panels with NDIR/WMS combination can further offset such a relatively small footprint and make this portion of the flux measurements nearly carbon-neutral.

By contrast, present instruments that employ CRDS and ICOS gas sensing technologies require about 600 W of power or more (primarily due high-powered vacuum pumps and demanding climate control), and result in over 3200 kg of CO_2 emissions per year. The grid power requirements and associated construction may further increase this, already substantial, carbon footprint.

SUMMARY OF EXPERIMENTAL DESIGN

- The design stage is an opportunity to avoid many future complications
- Main parts: purpose, variables, instruments, tower, location, maintenance
- Purpose will determine variables: include all needed for EC corrections
- Variables will determine list of instruments, software needs, infrastructure
- Instruments: fast, sensitive to tiny changes, ‘small’, and ‘aerodynamic’
- Software is generally available, but some portions may have to be written
- Desirable location : large, flat, uniform, at least - manageable/correctable
- Maintenance plan is a key to good data coverage: needs to be very detailed
- Carbon footprint of the study may be considered during the planning stage

In summary, the experiment design stage is an opportunity to avoid later complications.

The key parts of the design include defining the purpose, variables, instruments, tower, location, and developing a maintenance plan.

The purpose helps to determine a list of variables, including those needed for Eddy Covariance corrections.

The list of variables also helps to determine the list of instruments, software needs, and infrastructure. Instruments should be fast, sensitive to small changes, ‘small’ in size, and ‘aerodynamic’.

Software is generally available, but some portions may have to be written. The site should be large in size, uniform, or at least manageable.

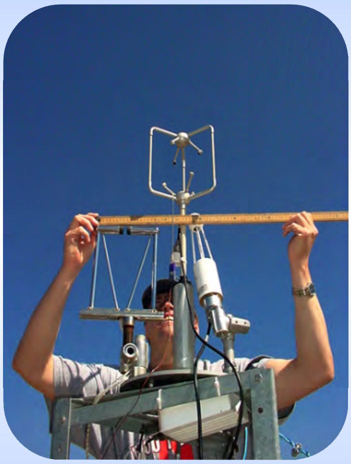
The carbon footprint of the future experiment may also be considered during the design stage.

Good maintenance planning is a key to good data coverage, and a well thought out and detailed maintenance plan will be the best insurance that the time invested in the experiment will produce accurate and meaningful data.

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 2. Experimental Implementation

EXPERIMENTAL IMPLEMENTATION



- Placing tower
- Placing Instruments
- Testing data collection
- Testing data retrieval
- Collecting data
- Keeping up maintenance

The Experiment implementation stage comes after the field experiment has been carefully designed and planned.

The main parts of the experiment implementation are: placing the tower within chosen experiment site, placing instruments on the tower, testing data collection and retrieval processes, collecting scientific data, and keeping up the maintenance.

A particularly good source of information on tower and instrument set up are the following flux network web-sites:

Munger J.W. and H. W. Loescher. Guidelines for making Eddy Covariance flux measurements

http://public.ornl.gov/ameriflux/measurement_standards_4.doc

Fluxnet-Canada Measurement Protocols, by Fluxnet-Canada Network Management Office - http://www.fluxnet-canada.ca/pages/protocols_en/measurement protocols_v.1.3_background.pdf

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

TOWER PLACEMENT

- Tower location is restricted by what it can 'see' upwind
- Location should be optimal to represent the area of interest for most wind directions or for prevailing winds
- At the very least, location should allow sampling of representative area of interest for prevailing wind directions

Tower location is restricted by what it can 'see' upwind. If possible, the location of the tower within the site should be optimized to represent the area of interest for most wind directions, but at the very least, its location should represent the area of interest for the prevailing wind directions.

The size of the area of study, canopy height, and topography may restrict fetch, instrument placement, and thus, affect tower placement criteria. Some helpful information will be given in the following pages, and also can be found in the following references:

http://public.ornl.gov/ameriflux/measurement_standards_4.doc - Munger J.W. and H. W. Loescher. Guidelines for making Eddy Covariance flux measurements

http://www.cdas.ucar.edu/mayo2_workshop/presentations/C-DAS-Lawf.pdf - B. Law, 2006. Flux Networks – Measurement and Analysis

http://www.cmar.csiro.au/ozflux/ozflux2010/L13Flux-tower-design.pdf - "Thoughts on Flux Tower Design" by P. Isaac et al., 2009. OzFlux Presentation.

Gash, J.H.C. 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology 35: 409-413

Horst, T.W., and J.C. Weil. 1994. How far is far enough? The fetch requirement for micrometeorological measurement of surface fluxes. J. Atmos. Oceanic Tech. 11: 1018-1025

SENSOR HEIGHT AND SAMPLING FREQUENCY

Height of the sensor placement is restricted from both top and bottom:

from the top:	by available upwind fetch for area of interest
from the bottom:	by frequency response errors and corrections

- Sensor located too high may 'see' outside the area of interest
- Sensor above boundary layer will 'see' flows unaffected by the surface
- Sensor located too low may not register flux transport by small eddies

The height of the sensor placement is restricted from both top and bottom. From the top it is restricted by the available upwind fetch for the area of interest, and from the bottom - by the frequency response errors and related corrections.

A sensor located very high, above the boundary layer, will 'see' flows unaffected by the studied surface. A sensor located too high within boundary layer may 'see' some fluxes outside the area of interest. A sensor located too low may see too small of an area and not represent the entire site, and may not register transport of the flux by small eddies occurring at very high frequencies.

The general rule of thumb is that the measurement height should be 100 times smaller than the desired fetch to avoid sampling outside the area of interest. However during low wind and stable conditions at night, this ratio may grow from 1:100 to 1:500.

The lowest placement height should also be restricted to make sure that the instrument is located above the roughness sub layer. The rule of thumb for the lowest location is that the instrument height should ideally be twice the canopy height. If the terrain is patchy, with scattered bushes or trees, the ratio may need to increase to 5 times the canopy height.

In terms of instrument path length, the instrument should preferably be located at a height 4 - 5 (or more) times the instrument path length.

Gash, J.H.C. 1986 A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary Layer Meteorology 35: 409-413

http://www.cdas.ucar.edu/may02_workshop/presentations/C-DAS-Lawf.pdf - B. Law, 2006. Flux Networks – Measurement and Analysis

FOOTPRINT

OUTLINES

EFFECT OF MEASUREMENT HEIGHT (EXAMPLES OF FIELD DATA)

EFFECT OF ROUGHNESS (EXAMPLES OF FIELD DATA)

EFFECT OF THERMAL STABILITY (ADOPTED FROM LITERATURE)

In very simple terms, flux footprint is the area "seen" by the instrument at the tower. In other words, it is an area upwind from the tower, such that fluxes generated in this area are registered by the tower instruments. Another frequently used term, fetch, usually refers to the distance from the tower when describing the footprint.

Understanding the concept of the flux footprint is essential for proper planning and execution of an Eddy Covariance experiment. Therefore, the next 15 pages will be dedicated exclusively to the concept of footprint, with detailed explanations and practical examples.

First, we will look at how the footprint is affected by measurement height. Then, we'll look at how the roughness of the surface affects what the instrument can "see", and finally, how thermal stability affects the footprint.

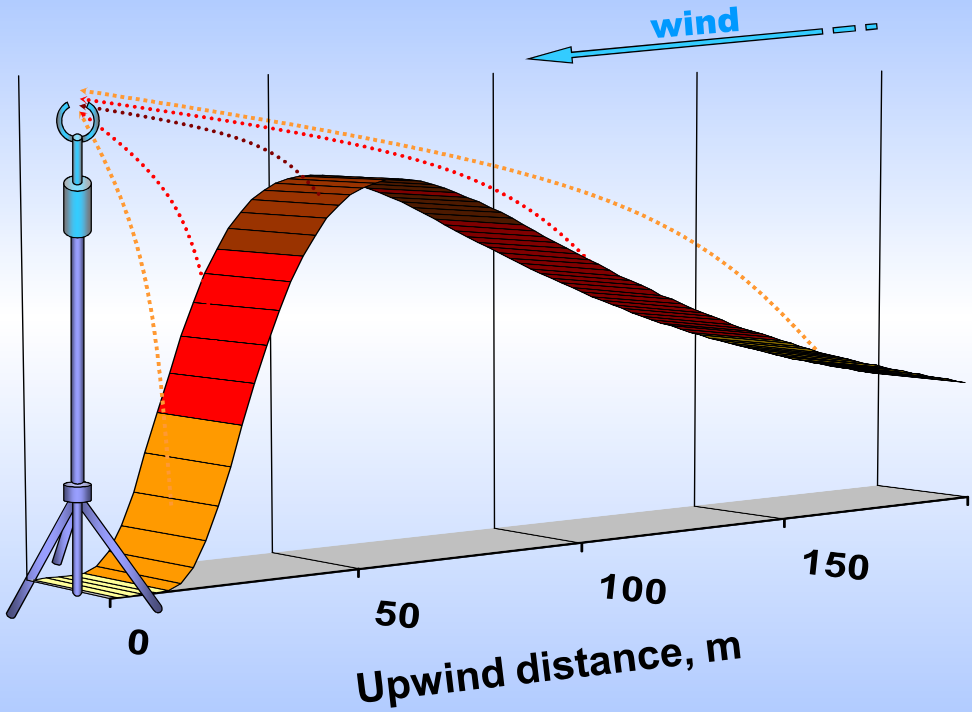
Burba, G.G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K.G. Hubbard and M.V.K. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland, 77-87

Gash, J.H.C. 1986, A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary Layer Meteorology 35: 409-413

Schuepp, P.H., M.Y. Leclerc, J.I. Macpherson, and R.L. Desjardins. 1990. Footprint Predictions of Scalar Fluxes from Analytical Solutions of the Diffusion Equation. Boundary-Layer Meteorology, 50: 355-373

Even more complex situations may exist when area of the footprint is not homogeneous. Schmid, HP, Lloyd, CR. 1999. Spatial representativeness and the location bias of flux footprints over Inhomogeneous areas. Agric. For. Meteorol, 93, 195-209

VISUALIZING THE CONCEPT



Here the flux footprint is visualized: the darker the red color – the more contribution that is coming from the area. So, most of the contribution usually comes, not from underneath the tower or from kilometers away, but rather from somewhere in between.

To see actual distances and contributions, let's look at the main features of the dependence of the flux footprint on measurement height, surface roughness and thermal stability. We will use as an example actual latent heat flux data, or evapotranspiration (ET), at the tall grass prairie site near Ponca City, OK.

To demonstrate the effect of measurement height and roughness in near-neutral conditions two days were chosen from the growing season of 1999.

One was a clear day shortly after a prescribed burn. With virtually absent vegetation, the surface was smooth (with roughness parameter of about 0.001 m). The thermal stability was near-neutral, with z/L ranging for most of the day from –0.003 to 0.05.

By contrast, another day had a relative large canopy height of 0.6 m, and roughness parameter of about 0.08 m. It also had near-neutral conditions, with stability parameter, z/L ranging for most of the day from -0.08 to 0.2.

MODELS

For near-neutral conditions:

$$CNF(x_L) = -\int_0^{x_L} \frac{U(z-d)}{u_* k x^2} e^{-\frac{U(z-d)}{u_* k x}} dx = e^{-\frac{U(z-d)}{u_* k x_L}}$$

CNF is Cumulative Normalized contribution to Flux measurement, %
x_L is distance from the station, m
U is mean integrated wind speed, m s^{-1}
z is measurement height, m
u_* is friction velocity, m s^{-1}
d is zero plain displacement, m
k is von Karman constant (0.4)

Schuepp, P.H., Leclerc, M.Y., Macpherson, J.I., and R.L. Desjardins (1990)
'Footprint prediction of scalar fluxes from analytical solution of the diffusion equation'

There are number of models to evaluate footprint contribution from the given distance. For near neutral conditions, one of the reasonably simple yet descriptive models is by Schuepp et al. and it estimates Cumulative Normalized contribution to Flux measurement (CNF) computed from analytical solutions of the diffusion equation for near-neutral conditions.

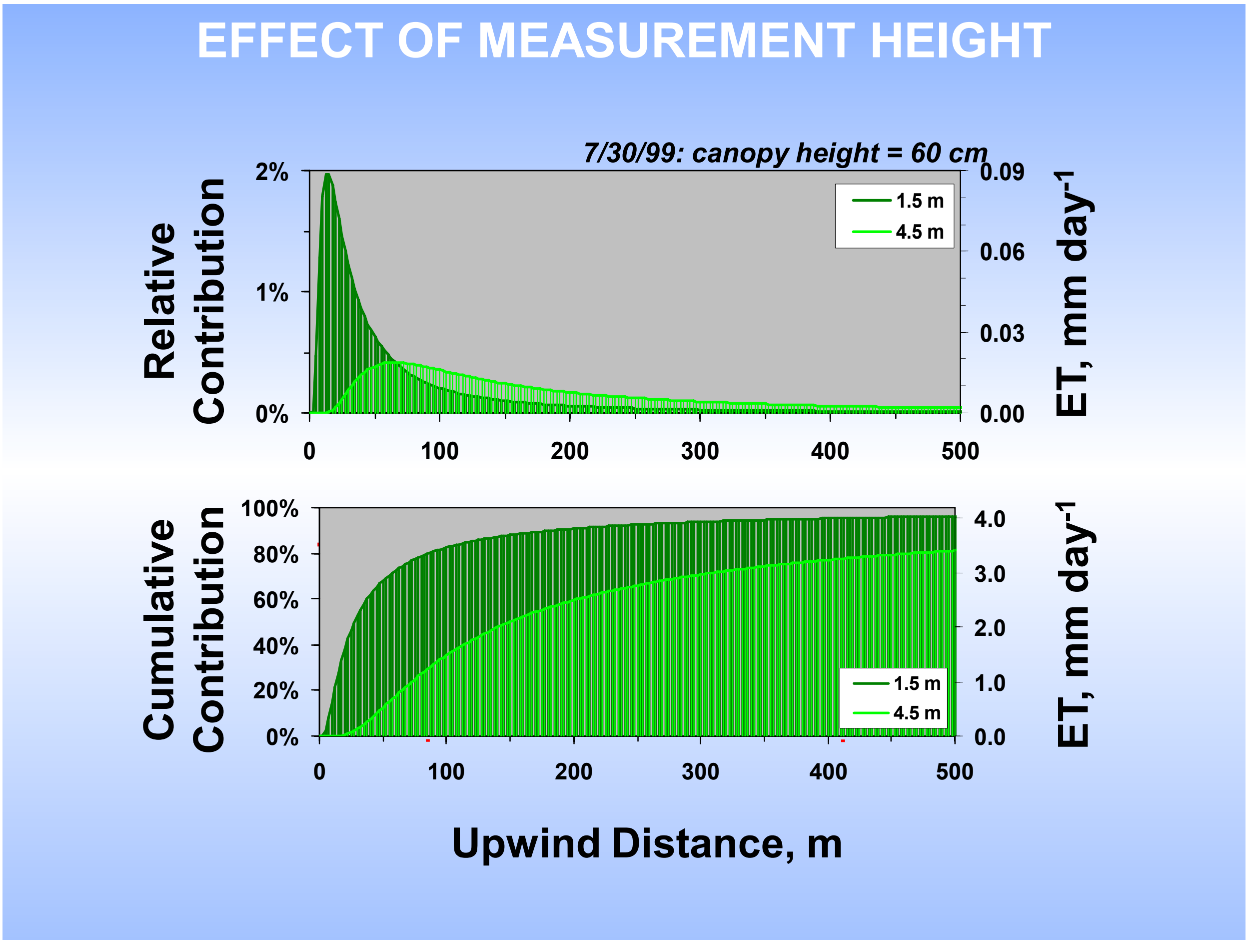
Model inputs are: instrument height, canopy height, wind speed, desired distances from the tower, friction velocity, and zero-plane displacement. From these, the model computes how much of the measured flux comes from what distance.

Schuepp, P.H., M.Y. Leclerc, J.I. Macpherson, and R.L. Desjardins. 1990. Footprint Predictions of Scalar Fluxes from Analytical Solutions of the Diffusion Equation. Boundary-Layer Meteorology, 50: 355-373

Finn, D., Lamb, B., Leclerc, M.Y., and T.W. Horst. 1996. Experimental evaluation of analytical and largrangian surface layer flux footprint models. Boundary-Layer Meteorology 80: 283-308

Gash, J.H.C. 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology 35: 409-413

Horst, T.W., and J.C. Weil. 1992. Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorology 59: 279-296



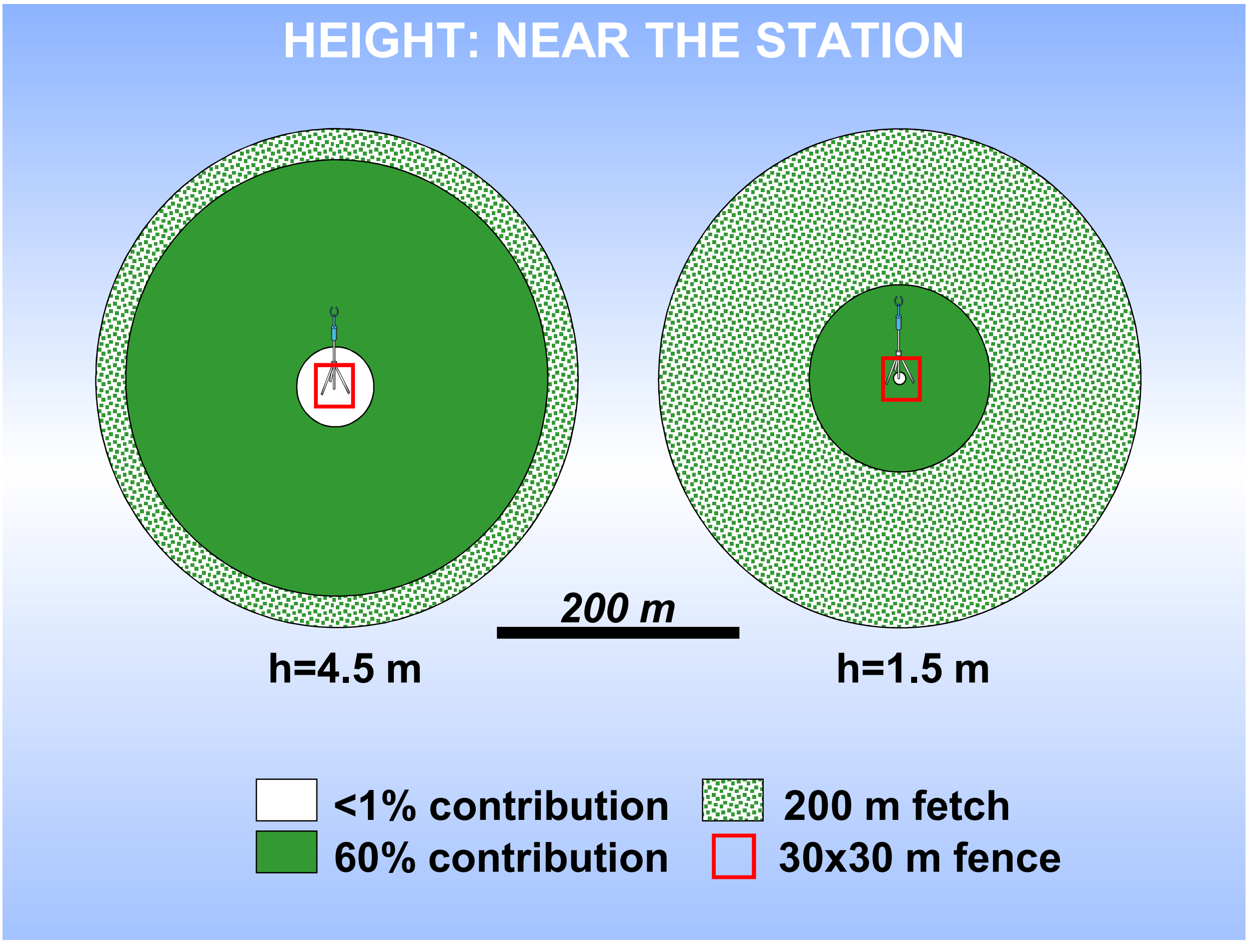
In this example, the values of latent heat flux that were contributed from the upwind distance are plotted in the figures above.

These plots (and the following similar plots) show how much of the total flux came from each upwind distance such that the integration (area below the curve) of the flux contributions by distance (from zero to infinity) would give the total evapotranspiration from the site.

When measured at the height of 4.5 m, the peak contribution of the ET came from the upwind distance of about 60-65 m, while an area within 20 m from the station did not contribute to any of the measured flux. In terms of cumulative contribution, 80% of the total daily flux (3.4 out of 4.2 mm) came from an upwind distance of 20-450 m.

At the height of 1.5 m a dramatic change in the contribution is observed. Peak contribution came from an upwind distance of about 12-18 m. Over 80% of daily ET came from an area within 80 m from the station (versus a 20-450 m zone for the 4.5 m measurement height).

Burba, G.G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K.G. Hubbard and M.V.K. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland, 77-87



These are the same data as on the previous page, but plotted as viewed from the top. They demonstrate the potential contribution of the footprint for 4.5 and 1.5 tall towers from all wind directions. The tower is located in the center of each plot.

Looking at the plot on the right, please note how important it is to keep the area around the station undisturbed and representative of the site if the measurement height is low.

MEASUREMENT HEIGHT SUMMARY

- Footprint strongly increases with measurement height:

  at 1.5 m over 80% of the ET came from within 80 m upwind

  at 4.5 m over 80% of the ET came from within 450 m upwind

- Footprint near the station is also strongly affected:

  at 1.5 m, the area 5 m around the instrument did not affect ET

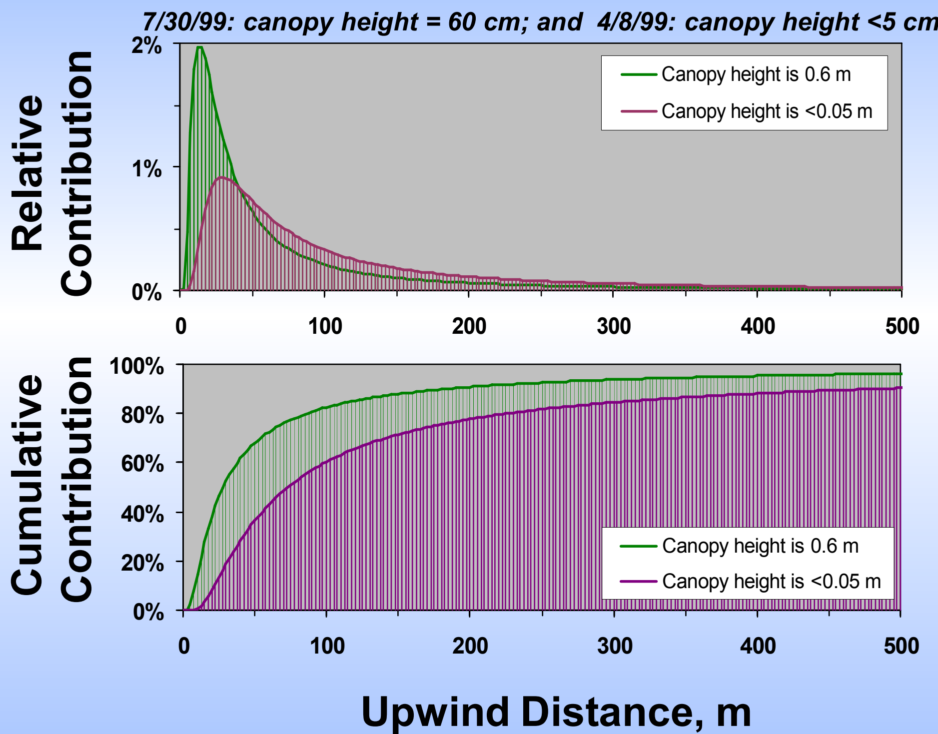
  at 4.5 m, the area over 32 m around the instrument did not affect ET

- Both sufficient fetch requirement and undisturbed area around instrument are very important for proper footprint at any measurement height

Overall, with increased measurement height, the upwind distance to the peak contribution increased (while the magnitude of the peak contribution reduced). The upwind distance covered by the station increased dramatically, as did a zone of "no contribution" around the station.

An important practical implication of the effect of the measurement height on flux footprint is that both sufficient fetch and an undisturbed area around the instrument are very important for the proper footprint at a given measurement height.

EFFECT OF CANOPY ROUGHNESS



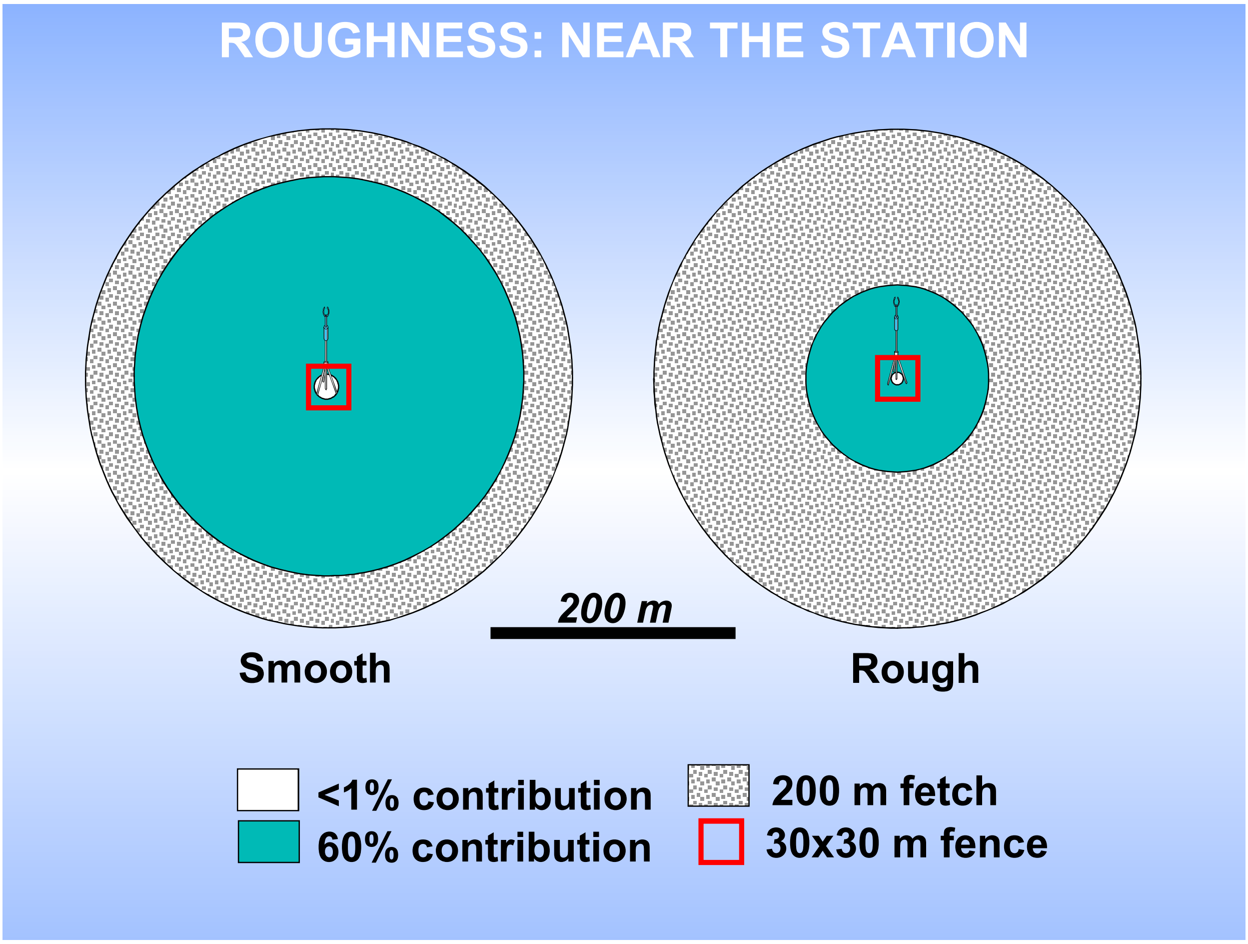
The effect of roughness on the flux station footprint is demonstrated in these figures.

For the 1.5 m measurement height, the largest contribution came from 12-18 m (2% of ET) on the day with relatively high roughness (canopy height 60 cm).

For the same measurement height on the day with low roughness (canopy height <5 cm), the peak contribution shifted to about 30-35 m of upwind distance, and was 2 times smaller (0.01% of ET).

In terms of cumulative contribution (the lower figure), for a rough surface, over 80% of the ET (3.4 out of 4.2 mm) came from within 80 m upwind, while for a smooth surface the same contribution came from within 250 m.

Burba, G.G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K.G. Hubbard and M.V.K. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland, 77-87



These are the same data as on the previous page, plotted as viewed from the top. They demonstrate the potential contribution of the footprint for smooth and rough surfaces from all wind directions. The tower is located in the center of each plot.

The "no contribution" zone was within 5 m around the station for the rough surface, and 10 m for the smooth surface.

Please note again how important it is to keep the area around the station undisturbed under both roughness conditions.

ROUGHNESS SUMMARY

☆ Footprint decreases with increased roughness:

at the sensor height of 1.5 m:
for rough surface over 80% of the ET came from within 80 m upwind
for smooth surface 80% of ET came from about 300 m upwind

☆ Footprint near the station is also affected by roughness:

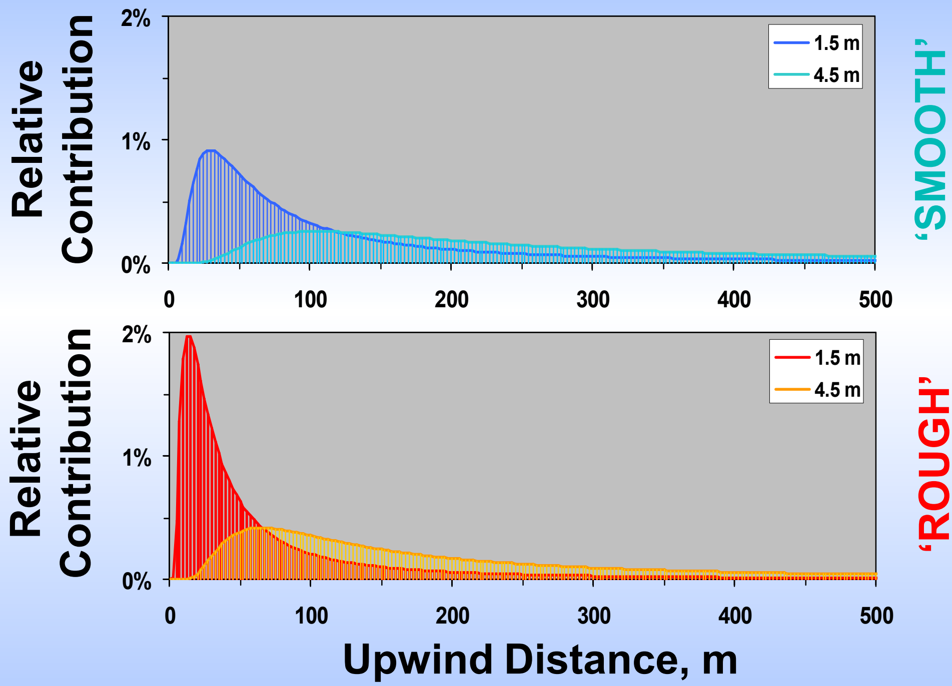
for rough surface area 5 m around the instrument did not affect ET
for smooth surface area 10 m around the instrument did not affect ET

☆ Both sufficient fetch requirement and undisturbed area around instrument are very important for proper footprint at any roughness

Overall, with increased roughness, upwind distance to the peak contribution decreased, the magnitude of the peak contribution increased, while the upwind distance covered by the station and the zone of "no contribution" shrank in size, as compared to the "smooth" surface.

An important practical implication of the effect of the roughness on flux footprint is that both sufficient fetch and an undisturbed area around the instruments are very important for the proper footprint at any roughness.

HEIGHT AT DIFFERENT ROUGHNESSES

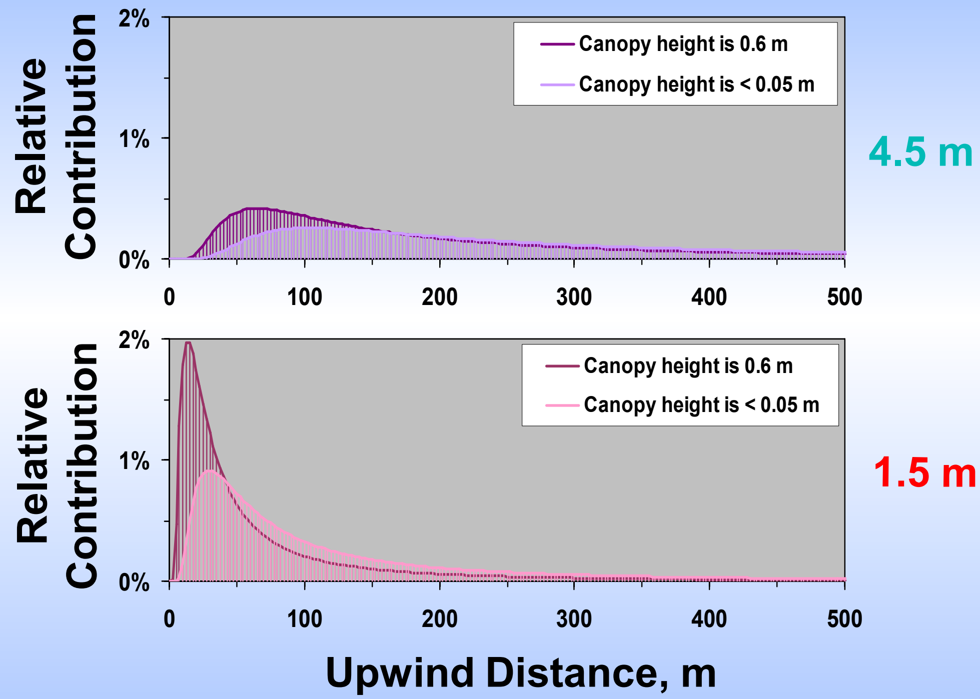


Here, the contribution from the upwind distance for different measurement heights is shown for the "smooth" surface in the top figure, and for the "rough" surface in the bottom figure.

For the "rough" surface, the measurement height had a more profound effect on footprint than for the "smooth" surface. The peak contribution increased 3 times with an increase in measurement height on 4/8/99 (for the smooth surface), while for the rough surface, the same increase in measurement height led to a peak contribution increase of 5 times.

Burba, G.G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K.G. Hubbard and M.V.K. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland, 77-87

ROUGHNESS AT DIFFERENT HEIGHTS



Contribution from the upwind distance for different roughness is shown for a 4.5 m measurement height in the top figure, and for a 1.5 m measurement height in the bottom figure.

For the 4.5 m measurement height, the peak contribution increased 1.3 times in magnitude and shifted twice as close to the station with increased roughness. For the 1.5 m measurement height, the peak increased 2 times (from 0.01 to 0.02 % of ET).

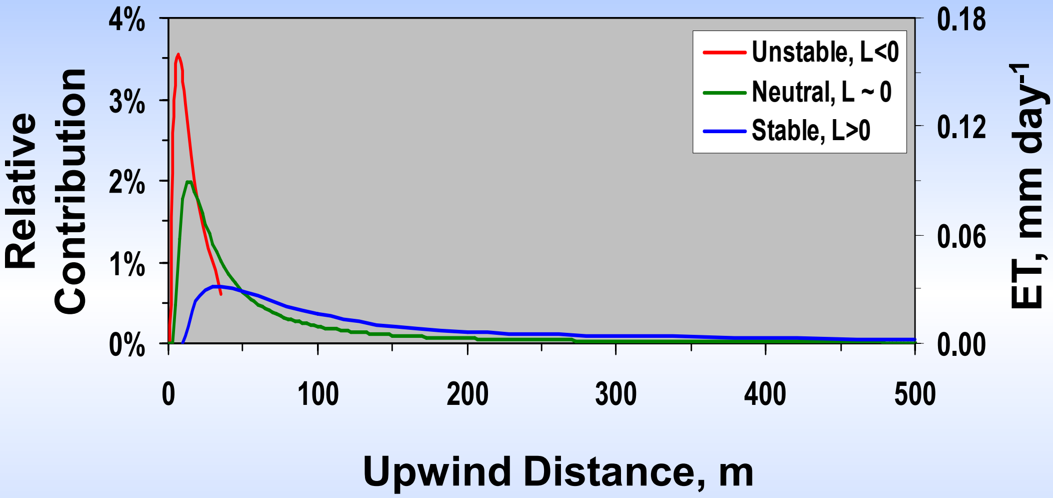
HEIGHT AND ROUGHNESS SUMMARY

- For a rough surface, the measurement height has a more profound effect on footprint than for a smooth surface
- For a lower measurement height, the roughness has a more profound effect on footprint than for higher instrument placement
- Both factors should be included in the calculation for optimal instrument placement

Overall, the rough surface measurement height had a more profound effect on the footprint than for the smooth surface. For a lower measurement height, roughness had an even more profound effect on the footprint than for a higher measurement height.

Therefore, for practical purposes, both measurement height and surface roughness should be regarded for optimal tower positioning and instrument placement.

EFFECT OF STABILITY



Adopted from Leclerc and Thurtell (1990)

The effect of stability on the upwind distance contribution of latent heat flux is shown in this figure. (adopted from Leclerc and Thurtell, 1990).

For the same measurement height and roughness, changes in atmospheric stability can expand the footprint several times.

For the height of 1.5 m and a canopy height of 0.6 m, very unstable conditions can lead to most of the flux footprint being within 50 m from the station.

In near-neutral conditions most of the footprint is located between 5 and 250 m from the station.

And during very stable conditions, the area of flux contribution is located between 15 and 500 m upwind.

Leclerc, M.Y., and G.W. Thurtell. 1990. Footprint prediction of scalar fluxes using a Markovian analysis. Boundary-Layer Meteorology 52: 247-258.

STABILITY SUMMARY

- For the same measurement height and roughness, atmospheric stability can increase footprint several times:

  for the height of 1.5 m and canopy height of 0.6 m:

  for very unstable conditions footprint is within 50 m
  for neutral conditions it is within 250 m
  for very stable conditions footprint is within 500 m

- Flux data at very stable conditions may need to be corrected or discarded due to insufficient fetch

- Flux data at very unstable conditions may need to be corrected or discarded due to the fact that large portion of the flux comes from disturbed area around instrument

Some important practical implications of the effect of stability on the footprint for station positioning and data processing are the following:

Flux data at very stable conditions may need to be corrected or discarded due to the insufficient fetch, and, flux data at very unstable conditions may need to be corrected or discarded due to the fact that large portion of the flux comes from an area around the instrument (which is usually disturbed to some degree by maintenance activity).

In some cases, when the specific microclimate of the site leads to a consistent prevalence of stable conditions, tower placement and measurement height may need to be adjusted to avoid large losses of data due to insufficient fetch.

SUMMARY OF FOOTPRINT

FLUX FOOTPRINT DEPENDS ON:

Measurement height
Surface roughness
Thermal stability

SIZE OF FOOTPRINT INCREASES WITH:

Increased measurement height
Decreased surface roughness
Change in stability from unstable to stable

AREA NEAR INSTRUMENT TOWER MAY CONTRIBUTE A LOT IF:

Measurement height is low
Surface roughness is high
Conditions are very unstable

Flux footprint describes a contributing area upwind from the tower. This is the area that the instruments can "see".

Flux footprint mainly depends on measurement height, surface roughness and atmospheric thermal stability. The size of the footprint increases with an increase in measurement height, with a decrease in surface roughness, and with changes in thermal stability from unstable to stable.

The area near the tower may contribute a lot, if the measurement height is low, surface roughness is high, or if conditions are very unstable.

It is important to note that both fetch requirement and conditions of the surface in the immediate surroundings of the flux stations can and should be regarded for station placement, maintenance and for data quality control.

Gash, J.H.C. 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary Layer Meteorology 35: 409-413

Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., et al., 2005. Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modeling. Theoretical and Applied Climatology.

Schmid, H.P. 1994. Source areas for scalars and scalar fluxes. Boundary-Layer Meteorology 67: 293-318.

Stannard, D.L. 1997. A theoretically based determination of Bowen-ratio fetch requirements. Boundary-Layer Meteorology 83, 375-406.

Swuepp, P.H., Leclerc, M.Y., Macpherson, J.I., and R.L. Desjardins. 1990. Footprint prediction of scalar fluxes from analytical solution of the diffusion equation. Boundary-Layer Meteorology 50: 355-373.

TESTING DATA COLLECTION

- Instrument interaction
- Data interruptions
- Power requirements

Some of the key items to check after the tower and instruments have been set up are instrument interaction, data interruptions, and power conditions.

Since most of the set-ups for Eddy Covariance are made from a number of off-the-shelf instruments, from different manufacturers, it is advisable to make sure that there is no miscommunication, unexplained errors, lockups and other data interruptions when these instruments start interacting. For example, a digital-to-analog converter may need to be reconfigured in a specific way to accept the signal from a specific instrument.

It is also advisable to assess data interruptions due to weather events, and determine how fast they go away after the event (rain, snow, dew, power interrupt during storm, etc.), and what can be done about it.

Power grid variation, power backup and variation in power consumption are also important items to check, because power load on the tower may vary. One has to make sure that power requirements include the peaks of such variations to avoid blown fuses or deep discharge of backup batteries.

Fluxnet-Canada's field protocol addresses most of these and other such issues in detail, and can be accessed via PDF file online by following the link: http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf

Ground loops during analog data collection, radio interference with unshielded cables, and positioning instruments in the way of the directional transmitter, or antennae, have been known to cause "unexplained" errors and noise. These should be carefully checked in the field.

TESTING DATA RETRIEVAL

- Manually
- Wire
- Wireless
- Daily control
- Online control

Data retrieval is another important process to test. Data can be retrieved by hand by swapping a memory card. Data can be delivered via the Internet. The same can be done through wireless Internet or radio.

The better the connection one has to the site, the easier it is to do daily control of transmitted data, or online control of the data in real-time.

Properly configured connections may also allow for remote setup of the instruments (change in calibration coefficient, voltage output range, etc.), remote reset of the instrument or PC after lockup, and other numerous useful tasks, saving time and money on travel to the site.

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf [Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003]

KEEPING UP MAINTENANCE

- Important to keep maintenance current for the entire project duration
- Data gaps jeopardize final results
- Events such as lightning, ice storms, wind gusts, mouse damage, *etc.* <u>will</u> happen
- Spare sensors and emergency protocols are needed to avoid large data losses

Maintenance is one of the most important parts of the execution of an Eddy Covariance field experiment. This should be done for the duration of the entire project. Planning in the beginning of the experimental design should assure the ability to keep the maintenance current.

Events such as lightning, ice storms, wind gusts, and rodent damage are likely to happen several times a year during long-term deployment of the instruments. If not planned beforehand, they may lead to large data gaps.

Each data gap jeopardizes results and affects the final integrated number, so spare sensors and emergency protocols should be a part of routine planning and maintenance to help avoid such data losses.

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf [Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003]

EXPERIMENT IMPLEMENTATION SUMMARY

- Placing tower: maximize useful footprint from all wind directions
- Placing instruments: at a maximum height which still allows useful footprint
- Testing collection and retrieval: test thoroughly to avoid data gaps
- Collecting data: wireless, cable, daily checks
- Maintenance: required throughout the project to avoid data gaps

In summary, experiment implementation requires proper tower and instrument placement, rigorous tests of data collection and retrieval, remote communications with the site, and regular maintenance.

The tower should be placed preferably in the center of the studied area, in such a way that the useful footprint from all wind directions is maximized. If there is one prevailing wind direction, the tower can be placed on the edge of the area of interest to maximize footprint.

Instruments should be placed at maximum height, which still allows for a useful footprint.

Testing the data collection and retrieval should be done thoroughly to avoid data gaps.

Collecting the data should be done by wireless, wire or some other way, preferably allowing for daily checks or even real-time checks.

Maintenance should be kept up throughout the duration of the entire project to avoid collecting bad data over long periods or large data gaps.

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 3. Data Processing and Analysis

DATA PROCESSING & ANALYSIS

Instantaneous data	→	Mixed data	→	Averaged data
convert units de-spike apply calibrations rotate correct for time delay de-trend average		apply corrections		quality control fill-in integrate check analyze/publish

Each research group uses a slightly different way of processing Eddy Covariance data to fit their specific needs, site-specific design, and sampling conditions. Here we will give one particular example of the generalized traditional way to process data. The goal for this method will be to get the flux calculations as close as possible to the reality of what's actually happening in the field.

The major steps in this process include: converting signals from voltages to physical units; de-spiking; applying calibration coefficients if needed; rotating coordinates; correcting for time delays; de-trending if needed; averaging fast data over 0.5 to 4 hour periods; applying frequency response, density and other corrections; conducting quality control; filling-in missed periods and integrating long-term flux data. It is also recommended to double-check the entire process before analyzing and publishing the data.

There are several useful links below, as well as several references on the methodology of data processing:

http://www.cdas.ucar.edu/may02_workshop/presentations/C-DAS-Lawf.pdf - B. Law, 2006. Flux Networks – Measurement and Analysis

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf - Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C. and Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy. Global Change Biology, 2(3): 169-182

Foken, T. and Oncley, S.P., 1995. Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'. Bulletin of the American Meteorological Society, 76: 1191-1193.

Twine, T.E. et al., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology, 103(3): 279-300.

UNIT CONVERSION

- Check that all units for instantaneous flux calculations are appropriate and consistent to avoid errors in fluxes/corrections calculated online
- Double-check that auxiliary sensors use correct calibration coefficients to avoid errors in flux corrections, and in the mean data
- Some researchers may choose to convert CO_2 and H_2O signals into mixing ratios (mol mol^{-1} dry air) at this stage to avoid the need to apply Webb-Pearman-Leuning correction later on

Unit conversion involves checking that all of the units for instantaneous outputs are appropriate. Units need to be matched carefully to avoid errors in fluxes calculated on-line or corrections applied later. It is also important to double-check that relevant auxiliary data use the correct calibration equations to avoid errors in flux corrections, or in mean data.

Usually, unit conversion is one of the first steps in processing of the instantaneous data. Some, however, prefer to de-spike the data first, and then remove periods with outrageous values, and only then perform unit conversion and the rest of the processing. If done carefully, such a sequence of steps should yield the same results as the one presented here. However, it is important to note that setting de-spiking criteria on voltages needs to account for non-linearity in some voltage-to-unit conversions.

In other words, what may look like a spike in the raw voltage signal may not end up actually being a spike after conversion. The corollary, that what is an actual spike in the converted data may not look like a spike in the raw voltage signal is also true. Therefore, the spike criteria may not always be the same for volts and converted units.

Some groups may also choose to convert CO_2 and H_2O signals into mixing ratios (mol mol^{-1} dry air) at this stage, to avoid the need to apply the Webb-Pearman-Leuning correction at a later stage.

It is important to note, however, that point-by-point conversion of the signal to a mixing ratio for open path instruments is associated with large potential uncertainties and errors. This is because vertical wind measurements and scalar measurements are not done in the same volume, and because sensor separation and related time delay may change with wind speed and direction within the same averaging period. One needs to be cautious when doing point-by-point corrections for open path instruments, and you may want to compare the results to those with traditional Webb-Pearman-Leuning corrections before finalizing the workflow.

DE-SPIKING

- High frequency instantaneous data will have occasional spikes due to both electronic and physical noise
- Spikes should be removed and bad points should be replaced with running means to avoid errors in further calculations
- De-spiking could be done on-line immediately after data collection or later during post-processing
- Caution should be used to avoid removing too much data
- Each Eddy Covariance system will have slightly different spike problems
- Researcher should examine instantaneous data periodically to make sure that spike removal is appropriate for the conditions

High frequency instantaneous data will have occasional spikes due to both electronic noise and some physical reasons.

After these spikes are removed, bad points can be replaced with running means or by some other method to avoid errors in further calculations. The procedure can be done on-line, right after data collection, or during post-processing.

Each Eddy Covariance system will have slightly different spike problems, and the researcher needs to look at instantaneous data periodically to make sure that spike removal criteria are appropriate for the conditions. Caution should be used not to set the criteria too strict, removing too much data.

For example, the de-spike criterion can be set to remove signals that are more than 6 times the standard deviation for a given averaging period so that all outliers are considered spikes and are removed.

While too many spikes usually indicate an instrument or electronic problem, there are conditions, such as nighttime storage release, that may look like spikes, but are in fact natural phenomena.

Vickers, D. and Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package.
http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf

CALIBRATION COEFFICIENTS

- Applying calibration coefficients is not a trivial matter in Eddy Covariance
- Many researchers choose to calibrate closed-path gas analyzers every night or even more frequently to assure highest data quality
- In such cases, calibration parameters may differ slightly every day and software should be written to incorporate these changes into the data
- For open-path or enclosed sensors, calibration coefficients are typically less involved and with proper factory or lab calibrations every few months, they can usually be set in the embedded instrument software

Applying calibration coefficients may not be a trivial matter in Eddy Covariance calculations.

Many researchers choose to make a calibration of the closed-path sensor every night, or even more frequently, to assure the highest data quality.

In such cases calibration coefficients will differ a little bit for every day, and software should be written to incorporate these changes into the data.

For open-path and enclosed sensors, calibration coefficients are less involved. With proper factory/lab calibration every few months, they can usually be set in the instrument software itself.

COORDINATE ROTATION

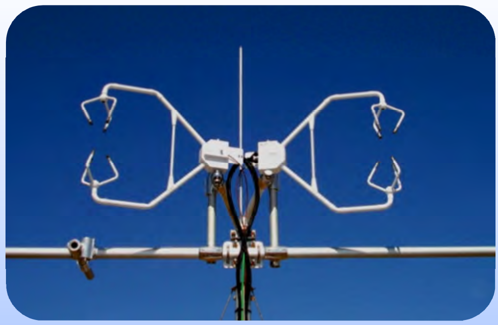
- Sonic anemometer can not be leveled perfectly, such that its w axis is exactly perpendicular to the mean flow, or mean wind, streamlines

- The w signal may be contaminated by the other two 3-D wind components

- Several ways to correct such a situations:

  1) rotating so that mean w=0

  2) using planar fit method



A sonic anemometer cannot be leveled perfectly, such that its w axis is always perpendicular to the mean flow/mean wind streamlines. The w-signal will likely be contaminated by the other two 3-D wind components. There are traditional and also newer ways to correct this situation. One well-established technique is to rotate the coordinates so that the mean "w" is equal to zero. Another popular way is to use a planar fit method.

Rotation of w', u' and v' at this early stage of data reprocessing may save time at later stages, because one would not need to rotate all the covariance's (e.g. u'w', w't', w'c', w'q', etc.).

Useful details on how to do coordinate rotation are provided by Lee, Massman and Law in Chapter 3 (pp. 33-64) of the Handbook of micrometeorology. A guide for surface flux measurement and analysis. Complete details on the book are available in the references listed below.

It is also important to note that some models of sonic anemometers may require an additional cross-wind correction before coordinate rotation is done. In other models such a correction is done internally. Please refer to pages 8-9 in the Documentation and Instruction Manual of the Eddy Covariance Software Package for the list of the sonic anemometer models and other details for such corrections, and on pages B-1 to B-2 in CSI's Open Path System Operator's Manual.

Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

http://www.geo.unibayreuth.de/mikrometeorologie /ARBERG/ARBERG26.pdf Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package.

http://www.campbellsci.com/documents/manuals/ opecsystem.pdf CSI, Inc. 2004-2006. Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH20.

COORDINATE ROTATION (CONTINUED)

- Rotating to 'mean w=0' can be done in several stages:

  1st stage: rotate to make v=0 (align u and x)
  2nd stage: rotate to make w=0 (align w and z)
  3rd stage: rotate to make w'v'=0 (align z-y plane)–rarely used

- Planar fit is a somewhat more complex rotation method

- After u, v, and w data have been collected over a long period, one could mathematically establish a 'hypothetical' plane, so 'true' vertical flux should be perpendicular to this plane

- It may be particularly helpful when measurements are done over complex terrains (e.g., hillsides, valleys)

Rotating to create a 'mean w=0' can be done in several stages: 1st rotation: turn to set v=0 (align u and x); 2nd rotation: turn to set w=0 (align w and z); 3rd rotation: turn to set w'v'=0 (align z-y plane – used rarely).

The planar fit is a somewhat more complex rotation method, but it may be particularly helpful when measurements are done over complex terrains (e.g., hillsides, valleys). In this method, after u, v, and w data have been collected over a long period, one could mathematically establish a 'hypothetical' plane, so that a 'true' vertical flux will be perpendicular to this plane. Unlike rotation method, planar fit requires long-term installations with instruments remaining undisturbed over long periods.

A somewhat different approach has been proposed by Wilczak, Oncley, and Stage, in a paper titled "Sonic anemometer tilt correction algorithms." in Boundary-Layer Meteorology, 1999 pages 127-150.

It is important to mention another anemometer correction: an angle of attack correction that results from uneven cosine response of some sonic anemometers to the horizontal wind angle. It is not applicable to all anemometers and the correction may be fully or partially applied by manufacturers. Please see factory manuals for the specific anemometer manufacturer and model for details.

Gash, J.H.C., Dolman, A.J., 2003. Sonic anemometer (co)sine response and flux measurement. I. The potential for cosine error to affect sonic anemometer-based flux measurements. Agric. For. Meteorol., 119,195–207

Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package. http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf
van der Molen, M.K., Gash, J.H.C., Elbers, J.A., 2004.

Sonic anemometer (co)sine response and flux measurement. II. The effect of introducing an angle of attack dependent calibration. Agric. For. Meteorol., 122,95–109

TIME DELAY

- Compensates for time delay in signal acquisition from different instruments
- When using a closed path sensor, air sampled by the sonic anemometer may get to the closed path gas analyzer several seconds later
- Without correcting for this delay, fluctuations in w' will not correlate with fluctuations in gas concentration, and flux will be drastically underestimated
- Time delay is usually corrected in one of two ways:

  (1) theoretically, via flow rate, tube diameter etc.
  (2) empirically, by running circular correlation, shifting the delay scan-by-scan until maximum correlation (flux) is found
- For open path sensors, the time delay may be on the order of a few scans (not seconds), but should still be applied to avoid small flux loss

Matching the time series from a sonic anemometer and from a gas analyzer requires compensating for time delays in the signal acquisition from these instruments.

This is especially true when using a closed path sensor, since air sampled by the sonic anemometer gets to the closed path gas analyzer several seconds later than w-signal. Without correcting for such delays, fluctuations in w' would not correlate well with fluctuations in gas concentration, and flux could be underestimated or even zeroed.

Time delay is usually corrected in one of two ways: (1) Theoretically, via the flow rate, tube diameter, etc. or (2) Empirically, by running a circular correlation, and shifting the delay scan-by-scan until a maximum correlation (flux) is found.

For open path sensors time delay may be in the order of a few scans (not seconds), but it also should be compensated for to avoid smaller flux loss.

Time delay using circular correlation should be computed when turbulence is developed sufficiently enough (U>1 m/s, u*>0.1) and flux is large enough to see a good correlation between w' and c' to confidently compute such a delay.

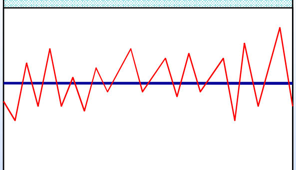
http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf- Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package.

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf– Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003

DE-TRENDING

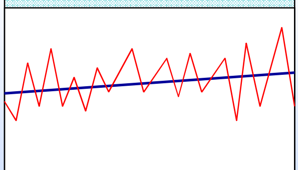
- Mean values are subtracted from instantaneous values to compute flux
- This requires establishing what would be the mean for a given time series
- There are three main ways to look at it, and three respective techniques

Block averaging
(mean removal)



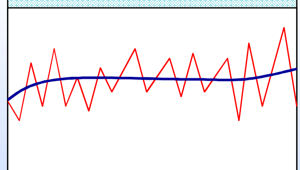
- Simplest situation
- Many prefer this method
- May gain artificial flux

Linear detrending
(linear trend removal)



- ex., If sensors drift, or
- Rapid diurnal changes
- May lose some flux

Non-linear filtering
(n-l trend removal)



- Complex situation
- Same as high pass filter
- May lose a lot of flux

During de-trending, the mean values are subtracted from instantaneous values to compute flux. This requires establishing what would be the mean for a given time series. There are three main, traditional ways to look at it, along with three respective techniques: block averaging, linear de-trending and non-linear filtering.

Each way may be appropriate for a specific situation. And even though block averaging is the most popular way to de-trend (and sometimes viewed as no de-trending at all), complex terrains and rapid changes in concentrations in some regions may require the use of linear and non-linear filtering. At the same time it is important not to over-filter, because flux contribution in the low frequency part of the co-spectra would be lost as a result of over filtering.

Generally, however, linear and non-linear de-trending is not recommended as it can leave spectral artifacts in the data and can mask improper averaging times.

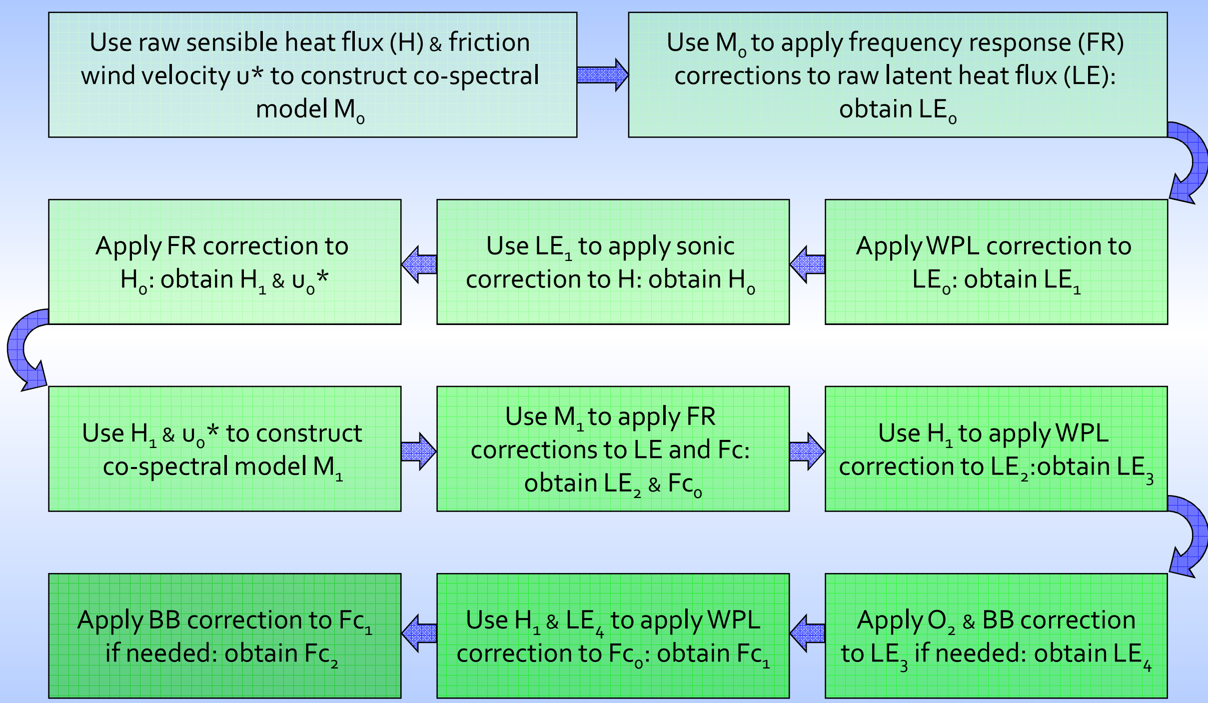
More information on the best approach to filtering for specific situations can be found in Chapter 2 of the "Handbook of micrometeorology. A guide for surface flux measurement and analysis" and in Baldocchi's article on the web titled "Advanced Topics in Biometeorology and Micrometeorology":

Chapter 2 by Moncrief, Clement, Finnigan and Meyers (pp. 7-30) of Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

http://nature.berkeley.edu/biometlab/espm228/
Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

Choosing a time constant recursive filter for de-trending, especially non-linear, i.e. removing a mean is not the same as choosing an averaging period. However, often people just use block averaging for the same period as averaging.

APPLYING CORRECTIONS



Applying corrections can be a complicated and iterative process, especially if using one's own custom code. Following a fixed sequence of steps is very important. The diagram on this page gives one example of the workflow for applying the corrections. FR refers to frequency response corrections, WPL – to the Webb-Pearman-Leuning density term, O_2 stands for the oxygen correction, and BB stands for the band-broadening correction.

Fortunately, such lengthy sequences are usually done automatically by the processing software, and the user only needs to make sure that the order of steps is appropriate, and that no steps are missing. In the latest programs, even the sequence of the steps is usually set automatically.

Please also note that some of the corrections may have been already applied by the instrument manufacturer. Please be sure to consult the factory manuals on this matter.

It appears to be a general consensus that for closed-path measurements, the frequency response corrections are applied before a Webb-Pearman-Leuning correction. For more details refer to Chapter 7 in the "Handbook of micrometeorology. A guide for surface flux measurement and analysis." We will discuss the details of these corrections in the following pages.

Chapter 7 by Massman (pp. 133-158) in [Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp]

Fuehrer, P.L. and Friehe, C.A., 2002. Flux corrections revisited. Boundary Layer Meteorology, 102:415-457

Moncrieff, J.B., Y. Mahli and R. Leuning. 1996. 'The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water', Global Change Biology, 2, 231-240

http://www.eol.ucar.edu/rtf/facilities/isff/heat_fluxes.shtml - Horst, T.W., 2003. Corrections to Sensible and Latent Heat Flux Measurements.

FREQUENCY RESPONSE CORRECTIONS

- Family of corrections compensating for the flux losses at different frequencies (eddy sizes)
- Number of reasons for losses, all related to sensors and EC system frequency response

Frequency response corrections:

Time response
Sensor separation
Scalar path averaging
Tube attenuation
High pass filtering
Low pass filtering
Sensor response mismatch
Digital sampling

Frequency response corrections are a family of corrections that compensate for the flux losses at different frequencies of turbulent transport. There are a number of separate reasons for these losses, but all of them are related to the sensor performance and to the frequency response of the Eddy Covariance system. The main frequency response corrections include the following: time response; sensor separation; scalar/vector path averaging; tube attenuation; high pass filtering; low pass filtering; sensor response mismatch; and digital sampling.

Before discussing each of the frequency response corrections, let's look at an extreme example illustrating the importance of the frequency response in general. Imagine that measurements are taken 30 cm from the ground with a bulky instrument which has a 200 cm path and a sampling frequency of 5 Hz.

Most of the flux transport at this height would be done by very small eddies at very high frequencies. The described instrument would average out most of the transport in the long path, it would miss a good portion of the transport due to its slow 5 Hz sampling rate, and it may generate a relatively large proportion of its own turbulence that is not representative of the environment of interest. As a result, fluxes may be greatly underestimated even after applying large corrections of the order of several hundred percent. Most of the real situations will likely be less extreme, but there can still be many factors responsible for missed flux at different frequencies.

One of the cornerstone papers on the subject is by C.J. Moore, titled "Frequency response corrections for eddy correlation systems." Additional resources on the frequency response corrections can be found below:

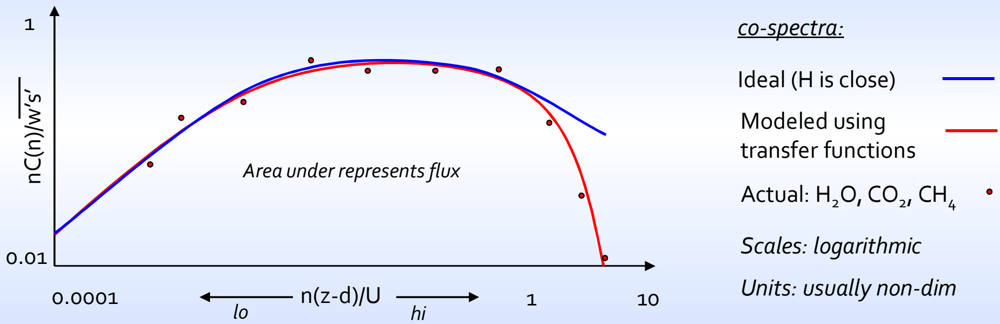
Chapter 4 by Massman, W. and R. Clement (pp. 67-101) in [Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.]

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package. http://www.geo.uni-ayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

CO-SPECTRA

Frequency response corrections are calculated from instantaneous data via co-spectra (distribution of flux transport by frequency):



Transfer functions describe how each sampling problem would affect ideal co-spectra at each frequency

As a first step in the frequency response correction process, let's look at co-spectra. Co-spectra is a distribution of the co-variance of the w' and a scalar by frequency. It is an important component in calculating frequency response corrections. Co-spectra describe how much of the flux is transported at each frequency. It can also be seen as a Fourier transform of the time series into the frequency domain, with the integrated area under the non-dimensional co-spectra curve ideally equal to 1 (representing 100% of the measured flux).

The ideal co-spectra for a given height and condition is usually modeled after Kaimal et al. (1972) and is marked in blue on the plot. Modern sonic anemometers are capable of very fast sampling with small errors over relatively short paths. In addition, since the instantaneous temperature is derived from the same data as w', no sensor separation or time delay occurs between the two signals. Therefore, sonic sensible heat flux co-spectra ($w'T_{sonic}'$) is often close enough to the ideal to not require frequency corrections, especially in the middle of the day with good turbulent exchange high above canopy.

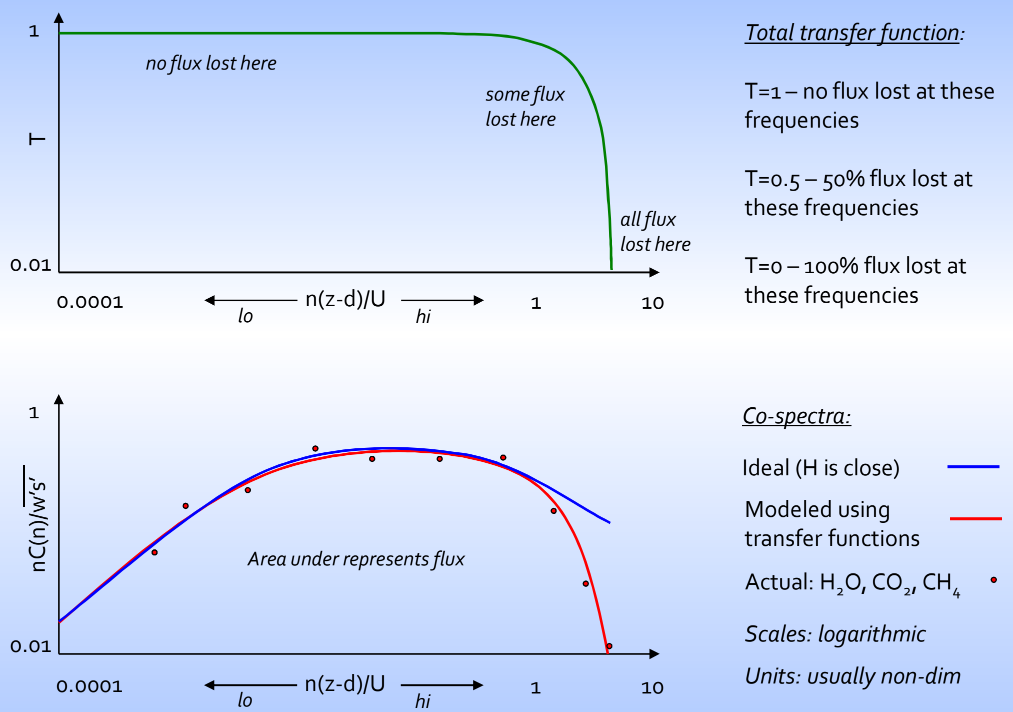
The actual gas flux co-spectra curve is usually located below the ideal or sensible heat flux co-spectra, especially at high frequencies. This position of the curve indicates flux losses related to deficiencies in frequency response when measuring co-variances between w' and instantaneous gas fluctuations. Such deficiencies are due to time response, tube attenuation (for closed path), sensor separation, path averaging, filtering, etc. Functions describing how each of these deficiencies would affect an ideal co-spectra and bring the co-spectra curve down at each frequency are called transfer functions.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y. and Coté, O.R., 1972. Spectral characteristics of surface layer turbulence. Quarterly Journal of The Royal Meteorological Society, 98: 563-589

Su, H.-B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S. and Oliphant, A.J., 2004. Spectral Characteristics and Correction of Long-Term Eddy-Covariance Measurements Over Two Mixed Hardwood Forests in Non-Flat Terrain. Boundary Layer Meteorology, 110: 213-253

TRANSFER FUNCTIONS



Above is an example of how a transfer function predicts what would happen to the ideal (no loss) co-spectrum at given atmospheric conditions due to diminished frequency response at high frequencies.

Please note how the actual and modeled co-spectra decrease below the ideal co-spectrum when the transfer function goes down from 1 at high frequencies.

The total transfer function is a product of the different transfer functions, each of which describes flux losses at specific frequencies due to a specific reason.

If one knew the effect (or the shape) of the transfer function on the co-spectra, one could correct the shape of the actual co-spectra back to the ideal co-spectra, thus correcting the flux and increasing its magnitude.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35.

Chapter 4 by Massman, W. and R. Clement (pp. 67-101) in [Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.]

Moncrieff, J.B., Y. Mahli and R. Leuning. 1996. 'The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water', Global Change Biology, 2, 231-240

APPLYING FREQUENCY RESPONSE CORRECTIONS

- Frequency response corrections can be applied via transfer functions to: (a) Kaimal-Moore's co-spectral models, or (b) actual H co-spectra
- Co-spectral models are perhaps more advisable; they are sets of equations (for unstable, stable and neutral conditions)
- Models use stability parameter (z/L), non-dimensional frequency (f=n(z-d)/U), measurement height (z), zero plane displacement (d), and mean wind speed (U) to come up with co-spectral energy per each frequency (nC(n))
- Co-spectral models are adjusted for the transfer functions at each frequency, and a correction factor is determined for the entire co-spectrum
- Applying all frequency response corrections can increase fluxes up to 30% or more; correction are often larger at night

In general, frequency response corrections can be applied via transfer functions either to Kaimal-Moore's co-spectral models, or to actual sensible heat flux co-spectra. Using co-spectral models is, perhaps, more advisable, because they are independent of potential errors or instrumental problems with sensible heat flux co-spectra.

Co-spectral models are sets of equations for unstable, stable and neutral conditions. They use parameters for: stability (z/L), non-dimensional frequency (f=n(z-d)/U), measurement height (z), zero plane displacement (d), and mean wind speed (U), to come up with co-spectral energy for each frequency (nC(n)).

The co-spectral model is adjusted for the transfer functions at each frequency, and a correction factor is determined for the entire co-spectrum based on the integrated area under the actual co-spectra curve in comparison with the ideal co-spectra (a value of 1).

Applying all frequency response corrections can increase fluxes by up to 30% or more, especially at night.

It is also important to note, there is an alternative method to computing frequency response corrections proposed by Bill Massman in a paper titled "A simple method for estimating frequency response corrections for eddy covariance systems." A complete reference is listed in the References section at the end of this book.

Moore, C. 1986. Frequency response corrections For eddy covariance systems. Boundary Layer Meteorology. 37, 17-35

Kaimal, J.C., Wyngaard, J.C., Izumi, Y. and Coté, O.R., 1972. Spectral characteristics of surface layer turbulence. Quarterly Journal of the Royal Meteorological Society, 98: 563-589

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package. http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf

TIME RESPONSE

- To compensate for the loss of flux due to inability of sensors to respond fast enough to small fluctuations which contribute to the flux
- Time response transfer function is applied to fluxes of H_2O, CO_2, CH_4

$$T_\tau(n) = \frac{1}{\sqrt{1+(2\pi n\tau)^2}}$$

$T\tau$ – transfer function for time response
n - frequency
τ – dynamic time response of the sensor

Let's briefly go through the frequency response corrections and the associated transfer functions one-by-one, and construct a total transfer function required for the correction factor that was described on the previous page.

The first one is a time response correction. This correction compensates for the loss of flux due to the inability of sensors to respond fast enough to small fluctuations contributing to the flux. The associated transfer function is usually applicable to gas and water fluxes. However, theoretically, it is also needed for sensible heat and momentum fluxes, when the measurements are done very close to the ground, or when the time response of the sensor is insufficient.

This and other transfer functions are usually incorporated into the processing software, but it is still useful to understand what factors are responsible for flux reduction. For example, in the case of the time response correction, the key responsible factor is dynamic time response of the sensor, as can be seen from the equation at the top of this page.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://nature.berkeley.edu/biometlab/espm228Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

SENSOR SEPARATION

- To compensate for the loss of flux due to the inability of the vertical wind speed and scalar sensors to sample in the same volume
- Usually applied to fluxes of H_2O, CO_2, CH_4, *etc.*
- Not for H: “T” is often sampled in same volume as “w” by sonic anemometer

$$T_s(n) = e^{-9.9(np_{xy}/\bar{u})^{1.5}}$$

T_s – transfer function for sensor separation
p_{yx} – sensor separation distance
u – mean wind velocity

The horizontal sensor separation correction compensates for the loss of flux due to the inability of the vertical wind speed and scalar sensors to be sampled in exactly the same volume. It is usually applied to gas and water fluxes, but not to sensible heat (~w’T’) and momentum (~w’u’) fluxes. For momentum and sensible heat fluxes, the sonic anemometer samples vertical and horizontal wind speed and instantaneous temperature in the same volume at the same time so a separation correction is not required.

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package. http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://www.eol.ucar.edu/rtf/facilities/isff/heat_fluxes.shtml - Horst, T.W., 2003. Corrections to Sensible and Latent Heat Flux Measurements

TUBE ATTENUATION

- To compensate for the loss of flux due to the fact that sampling air through the inlet tube attenuates (dampens) small fluctuations
- Required for closed path analyzer fluxes of CO_2, H_2O, CH_4

$$T_t(n) = e^{-4\pi^2 \Lambda a L n^2 / \overline{u}_t^{\,2}}$$

T_t – transfer function for tube attenuation
Λ – attenuation parameter for each gas
a – tube radius
L – tube length
u_t – mean tube flow velocity

A tube will always attenuate (or dampen) small fluctuations in flow drawn through it. The tube attenuation correction compensates for the loss of flux that occurs due to this damping of the sampled air through the inlet tube. This correction is applied to gas and water fluxes measured with a closed-path sensor.

It also can be used as a tool to determine what intake tube length is sufficient to attenuate most of the temperature fluctuations. In that case the sensible heat portion of the WPL correction would become negligible.

The mean tube flow velocity can be computed as a flow rate divided by the cross-sectional area of the tube. For further details on this and other attenuation parameters, please refer to the Massman (1991) reference below.

There is growing evidence that attenuation of water vapor flux can be significantly affected by relative humidity, in addition to the tube length and diameter, flow rate, wall cleanliness, and wall and air temperatures.

A slightly different formulation is provided in [http://nature.berkeley.edu/biometlab/espm228/ Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

Massman, W.J., 1991. The attenuation of concentration fluctuations in turbulent flow through a tube. Journal of Geophysical Research, 96 (D8): 15269-15273

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Massman, W.J., Ibrom, A., 2008. Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow. Atmospheric Chemistry and Physics, 8(20): 6245-6259

DIGITAL SAMPLING

- To compensate for the aliasing during the digital sampling
- Applies to all fluxes
- Often assumed negligible

$$T_{ds}(n) = 1 + \left(\frac{n}{n_s - n}\right)^3$$

for $n<=n_s/2$

T_{ds} – transfer function for digital sampling
n_s – sampling frequency (ex: 10 or 20 Hz)

A digital sample takes a 'snapshot' of the value being measured at one instance in time. Some time passes (maybe only a fraction of a second) and then another 'snapshot' is taken. Since the measurement is not continuous there can be errors introduced into the final values. The digital sampling correction compensates for digital sampling errors. It applies to all fluxes.

This and other computations are done for the frequencies below the critical, or Nyquist, frequency ($n<=ns/2$) to avoid aliasing in the rightmost part of co-spectra for frequencies above the Nyquist frequency ($>ns/2$).

Digital sampling corrections, as well as all subsequent frequency response corrections, are often assumed negligible for modern instruments. However, caution should be exercised when experimenting with novel or custom-made instruments, or non-standard settings and conditions.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://nature.berkeley.edu/biometlab/espm228Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

PATH AND VOLUME AVERAGING

- To compensate for the loss of flux due to the fact that very small eddies are lost when averaged over a path (not a point)
- Applied to all scalar fluxes

$$T_{sp}(n) = \sqrt{\frac{3 + \exp(-2\pi n \frac{p_s}{u}) - (\frac{4}{2\pi n \frac{p_s}{u}})(1 - \exp(-2\pi n \frac{p_s}{u}))}{2\pi n \frac{p_s}{u}}}$$

T_{sp} – transfer function for scalar path averaging
p_s – scalar path length
u – mean wind velocity

- There is a similar correction for momentum: vector path averaging

Path or volume averaging corrections compensate for the loss of flux due to the loss of very small eddies. These eddies are lost when averaged over a path and are not sampled in just one point.

This correction applies to all scalar fluxes, and has a special formulation for the case of momentum flux that has a vector path average.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package.

HIGH-PASS FILTERING

- To compensate for the loss of flux in the low frequency part of co-spectrum due to averaging, linear de-trending, or non-linear filtering
- Applies to all fluxes; example of recursive high-pass filter:

$$T_{hi}(n) = \frac{2\pi n \tau_f}{\sqrt{\dfrac{1+\dfrac{(2\pi n \tau_f)^2}{1}}{(1+\dfrac{1}{\tau_f n_c})}}}$$

T_{hi} – transfer function for high pass filtering
τ_f – high pass filter constant
n_c – cutoff frequency; ½ sampling frequency

High-pass filtering corrections can sometimes be used to compensate for the loss of flux that occurs in the low frequency part of a co-spectrum due to: averaging, linear de-trending, or non-linear filtering. It applies to all fluxes.

Anti-aliasing filters are often not recommended.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://nature.berkeley.edu/biometlab/espm228
Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

LOW-PASS FILTERING

- To compensate for the loss of flux in the high frequency part of co-spectrum mostly due to use of the anti-aliasing filters
- Applies to all fluxes; example of recursive low-pass filter:

$$T_{lo}(n) = 1 - \frac{2\pi n \tau_f}{\sqrt{1 + \frac{(2\pi n \tau_f)^2}{\frac{1}{(1 + \frac{1}{\tau_f n_c})}}}}$$

T_{lo} – transfer function for low-pass filtering
τ_f – low-pass filter constant
n_c – cutoff frequency; ½ sampling frequency

Low-pass filtering corrections can sometimes be used to compensate for the loss of flux in the high frequency part of a co-spectrum.

These losses are due mostly to the use of anti-aliasing filters. It also applies to all fluxes.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://nature.berkeley.edu/biometlab/espm228 Baldocchi, D. 2006. Advanced Topics in Biometeorology and Micrometeorology

SENSOR RESPONSE MISMATCH

- Sometimes used in data processing programs (e.g. EdiSol) to compensate for differences when slower-response and faster-response instruments work together
- Often assumed to be negligible or incorporated as a part of the time delay correction when using circular correlation

$$T_m(n) = \frac{1 + (2\pi n)^2 \tau_1 \tau_2}{\sqrt{(1 + (2\pi n \tau_1)^2) + (1 + (2\pi n \tau_2)^2)}}$$

T_m – transfer function for sensor resp. mismatch
τ_1 – dynamic time response of sensor 1
τ_2 – dynamic time response of sensor 2

Sensor response mismatch corrections are sometimes used in data processing programs (e.g. EdiSol) to compensate for differences when both slower-response and faster-response instruments are used together.

This correction is often assumed negligible or incorporated as a part of time delay correction when using circular correlation.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

TOTAL TRANSFER FUNCTION

time response for each of two individual signals

because filtering was done for each of 2 signals

$$T_{all}(n) = T_{\tau c}(n) T_{\tau w}(n) T_t(n) T_{ds}(n) T_s(n) T_{hi}^2(n) \sqrt{T_{sp}(n) T_{vp}(n)}$$

Some researches use square root of T_t depending on how they write their T_t function

because these functions were developed for the spectrum (loss in signal squared)

- Total transfer function is a product of individual transfer functions
- Important moment - to avoid double-correcting or under-correcting
- Depending on particular system - not all transfer functions may be needed

Here is an example of the total transfer function, which is the product of several individual transfer functions.

It is important to avoid double-correcting or under-correcting during this process, especially when a flux processing routine is custom written.

For example, sensor response mismatch may have already been fully or partially compensated by circular correlations to determine a time delay.

Depending on the particular system - not all transfer functions may be needed. They can be removed from the total equation or set to 1 (which has no effect on flux loss).

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

http://nature.berkeley.edu/biometlab/espm228 Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

FREQUENCY RESPONSE SUMMARY

- Intended to compensate for the flux losses at different frequencies due to diminished frequency response of the Eddy Covariance system
- Main corrections include: time response, sensor separation, scalar and vector path averaging, tube attenuation, high and low pass filtering, digital sampling, sensor response mismatch
- Applied to a co-spectra via transfer functions describing losses at each frequency for each individual reason
- Main pitfalls: not correcting, double-correcting, under-correcting

In summary, frequency response corrections are intended to compensate for the flux losses at different frequencies due to a diminished frequency response of the Eddy Covariance system.

Key corrections include: time response, sensor separation, scalar and vector path averaging, and tube attenuation. High and low pass filtering, digital sampling, and sensor response mismatch may also be important in some conditions.

Frequency response corrections are usually applied to a co-spectrum via transfer functions that describe losses at each frequency. The main pitfalls during this process are: not correcting, double-correcting, and under-correcting.

The majority of the commercially available software and free software take care of this step internally. In most cases, the researcher just needs to make sure to enter the right parameters into the software, and to use this software before WPL and other corrections are applied.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35.

CHOOSING TIME AVERAGE

- Averaging interval should not be too long - such that non-turbulent transfer could contribute, diurnal cycle is not seen, or too small - such that high-pass filtering may lead to missed input from larger eddies and to a reduction in flux

- Several ways to decide on averaging time, for example:

  Mandatory - use standard times 30 min or 1 hour – may not be best for all conditions

  Empirical - attempt different reasonable averaging times (e.g., 10 min, 30 min, 1 hr, 2 hrs, 4 hrs); choose the one with largest flux

  Ogives method – cumulative co-spectra constructed over range of frequencies; the point after which no flux added is used as averaging time

The averaging interval should not be too long. If it is too long, it may include slow, non-turbulent contributions to the turbulent flux. Also, the diurnal cycle of the measured flux may be masked or eliminated by intervals of 5-6 hours or longer. The averaging interval must also not be too short. If it is too short it can lead to an effect similar to a high pass filter that will result in missed contributions from lower frequencies, and finally to underestimation of the measured flux. There are several ways to choose an averaging time. The most widely used approaches are mandatory, empirical and ogives.

The mandatory approach simply uses standard averaging times of 30 min or 1 hour. It is easy to execute, and it works well for many traditional settings, but it may not be best for all conditions. The empirical approach analyses the data with different (reasonable) averaging times (e.g., 10 min, 30 min, 1 hr, 2 hrs, 4 hrs), and chooses the one with largest flux. The ogives method relies on cumulative co-spectra constructed over a range of frequencies. At some point as the accumulated period is lengthened, no more flux is added. This then becomes the best averaging time. This is, perhaps, the most flexible and justified approach, but it requires substantial data processing and analysis. The method is described in detail in pages 18-21 in the Lee, Massman and Law's Handbook on Micrometeorology.

It is important to note that while they are usually done together, choosing an averaging period does not have to be the same as choosing a time constant recursive filter for detrending, especially in non-linear cases.

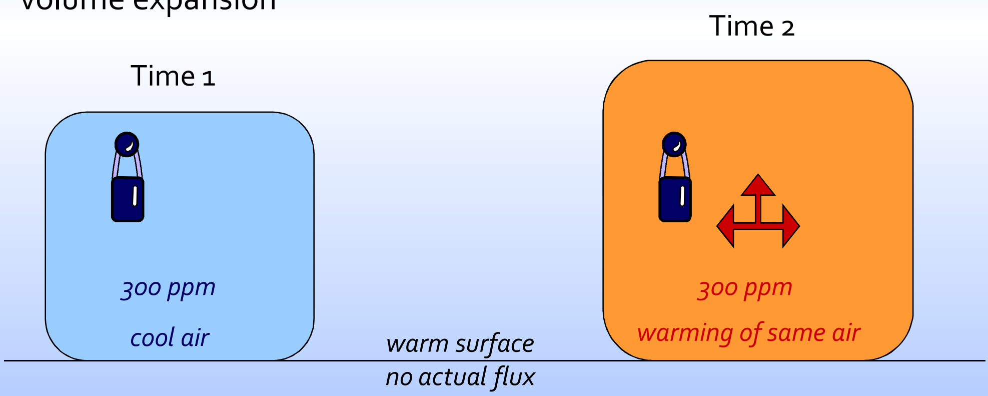
Chapter 2 by Moncrief, Clement, Finnigan and Meyers (pp. 7-30) of the Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

Finnigan, J.J., Clement, R., Malhi, Y., Leuning, R. and Cleugh, H.A., 2003. A Re-Evaluation of Long-Term Flux Measurement Techniques Part I: Averaging and Coordinate Rotation. Boundary-Layer Meteorology, 107: 1-48

Page 114 in Micrometeorology, 2009. By T. Foken. Springer-Verlag.

WEBB-PEARMAN-LEUNING CORRECTION

- Compensates for the effects of fluctuations of temperature (thermal expansion) and water vapor (dilution) on measured fluctuations in CO_2, H_2O, and other gases.
- One way to understand this process is by imagining a surface with actual zero flux and with warming air of constant gas concentration
- As a result of the warming, the instrument measures flux because of volume expansion



Adopted from Baldocchi, 2006

The Webb-Pearman-Leuning term, (often referred to as WPL, or "density term"), is used to compensate for the fluctuations of temperature and water vapor that affect the measured fluctuations in CO_2, H_2O, and other gases. One way to visualize this process is by simply imagining a surface that has an actual zero flux covered with warming air of constant gas concentration. As a result of the warming, an instrument would measure a flux simply because of volume expansion.

A more detailed way to visualize the WPL term is to imagine the process at a high frequency scale, for example, 10 Hz. If a CO_2-inert surface is warm and wet, then high-frequency updrafts in the vertical wind speed, w', would be a little warmer and a little wetter than downdrafts, because this indicates transport of the heat and water up from the surface into the atmosphere. So, then, for CO_2 flux, updrafts would have slightly lower CO_2 density than downdrafts, even though the averaged numbers may stay the same.

This high-frequency process can create an appearance of CO_2 uptake when there is no actual CO_2 flux, just because the surface is warm and or wet, or both.

The original reference for the above correction, also called density corrections, is [Webb, E.K., G. Pearman and R. Leuning. 1980. 'Correction of flux measurements for density effects due to heat and water vapor transfer', Quarterly Journal of Royal Meteorological Society, 106, 85-100].

http://nature.berkeley.edu/biometlab/espm228/
Baldocchi, D. 2006. Advanced Topics in Biometeorology and Micrometeorology

Ham, J.M. and Heilman, J.L., 2003. Experimental Test of Density and Energy-Balance Corrections on Carbon Dioxide Flux as Measured Using Open-Path Eddy Covariance. Agron J, 95(6): 1393-1403

Leuning and Massman in their respective chapters 6 and 7 (pp. 119-158) of the Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

WEBB-PEARMAN-LEUNING (CONTINUED)

- Relatively small during the growing season and relatively large during the off-season (could reach several times the actual flux)
- Applies to CO_2, LE, CH_4 or any other trace gas flux
- Equation here is for open path (closed-path is different):

$$Fc = Fc_o + \mu \frac{E}{\rho_d} \frac{q_c}{1 + \mu \frac{\rho_v}{\rho_d}} + \frac{H}{\rho C_p} \frac{q_c}{T_a}$$

Fc – final corrected flux	*q_c – mean CO_2 density*	*C_p – air, specific heat*
Fc_o – uncorrected flux	*ρ_d – dry air density*	*T_a – air temperature in K*
E – evapotranspiration	*ρ_v – H_2O vapor density*	*μ – ratio of mol. masses of air to water, μ=1.6077*
H – sensible heat flux	*ρ – total air density*	

The WPL term is usually relatively small during the growing season and relatively large during the off-season, when it could reach values several times the actual flux. It applies to CO_2, LE, CH_4 or any other trace gas flux via the general equation for open-path measurements that has been presented here. For closed path instruments, the last portion of the equation (sensible heat flux portion) is usually not used, because temperature fluctuations are assumed to be attenuated in the sampling tube. While this is true for long intake tubes, a sensible heat flux effect may not be entirely eliminated by tubes with lengths less than 50-100 cm or more depending on the internal diameter.

WPL terms are also not required in some instruments, such as LI-7200, that are capable of outputting true mixing ratio, or dry mole fraction, at high speed. When these output units are used for computing Fc_o, thermal expansion and water dilution of the sampled air have already been accounted for in the output.

Please also note the important differences between equations 12 and 24 in the original paper on WPL [Webb, E.K., G. Pearman and R. Leuning. 1980. 'Correction of flux measurements for density effects due to heat and water vapor transfer', Quart. J. Royal Met. Soc., 106, 85-100]. The former equation is for the uncorrected covariances, while the latter is for the final fluxes. The pressure fluctuation effect is routinely ignored in the above formulations, but may become significant during high winds, at high elevations, and in complex terrain.

Recently, an alternative form of WPL correction was proposed by Liu in "An Alternative Approach for CO_2 Flux Correction Caused by Heat and Water Vapour Transfer". Currently, it remains a subject of debate in the scientific community.

Liu H (2005) An Alternative Approach for CO_2 Flux Correction Caused by Heat and Water Vapour Transfer. BLM, 115, 151-168

Ham, J.M. and Heilman, J.L., 2003. Experimental Test of Density and Energy-Balance Corrections on Carbon Dioxide Flux as Measured Using Open-Path Eddy Covariance. Agron J, 95(6): 1393-1403

Leuning and Massman in their respective chapters 6 and 7 (pp. 119-158) of the [Lee, X., Massman, W. and Law, B.E., 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.]

INSTRUMENT SURFACE HEATING CORRECTION

Traditional WPL Term

$$F_{ct} = F_{co} + \underbrace{1.6077\frac{E_t}{\rho_d}\frac{q_c}{1+1.6077\frac{\rho_v}{\rho_d}}}_{\text{Water Flux Term (water dilution)}} + \underbrace{\frac{S_s}{\rho C_p}\frac{q_c}{T_a}}_{\text{Heat Flux Term (thermal expansion)}}$$

$$E_t = \underbrace{(1+1.6077\frac{\rho_v}{\rho_d})E_o}_{\text{Water Flux Term (water dilution)}} + \underbrace{(1+1.6077\frac{\rho_V}{\rho_d})\frac{S_s}{\rho C_p}\frac{\rho_v}{T_a}}_{\text{Heat Flux Term (thermal expansion)}}$$

$$F_{cnew} = F_{co} + 1.6077\frac{E_{new}}{\rho_d}\frac{q_c}{1+1.6077\frac{\rho_v}{\rho_d}} + \frac{(S_s + Added\_Heating)}{\rho C_p}\frac{q_c}{T_a}$$

$$E_{new} = (1+1.6077\frac{\rho_v}{\rho_d})E_o + (1+1.6077\frac{\rho_V}{\rho_d})\frac{(S_s + Added\_Heating)}{\rho C_p}\frac{\rho_v}{T_a}$$

$$F_{cnew} = \underbrace{F_{ct}}_{\text{Traditionally corrected flux}} + \underbrace{\frac{Added\_Heating}{\rho C_p}\frac{q_c}{T_a}(1.6077\frac{\rho_v}{\rho_d}+1)}_{\text{Correction due to added surface heating}}$$

This correction adjusts sensible heat flux portion of WPL term for small amount of heat added into the open path by an instrument surface.

Here and in further discussion on surface heating effect, we use S instead of H, and E_t instead of LE to distinguish in-path fluxes from the ambient.

The correction is usually important only for CO_2 fluxes in extremely cold conditions when using older open-path instruments (e.g., original LI-7500, *etc.*). Closed-path and enclosed instruments (*e.g.*, LI-7200 and LI-7000) are not affected in principle, because of temperature attenuation in the intake tube.

Newer open-path instruments (*e.g.*, LI-7500A, and LI-7700) may not be affected, or may be affected very little, because of low heat dissipation and different shape.

The hourly surface heating correction is quite small even in the cold (an order of magnitude smaller than WPL correction, and on the same order as open-path frequency response correction), and usually negligible in cool and warm conditions. It is often confused with other processes and should be treated with caution.

In situations when this correction is required, it can be easily measured with PRT wire with a few fast thermocouples in the path. It also can be estimated for past data, especially when analyzer was positioned nearly vertical.

This is a new correction, and a lot of questions are asked about it. While more studies are certainly needed regarding surface heating phenomenon, the latest details and explanations are provided in the Section II.4 of this guide.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

Grelle, A., and G. Burba, 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agricultural and Forest Meteorology, 147: 48–57

Jarvi, L., I. Mammarella, W. Eugster, A. Ibrom, E. Siivola, E. Dellvik, P. Keronen, G. Burba, and T. Vesala, 2009. Comparison on net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment. Boreal Environment Research, ISSN 1239-6095 (14): 14pp.

SONIC CORRECTION

- To compensate for humidity fluctuations and momentum flux affecting sonic temperature measurements
- Applies to sonic sensible heat flux
- Some instruments have momentum fluctuations portion of the correction applied in their software

$$\boxed{H = \rho C_p \overline{w'T_a'} + \underbrace{\rho C_p \frac{-0.51\overline{T}\,\overline{w'p_v'}}{\overline{\rho}_a}}_{\text{humidity fluctuations portion}} + \underbrace{\rho C_p \frac{\overline{u}\,\overline{T_a}\,\overline{u'w'}}{63012.50}}_{\text{momentum fluctuations portion*}}}$$

Sonic correction applies to a sensible heat flux measured with sonic anemometer - thermometers. It compensates for humidity fluctuations and momentum flux affecting sonic temperature measurements.

A sonic correction is an additive correction, consisting of the humidity fluctuations and momentum fluctuations combined with sensible heat flux to produce the final corrected flux value, as shown in the equation on this page.

Before applying this correction, it is important to refer to the user manual for the specific sonic anemometer to make sure that the correction was not already partially applied by the manufacturer in the instrument software. Momentum fluctuations portion of the correction is instrument-specific and may not be the same as on the example equation on this page.

It is also important to distinguish the sonic heat flux correction from the sonic temperature correction. A sonic temperature correction is a correction of the sonic temperature measurement and is not a flux correction. However, sonic temperature corrections may still be important for flux calculations, especially if the mean air temperature used in the various calculations comes from the sonic measurements.

Pages B-1 – B-5 in: http://www.campbellsci.com/documents/manuals/opecsystem.pdf. CSI, Inc. 2004-2006. Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH20.

Schontanus, P., Nieuwstadt, F.T.M. and de Bruin, H.A.R. 1983. Temperature measurements with a sonic anemometer and its application to heat and moisture fluxes. B.Layer Meteorology. 26, 81-93

http://www.eol.ucar.edu/rtf/facilities/isff/heat_fluxes.shtml - Horst, T.W., 2003. Corrections to Sensible and Latent Heat Flux Measurements

Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf

EXAMPLES OF OTHER CORRECTIONS

- *Oxygen correction:*

  Compensates for krypton hygrometer sensitivity to oxygen

  Applies to krypton hygrometer's LE

- *Foreign gas (band broadening) correction in NDIR measurements:*

  Compensates for the broadening of CO_2 IR absorptions band due to the presence of other gases in the sampling volume

  Applies to CO_2, may apply to other gases depending on instrument

  See LI-COR application note for details

These are several less common and instrument-specific corrections, such as oxygen and band broadening corrections for NDIR measurements.

Oxygen correction compensates for sensitivity to oxygen for a specific instrument, i.e., a krypton hygrometer, and is applied to a latent heat flux measured with this instrument. More information on the oxygen correction can be found below.

The band broadening correction compensates for the broadening of the CO_2 infrared absorption band due to the presence of water molecules in the sampling volume. It applies primarily to CO_2 flux measured with infrared gas analyzers, but may apply to other gases depending on the instrument. A similar band-broadening effect of oxygen is usually assumed negligible, since oxygen concentration is not as variable as water vapor.

The latest state of the art gas analyzers (*e.g.*, LI-7000, LI-7200 and LI-7500A) have this correction applied automatically in the instrument software. Older instruments or instruments by other manufacturers may require applying this correction. Please refer to specific instrument manuals for details. The principles of band broadening and related practical applications can be further studied in the references listed below.

McDermitt, D. K., Welles, J. M., Eckles, R. D., 1993: Effects of temperature, pressure and water vapor on gas phase infrared absorption by CO_2. LI-COR Application Note.

Chen, W.J., T.A. Black, P.C. Yang, A.G. Barr, H.H. Neumann, Z. Nesic, P.D. Blanken, M.D. Novak, J. Eley, R.J. Ketler, and R. Cuenca. 1999. Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. Global Change Biology 5: 41-53

Tanner, B.D., Swiatek, E. and Greene, J.P., 1993. Density fluctuations and use of the krypton hygrometer in Surface flux measurements. In: R.G. Allen (Editor), Management of irrigation and drainage systems: integrated perspectives. American Society of Civil Engineers, NY, pp. 945-952.

van Dijk, A., Kohsiek, W. and DeBruin, H.A.R., 2003. Oxygen sensitivity of krypton and Lyman-alpha hygrometers. Journal of Atmospheric and Oceanic Technology, 20: 143-151.

EXAMPLES OF OTHER CORRECTIONS (cont.)

- *Spectroscopic corrections in narrow-band or single line laser instruments:*

  recent laser-based technologies including WMS, ICOS, CRDS, *etc.*

  measurements may be affected by temperature, pressure, water, other gases, and by isotopes of the measured gas, *etc.*

  these effects are different from the Ideal Gas Law effects, such as temperature and pressure expansion/contraction and water dilution

  spectroscopic effects for laser-based measurements need to be corrected based on the specific technology, and on how it is used in a specific gas analyzer

In recent years the use of laser technologies for fast gas measurements has led to a development of a number of laser-based gas analyzers for Eddy Covariance flux measurements.

Instantaneous values of gas density measured by these analyzers for the purposes of flux measurements are affected by several important processes: (1) thermal expansion due to sensible heat flux; (2) water vapor dilution due to latent heat flux; (3) pressure-related expansion or contraction, and (4) spectroscopic effects, discussed in detail in Rothman *et al.* (2009).

The Webb-Pearman-Leuning terms (WPL; Webb et al., 1980) allows compensating for the instantaneous thermal expansion effect via sensible heat flux term, and compensate for instantaneous water vapor dilution effect via latent heat flux term, normally using statistics collected over 30 minutes to several hours.

Pressure-related expansion or contraction is usually neglected, but one may consider pressure effects if the study site is at high elevation. The correction can be done as part of the WPL using a third pressure term.

Spectroscopic effects are not corrected in WPL terms, because latter were developed based on NDIR technology, in which the spectroscopic effects (*e.g.*, line broadening) are quite small and usually corrected onboard of the instruments.

Depending on the specific instrument design, laser technology, and sampled absorption lines, the spectroscopic effects on the concentration and flux measurements may include the effects of temperature, pressure, water vapor or other foreign gas, isotopic composition of the sampled gas, etc.

The spectroscopic effects of Eddy Covariance flux measurements are not studied as well as Ideal Gas Law effects (*e.g.*, WPL), they may not be linear, and may significantly affect the gas concentration measurements at fast sampling rates, thus affecting the fluxes.

These effects need to be quantified and corrected for in Eddy Covariance flux computations for each specific gas sensing technology and its particular use in a specific instrument model.

SUMMARY OF CORRECTIONS

Procedures	Affected fluxes	Effect	Range
Spike removal	all	depends	0-15%
Time delay	mostly closed path	increases flux	5-15%
Coordinate rotation	all	depends	0-25%
Frequency response corrections	all	increase flux	5-30%
Webb-Pearman-Leuning correction	H_2O, CO_2, CH_4	depends	0-50%
Sonic temperature correction	sensible heat	depends	0-10%
Band-broadening correction for NDIR	mostly CO_2	depends	0-5%
Spectroscopic effects for LASERs	any gas	depends	0-30%
Oxygen correction	some H_2O	depends	0-10%

Since flux measurements are not perfect due to assumptions, instrumental problems, physical phenomena, and specifics of the particular terrain, there are a number of corrections that need to be applied to the raw flux value. The table on this page shows the common corrections, affected fluxes and typical mid-day warm-season ranges of these corrections in relation to the flux.

Please note that even though the size of a correction is shown as a percent of the flux for illustrative purposes, only some of the corrections are multiplicative, while others are additive.

Spike removal is applied to all fluxes, and usually affects not more than fifteen percent of the flux. Good instrument maintenance may help to minimize the effect of data spikes. A time delay correction adjusts the delay in the correlated time series, and is especially crucial for the closed-path systems. The correction may range between five and fifteen percent of the raw flux, and can be applied by shifting two time series in such a way that the covariance between them is maximized, or it can be computed as a theoretical time delay from the known flow rate and tube diameter.

Coordinate rotation corrects for an unleveled sonic anemometer in relation to mean flow, and affects all fluxes because of contamination of the vertical wind speed with a horizontal component. This correction can reach twenty-five percent of the raw flux or more, depending on the leveling of the sonic anemometer.

Frequency response corrections compensate for the flux losses at different frequencies of turbulent transport. They consist of the number of individual corrections (e.g., time response, sensor separation, scalar/vector path averaging, tube attenuation, high pass filtering, low pass filtering, sensor response mismatch, and digital sampling) combined in one final transfer function. They are applied to all fluxes, usually range between five and thirty percent of the flux, and can be somewhat minimized by proper experimental set up.

The Webb-Pearman-Leuning density term affects gas and water fluxes. The size and direction of this additive term varies greatly, from several hundred percent of the flux in winter, to only a few percent in summer. The sonic heat correction compensates for humidity fluctuations and momentum flux affecting sonic temperature measurements and usually affects not more than ten percent of sensible heat flux.

The band-broadening correction mostly affects gas fluxes measured by NDIR, and greatly depends on the instrument used. The correction is usually in the order of zero to five percent, and is either applied in the instrument's software, or described by the manufacturer in the instrument manual.

Spectroscopic effects for recent laser-based technologies may affect fast concentrations and fluxes. The extent is generally specific to the technology, and studied little, and should be treated with caution. Oxygen correction compensates for the oxygen in the path of a krypton hygrometer reading, and is usually not more than ten percent of the raw flux.

Finally, please note that none of these corrections are negligible, and combined, they may easily sum to over one hundred percent of the initial flux value, especially for small fluxes and for yearly integrations. This illustrates how important it is to minimize potential errors during experiment set up, and correct the remaining errors during data processing.

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 4. Surface Heat Exchange and Open-Path Gas Fluxes from Older Analyzers

INSTRUMENT SURFACE HEATING

This section focuses on the following 3 topics: (i) heating correction concept, (ii) the size of correction in comparison with other traditionally applied corrections, such as WPL term and frequency response corrections, (iii) future of open-path approach. The key segments are:

- Brief history of the topic development at LI-COR
- Brief review of the heating concept
- Size of heating effect for CO_2
- Impact of the heating effect on CO_2 budgets
- Impact of the heating effect on H_2O and other gases
- Dealing with past data
- Thoughts on the future of open-path measurements

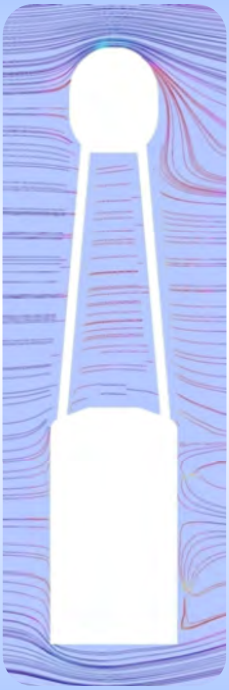
Open-path measurements are useful, low-maintenance, and stable. They have excellent frequency response, low power demands, and are ideal for long-term studies at remote sites. By the nature of their design, open-path instruments are also *open*, and cannot be protected from many influences, especially in case of large amounts of dust, water, and ice.

Many studies show excellent agreement between open-and closed-path eddy covariance flux measurements in warm and cold weather (Billesbach, *et al*., 2001; Miller, *et al*., 2004; Launiainen, *et al*., 2005; Amiro, *et al*., 2006; Morgenstern, *et al*., 2006; Hirata, *et al*., 2007; Haslwanter, *et al*., 2008; Wohlfahrt, *et al*., 2008 ; Clement, *et al*., 2009; *etc.)* And multiple studies confirmed the accuracy of Webb-Pearman-Leuning term (Webb, *et al*., 1980 ; Leuning, *et al*., 1982; Ham and Heilman, 2003; etc.) . Other studies have found some differences between open-path and closed-path measurements (Hirata, *et al*. 2005; Amiro, *et al*., 2006; Grelle and Burba, 2007; Ono, *et al*., 2008; Lafleur and Humphreys, 2008; Burba, *et al*., 2008; Serrano-Ortiz, *et al*., 2008; Jarvi, *et al*., 2009; Leuning, *et al*., 2009 ; Massman, *et al*, 2009; Zhang, *et al*., 2009 ; *etc.)*

Some open-to-closed path differences were attributed to the closed-path approach, such as frequency losses in CO_2 and H_2O fluxes, changes in tube attenuation with time and tube condition, effects of corners and sharp turns at high flow rates, condensation in the long tubes, incomplete T attenuation in short tubes, *etc.* Other differences were attributed to open-path approach, such as data quality during precipitation, fog and icing, residual wetness, severe dust conditions, pressure term, heating in the path, *etc.*

This section is focused on the latter phenomenon, the surface heating in the older open-path gas analyzers, and on the instrument surface heating correction compensating for this effect.

A BRIEF HISTORY AT LI-COR



2005: recognized the existence of heating effect – started experiments to derive corrections for older instrument, and to develop new instrument not susceptible to heating issues

2006: developed correction based on resistance approach, revised the correction based on Nobel (1980) formulation

2007: worked with Dr. Grelle on PRT solution – published paper in AFM (Grelle, *et al.*, 2007)

2008: summarized theory and correction methods in a paper in GCB (Burba, *et al.*, 2008)

2009: finished development of low-power dissipation instrument, LI-7500A, and enclosed low-power instrument not susceptible to heating issues, the LI-7200

A brief history of the LI-COR involvement in the surface heating studies is helpful for understanding the various versions of the theory and different direct and empirical methods for the correction.

In 2005 the existence of the heating effect phenomenon was recognized, and lab and field experiments were started to help develop the early theory. These were presented at the AmeriFlux and AGU 2005 meetings. At this time LI-COR also started to develop an enclosed instrument, which is not susceptible to the heating effect.

In 2006, the correction based on resistance approach was developed and presented at the AFM Meeting . Then the theory was revised based on the Nobel (1980) formulation, and presented at AGU Meeting. In this year we started to work with Dr. Clement on enclosed instrument field comparisons.

In 2007, field comparisons with Dr. Clement continued and a new work with Dr. Grelle on PRT solution was started and published in AFM (Grelle, *et al.*, 2007). We have also worked with Dr. Oechel's group on correcting Arctic data - presented at the AmeriFlux meeting, and continued to further develop theory and corrections. The latest information was presented at AmeriFlux meeting.

In 2008 the theory was summarized and correction methods were published in GCB (Burba, *et al.*, 2008). In this year the work on a low-power dissipation open-path analyzer had started.

In 2009, the enclosed sensor experiments were finished and published in AFM (Clement, *et al.*, 2009). And work with Dr. Vesala group on a new correction method was published in BER (Jarvi et al., 2009). This year we also finished development of low-power dissipation instrument, LI-7500A, and enclosed low-power instrument which is not susceptible to heating issues, the LI-7200.

Overall, 8 field experiments, and a total of 25 presentations of relevant findings were conducted all over the world during 2005-2009.

REVIEW OF HEATING CONCEPT

- As discussed in WPL term section, Eddy flux consists of two major parts: a measured flux and the Webb-Pearman-Leuning terms (thermal expansion and water dilution)

- These terms compensate for fast fluctuations of temperature and water vapor in the air affecting measured gas density

$$\underbrace{F_{ct}}_{\text{Final flux}} = \underbrace{F_{co}}_{\text{Raw flux}} + \underbrace{1.6077\,\frac{E_t}{\rho_d}\,\frac{q_c}{1+1.6077\,\frac{\rho_v}{\rho_d}}}_{\text{Dilution Term}} + \underbrace{\frac{S_s}{\rho C_p}\,\frac{q_c}{T_a}}_{\text{Expansion Term}}$$

Open-path instruments apply both parts of the WPL term, thermal expansion and water dilution, while classical closed-path instruments do not apply the thermal expansion part of WPL because high-speed temperature fluctuations are attenuated in the long intake tubes.

Traditionally, the sensible heat flux (S_s in the equation above) has been measured outside the open path of the gas analyzer by sonic anemometry-thermometry, or with the help of a fine-wire thermocouple installed near the sonic sample path.

Here and in further discussion on surface heating effect, we use S instead of H, and E_t instead of LE to distinguish in-path fluxes from the ambient.

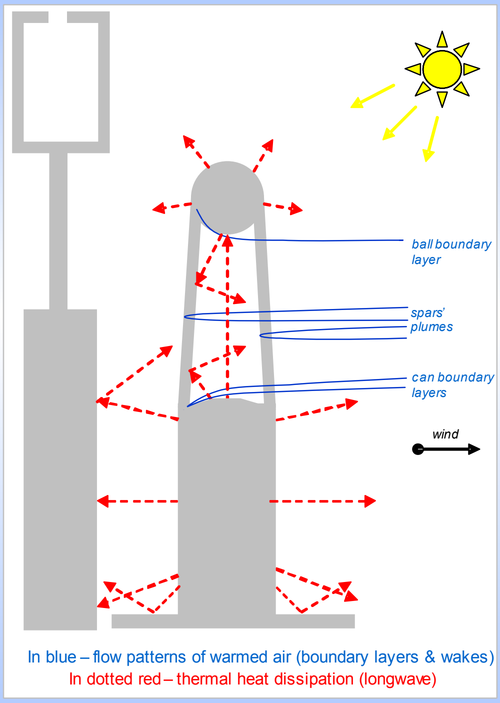
If warm instrument surfaces around the open path heat the air in the path, then there may be non-negligible differences between sensible heat flux inside the open path of the gas analyzer and that in ambient air, such that measured or estimated sensible heat flux inside the open path should be used in the WPL term instead of S_s measured in ambient air. Air temperature, T_a, is affected in a similar manner as S_s, but since it is in degrees K, its effect on the WPL terms is generally negligible.

The basis of the surface heating concept is the following: if instrument surface temperature is substantially different from the ambient temperature, it can lead to sensible heat fluxes inside the open-path cell that are different from those in the ambient air, thus affecting CO_2 densities measured in the instrument path.

It is reasonable to expect some artificial heat fluxes because the instrument surface comprises a heterogeneous spatial distribution of heat sources and sinks adjacent to the open path where measurement takes place. These sources and sinks affect the air in the path by conductive, convective and radiative heat exchange processes. In addition, the turbulence inside the open path itself may become a factor.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876.

VISUALIZATION OF SURFACE HEATING



- Electronics and sun may warm the surface and air in the open sample path
- Wind and long-wave exchange can cool them, or warm them up
- As a result, the temperature of surfaces around the open path may be different from ambient air temperature
- Such differences may result in added heating or cooling of air in the path
- Such additional heating or cooling should be included into WPL term

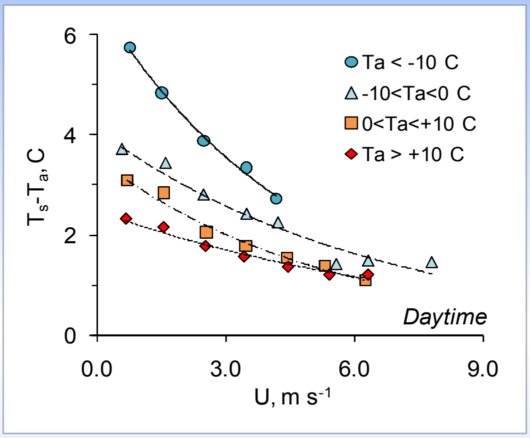
In order to understand how instrument surface heating can lead to apparent CO_2 uptake, let us consider an example of two brief sequential measurement intervals in which the instrument surface is warmer than surrounding air, with no actual ambient CO_2, latent, or sensible heat fluxes, and with no change in actual CO_2 mole fraction.

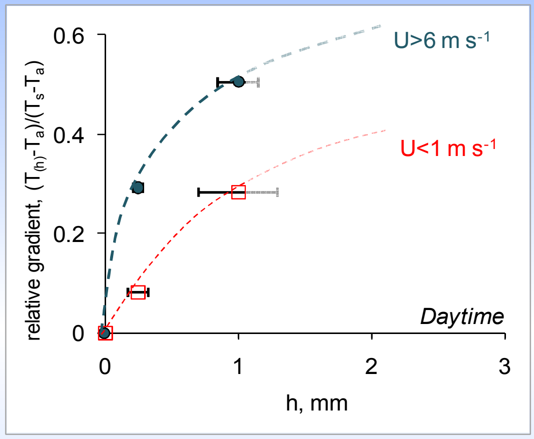
During the first interval, suppose the instantaneous horizontal wind speed is slightly below the average, such that the instantaneous deviation of horizontal wind speed from the mean is negative (u'<0); this means the instantaneous deviation of vertical wind speed from the mean (w') would be positive because momentum flux (w'u' overbar) must be negative, always toward the surface. The instrument surfaces would warm the air parcel to a temperature slightly higher than it was before it entered the optical path, and air expansion would take place. As a result, CO_2 number density would be lower than it would have been without the heating.

During the second interval, the instantaneous horizontal wind speed is slightly above the average, such that the instantaneous deviation of horizontal wind speed from the mean is positive (u'>0), and w' would be negative to keep momentum transfer toward the surface. The air is now heated less than in the first interval, and air expansion is smaller because there is less time for the instrument surface to heat the air in the path, and CO_2 number density would be closer to what it was before the air parcel entered the instrument open path.

Thus, updrafts (w'>0) would have systematically lower CO_2 number density than downdrafts (w'<0). As a result, a false uptake would be measured by eddy covariance with a warm open-path sensor when no actual CO_2, latent, or sensible heat fluxes are occurring in the ambient air outside the instrument path.

IS SENSOR SURFACE REALLY WARMER?





- Electronics and sun could heat the instrument by up to 3-6 °C below -10 °C
- Long-wave exchange cools surface at night, mostly compensating the electronics
- Wind usually cools surfaces during both day and night

- As a result, gradients formed above surface suggest small heat fluxes at daytime
- Most nights have very small or no heating effect in the conducted field studies

The actual surface heating affected by ambient air temperature and wind speed near the lower window of LI-7500 is shown in top left figure with the instrument powered on.

Heat was removed from the surface more effectively at higher wind speeds for all temperature ranges. Increases in wind speed led to decreases in the differences between air temperature and instrument surface temperature, with the largest absolute decrease (from about 6 °C to 3 °C) observed when wind speed increased from 0.5 m s^{-1} to 4.5 m s^{-1} during the coldest air temperatures (<-10 °C). In all cases, winds exceeding 6-8 m s^{-1} reduced heating of the lower window surface to near 1 °C above ambient.

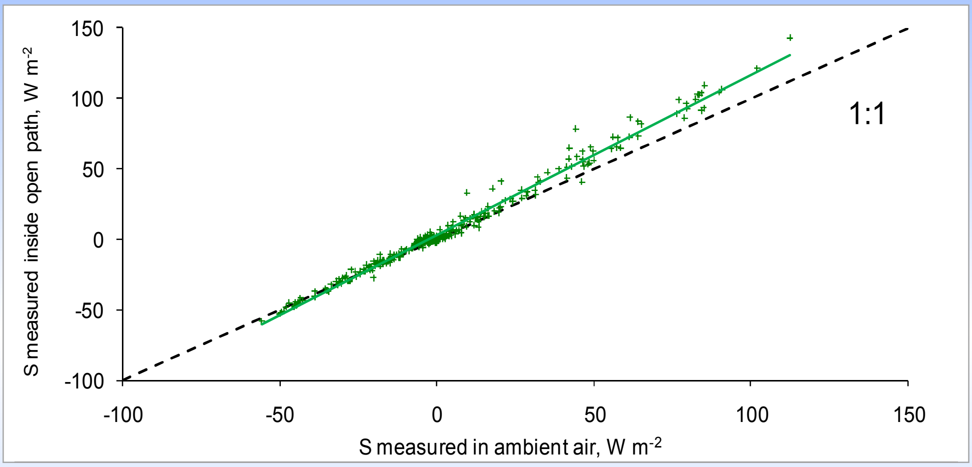
To further examine effects of the wind, temperature gradients above the bottom window were measured with fine-wire thermocouples placed at the window surface, and at 0.5 mm and 1.0 mm above the surface, as well as in the air outside the instrument.

Observed temperature gradients were very steep in the first 1 mm above the bottom window, sometimes exceeding 2.5 °C mm^{-1}. The top right figure shows the fractional change in the temperature gradient with height from the bottom window, for high and low wind speeds, over the duration of the experiment.

As anticipated, stronger winds led to a thinner boundary layer and steeper gradient in the first 1 mm, while weaker winds resulted in a more gradual temperature profile. The relationship also indicates that only 30-50% of the changes occur in the first 1 mm above the bottom window, and suggests that the thermal boundary layer (defined as 99% change; Schlichting, et al. 2004) can be on the order of several millimeters, depending on the wind speed.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

HOW STRONG IS THE HEATING?



- Direct measurements of heat flux inside the path show that instrument surfaces heated air by a small amount, up to 10-20 W m^{-2} above ambient, in the cold
- When not negligible, such "added heat" should be included into WPL term

In the experiment conducted over a CarboEurope site located close to Skyttorp, Sweden (Grelle et al, 2007) a platinum wire resistor (PRT; Johnson Matthey, London, UK; length 600 mm, diameter 0.1 mm) was threaded 6 times up and down around the instrument path volume between the cylinder and the "ball" of the LI-7500, adjacent to the optical path, covering all sectors of wind direction. The sensible heat fluxes adjacent to the LI-7500 optical volume were consistently higher than those outside the path by up to 20 W m^{-2} (Figure above).

This indicated that high-frequency temperature fluctuations from the fine-wire thermometer installed in the optical path of the LI-7500 were well-correlated with vertical wind speed, and that such fluctuations then can affect the WPL density terms for the CO_2 flux when measured by an open-path system.

Higher temperatures and heat fluxes within the LI-7500 optical volume than in the sonic measuring volume were consistent with the concept of instrument-induced heat fluxes.

Grelle, A., and G. Burba, 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agricultural and Forest Meteorology, 147: 48–57

PROPAGATION OF HEATING INTO WPL TERMS

$$F_{ct} = F_{co} + 1.6077\frac{E_t}{\rho_d}\frac{q_c}{1+1.6077\frac{\rho_v}{\rho_d}} + \frac{S_s}{\rho C_p}\frac{q_c}{T_a}$$

$$E_t = (1+1.6077\frac{\rho_v}{\rho_d})E_o + (1+1.6077\frac{\rho_V}{\rho_d})\frac{S_s}{\rho C_p}\frac{\rho_v}{T_a}$$

$$F_{cnew} = F_{co} + 1.6077\frac{E_{new}}{\rho_d}\frac{q_c}{1+1.6077\frac{\rho_v}{\rho_d}} + \frac{(S_s + S_i^{bot} + S_i^{top} + S_{ip}^{spar})}{\rho C_p}\frac{q_c}{T_a}$$

$$E_{new} = (1+1.6077\frac{\rho_v}{\rho_d})E_o + (1+1.6077\frac{\rho_V}{\rho_d})\frac{(S_s + S_i^{bot} + S_i^{top} + S_{ip}^{spar})}{\rho C_p}\frac{\rho_v}{T_a}$$

$$F_{cnew} = \underbrace{F_{ct}}_{\text{Traditionally corrected flux}} + \underbrace{\frac{S_i^{bot} + S_i^{top} + S_{ip}^{spar}}{\rho C_p}\frac{q_c}{T_a}(1.6077\frac{\rho_v}{\rho_d} + 1)}_{\text{Correction due to surface heating}}$$

Since the surfaces of the instrument were sometimes warmer than ambient, some heat fluxes should be generated by the surface.

The propagation of this additional heat from instrument surfaces surrounding the path into the flux calculations can be looked at in the framework of WPL correction and is shown above. The orange fill indicates added heat from bottom window, top window and spars (superscripts “bot”, “top” and “spar” respectively).

These surface heat fluxes can be computed using direct measurements or estimations, and then added to the ambient heat flux in the WPL term.

To directly measure the sum of the ambient and surface heat fluxes inside the open path one can use fine-wire thermometer (Grelle and Burba, 2007), or a set of fast response thermocouples (Massman, *et al.*, 2009).

Also, the added heat can be estimated using models, for example, after Nobel (1983) using measured instrument surface temperatures (Burba, *et al.*, 2008), or using regressions of surface and air temperatures and standard weather data (Burba, et al., 2008), or modeled after Jarvi, *et al.* (2009) using open-path and closed-path parameterization.

Considerable details of the methods correcting for the surface heating are provided in Burba et al. (2008). On the next page, a simple method for estimating surface heating correction based on Nobel formulation is briefly explained.

METHODS FROM GCB, 2008

General Equations		
General equation for the gas flux (F_c) over a homogenous horizontal plain for steady state conditions including WPL term (Webb et al, 1980)	$F_c = F_0 + \mu \frac{E}{\rho_d} \frac{\rho_c}{1 + \mu \frac{\rho_v}{\rho_d}} + \frac{S}{\rho C_p} \frac{\rho_c}{T_a}$	
General equation for the water vapor flux (E) over a homogenous horizontal plain for steady state conditions including WPL term (Webb et al, 1980)	$E = (1 + \mu \frac{\rho_v}{\rho_d})(E_0 + \frac{S}{\rho C_p} \frac{\rho_v}{T_a})$	
Sensible Heat Flux, S, for General Equations		
Traditional WPL correction technique. Sensible heat flux is computed in the ambient air from sonic temperature or from a fine-wire thermocouple in the open air (Baldocchi *et al.*, 1988)	$S = \rho C_p \overline{w'T_a'}$	*Method 1*
Enclosed LI-7500 technique. Sensible heat flux has been eliminated by attenuating temperature fluctuations in the long intake tube. Same principle is used in the reference closed-path measurements (LI-6262 or LI-7000)	$S = 0$	*Method 2*
Fine-wire PRT technique. Sensible heat flux inside the open path is measured directly by fine-wire PRT and used instead of ambient sensible heat flux measured in the open air (Grelle and Burba, 2007)	$S = \rho C_p \overline{w'T_{PRT}'}$	*Method 3*
Estimated heating correction technique. Total sensible heat flux for WPL term is computed by adding estimated sensible heat fluxes from key instrument surfaces (bottom window, top window and spar) around the open-path to the ambient sensible heat flux (Burba, 2006b)	$S = \rho C_p \overline{w'T_a'} + S^{bot} + S^{top} + 0.15 S^{spar}$	*Method 4*
Surface Sensible Heat Fluxes for Nobel Formulation used in Method 4		
Nobel (1983) formulation for S^{bot}, S^{top} and S^{spar}. T_s can be measured, or estimated via linear regression with Ta or via multiple regression with key weather variables	$S^{bot} = k^{air} \frac{(T_s^{bot} - T_a)}{\delta^{bot}}$ $S^{top} = k^{air} \frac{(r^{top} + \delta^{top})(T_s^{top} - T_a)}{r^{top} \delta^{top}}$ $S^{spar} = k^{air} \frac{(T_s^{spar} - T_a)}{r^{spar} \ln(\frac{r^{spar} + \delta^{spar}}{r^{spar}})}$ $\delta^{bot} = 0.004 \sqrt{\frac{l^{bot}}{U}} + 0.004$ $\delta^{top} = 0.0028 \sqrt{\frac{l^{top}}{U}} + 0.00025 / U + 0.0045$ $\delta^{spar} = 0.0058 \sqrt{\frac{l^{spar}}{U}}$	

There are 4 methods tested in the GCB-2008 paper to deal with instrument surface heating. Only Method #4 is suitable for correcting previously collected data, when no in-path temperature is available.

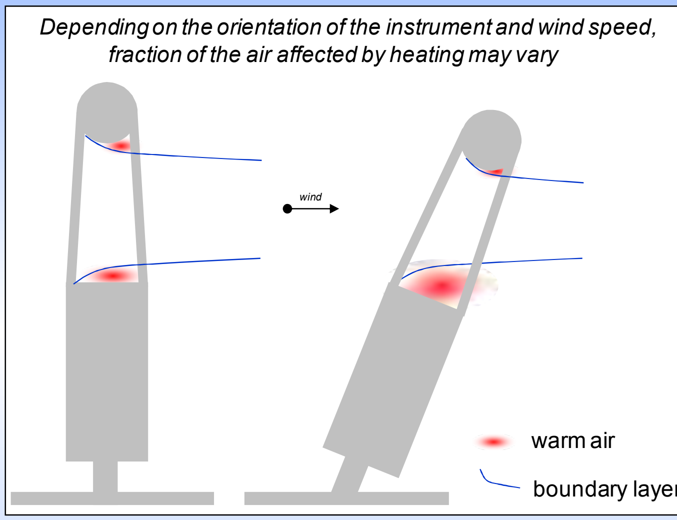
Unlike other 3 tested methods to estimate or measure sensible heat flux inside the open path, the linear or multiple regression techniques (Method 4) require just a few standard measurement inputs, but also they employ very significant assumptions and approximations, specifically:

(i) Surface temperatures are approximated from air temperature by regressions established for one-two instruments;
(ii) It is assumed that relationship holds for all conditions in other instruments, even though, for example snow, rain or dust on the instrument surface can modify the established regression during specific periods;
(i) Nobel formulation is used to compute sensibl- heat from approximated surface temperatures, measured air temperature, and wind;
(iv) It is assumed that Nobel equations are adequate and the same for slightly inclined sensor for all wind directions, and tower settings;
(v) Internal temperature control is assumed to behave identically in all instruments, independently of their age, prior usage, laser and detector conditions, power quality at the site, total power load at the tower, and other important engineering issues.

These are just the few most important examples from a long list of potential factors. Because of these, the expectations of the regression technique performance (Method 4) should not be too high.

It is also important to emphasize that applying heating correction, even by using Method 4, in most cases and for extremely cold sites, is considerably better than not applying it. Not applying the correction is the equivalent of assuming it to be zero.

SENSOR ORIENTATION



As a result, correction may be highly sensitive to:

- instrument orientation
- instrumental setup and wind direction
- thermal inertia during rapid change in ambient T

Orientation of the sensor far away from vertical can change the size of the correction. However, if one relies on the Nobel approach, this error may not be as big as it was in initially used gradient-resistance approach. It is because Nobel considers the average heat flux from the shape, not the heat flux at a specific spot. This approach also sacrifices spatial resolution for the overall robustness and simplicity.

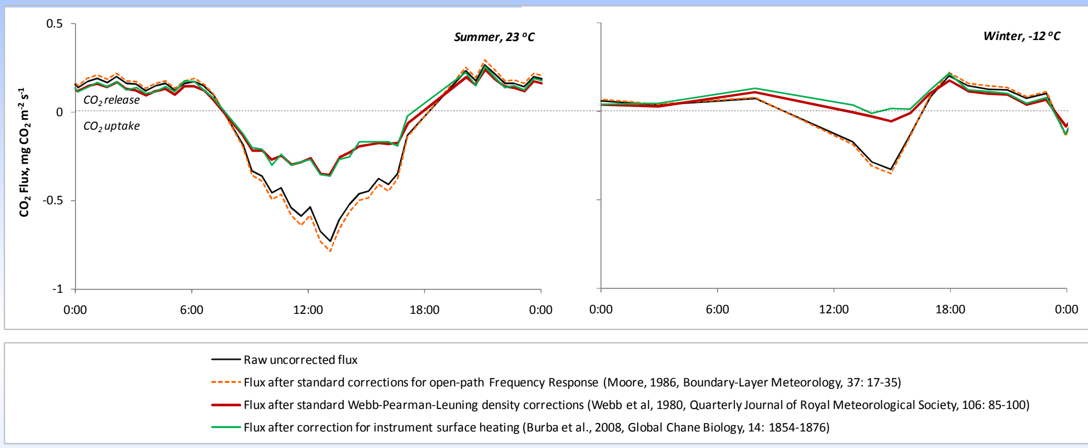
Strong incline of sensor may not be a problem if sensor path is perpendicular to the wind (wind blows "sideways"), may be a small problem when sensor inclined into the wind (ball first, then path, then cylinder), and may be a medium to severe problem when wind blows over the warm cylinder first then into the path and over the ball.

In terms of applying correction directly as shown in the GCB-2008 paper, the inclination of the sensor at 20 degrees from vertical would be close to a borderline situation, while the 15 degree inclination is quite safe, from our experience.

One way to check if the corrections work, or to tune the model, is to look at a few very cold days and to make sure that corrected fluxes are on average close to zero.

Some flux from bare frozen soil is expected, but it should be quite small. Hour-to-hour variability in corrected flux may be present, due to limitations of the estimating of the parameters involved in the model, but corrected daily averaged fluxes on very cold days should be very close to zero.

IMPACT OF HEATING - TWO DAYS IN RYEGRASS



- The heating impact was typically below 0.025 mg, or 0.6 µmol, of CO_2 m^{-2} s^{-1}
- It was about an order of magnitude smaller than WPL correction
- It was similar in magnitude to open-path frequency response corrections
- It was several times below typical closed-path frequency response correction
- The added heat needs to be treated with care, but also with understanding that it is much smaller than many traditional Eddy Covariance corrections

Due to the relative novelty of instrument surface heating concept and related correction, there was a fair amount of concern in the flux community about the size and importance of the effect and correction. In this and next four pages, the brief explanations and examples are provided on the surface heating effect and the correction, putting them into perspective with other traditionally applied errors and corrections for hourly Eddy Covariance fluxes.

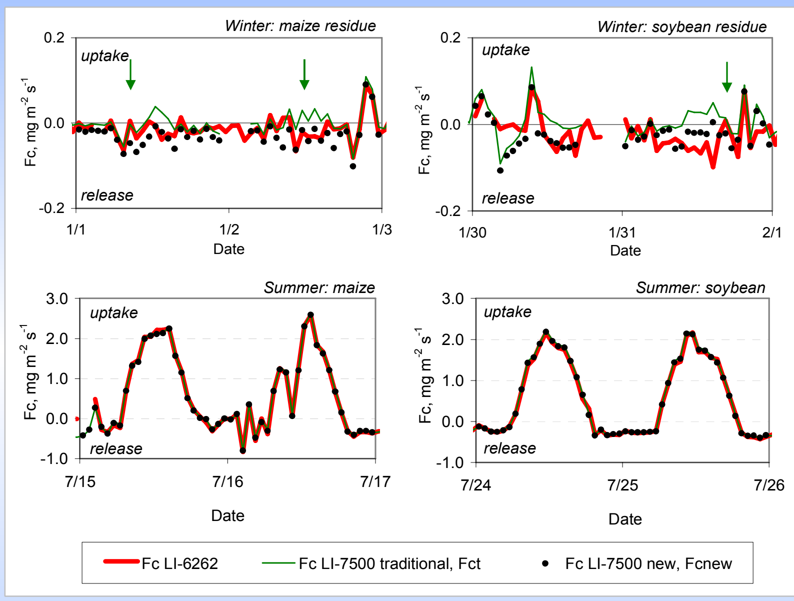
Two figures above give typical field examples of the CO_2 flux corrections in relation to the magnitude of the measured flux for the warm summer and cold winter days over ryegrass. In both cases, the largest correction by far is the WPL correction. It is nearly 50% of the raw flux in summer, and nearly 100% in winter.

It is also important to keep in mind that the WPL correction does not actually correct for any kind of instrument or measurement error, but rather compensates for normal and expected physical processes of thermal expansion and water dilution. Therefore a more appropriate name for the WPL correction is probably WPL term.

The second largest correction in summer is frequency response correction. It is usually considered quite small for open-path analyzers, located close to the sonic anemometer, and indeed is just a few percent of the raw flux in the above Figures. The heating correction in summer is significantly smaller than this frequency response correction, and is virtually negligible.

In winter, open-path frequency response correction and heating correction are of similar magnitude, and both are much smaller than raw flux or than WPL term.

IMPACT OF HEATING - 4 DAYS IN MAIZE & SOYBEAN



- Results were similar to ryegrass: small impact noticeable in winter
- Including heating into WPL helped to better match LI-7500 and LI-6262 in winter
- Summer fluxes were not significantly affected

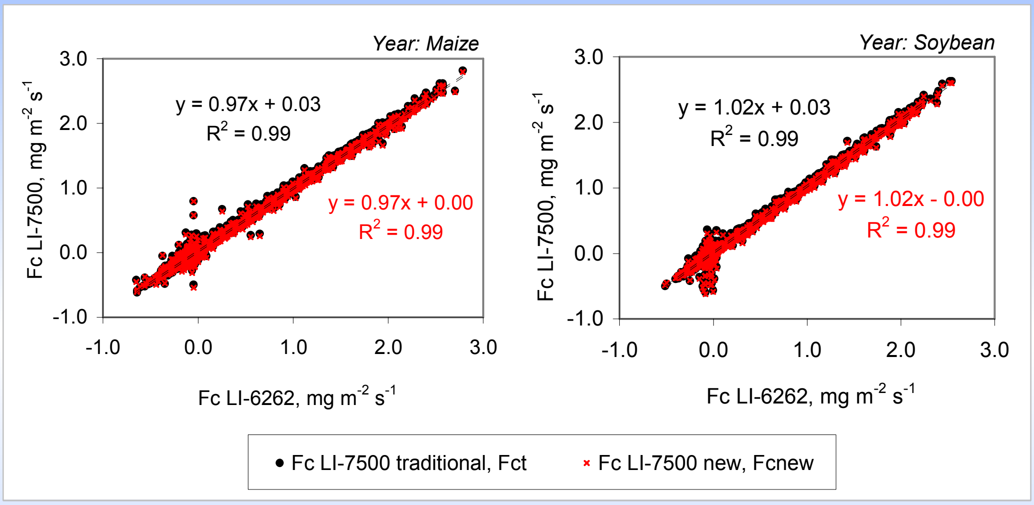
Here are few more examples of hourly fluxes in maize and soybean. Open-path fluxes uncorrected for the surface heating are compared with fluxes measured with closed-path instrument, LI-6262, and with open-path fluxes corrected for heating effects using the simplest method for the heating correction (Method 4 from GCB-2008 paper). Instrument surface temperatures were estimated via a linear model that computed the surface temperature from air temperature from empirical regression.

The estimated heating correction reduced apparent off-season uptake, and made the LI-7500 match the LI-6262 reasonably well even for such a small net flux (variations are on the order of 0.05 mg CO_2 m^{-2} s^{-1}). The magnitude of the additional correction itself was small, ranging from 0 to 0.1 mg CO_2 m^{-2} s^{-1}, and mostly below 0.025 mg CO_2 m^{-2} s^{-1}. Both maize and soybean fallow fields gave similar results.

During the warm summer season with large CO_2 fluxes, the differences between closed-path fluxes, traditionally corrected open-path fluxes, and open-path fluxes corrected with estimated heating corrections were very small to negligible in both maize and soybean.

Fluxes corrected for heating effects looked similar to the uncorrected ones during the warm season because air temperatures were high, so that instrument surface temperatures were closer to ambient, and because CO_2 fluxes were large, making the contribution of the added terms relatively insignificant.

IMPACT OF HEATING – YEARS IN MAIZE AND SOYBEAN



- The heating impact was so small, that it was almost unnoticeable in hourly data over a year
- It is, therefore, important not to arbitrarily discount open vs closed path differences during filtering and quality control, and to try to verify or disprove such observations

Overall, for the entire year, hourly open-path fluxes uncorrected for the surface heating (Fct) were well-correlated with the closed-path fluxes (R^2 = 0.99), yet showing an average offset of about 0.03 mg CO_2 m^{-2} s^{-1}. After the heating correction, the offset was eliminated, and open-path fluxes were even more similar to the closed-path fluxes.

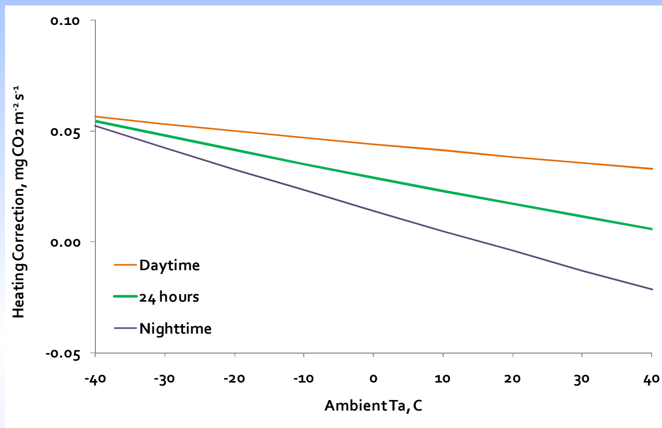
As seen from these figures, the heating effect is so small that it is almost unnoticeable in hourly data over the year. Applying the correction does provide slight improvement in the overall dataset, but all the slope and offset differences in these data are well within the typical error bars of the hourly Eddy fluxes ranging from about +/- 10% to +/-20% of the final flux number.

These data have an important practical implication for data processing and quality control. It is important not to arbitrarily discount the differences between open-path and closed-path fluxes, sometimes observed in the field datasets, as being due to the surface heating.

The differences between open- and closed-path fluxes, especially significant differences exceeding 0.025-0.03 CO_2 m^{-2} s^{-1}, may be caused by entirely different factors, such as errors in calibration, in processing code, in time delay, in WPL term, in frequency response corrections for open-path fluxes, or in much larger frequency response corrections for closed-path fluxes.

Such differences need to be carefully examined to determine which flux (open-path or closed-path) has an error, what is the cause of the error and how each error can be corrected, and whether the data during the problem period has to be removed from the final quality controlled dataset.

HOW STRONG IS OVERALL HEATING IMPACT ON HOURLY CO_2 FLUX?



- The heating impact is small, about 0.025 mg CO2 m^{-2} s^{-1}
- Typical summer daytime uptake flux is about 1-3 mg CO2 m^{-2} s^{-1}
- Typical summer nighttime release flux is about 0.2-1 mg CO2 m^{-2} s^{-1}
- Typical winter or unvegetated desert flux is about of 0.2-0.5 mg CO2 m^{-2} s^{-1}
- Heating impact is 1-2 order of magnitudes smaller then most of the measured CO2 fluxes

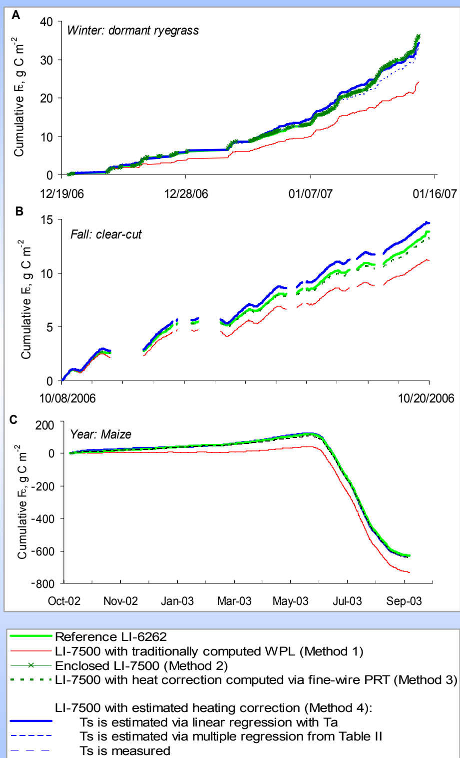
The figure above illustrates typical theoretical examples of the CO_2 flux corrections during daytime, nighttime and over a 24 hour period, depending on the magnitude of the ambient air temperature.

In all cases, the heating correction is 10 to 100 times smaller than typical measured hourly CO_2 fluxes.

It is also important to note that if observed differences between open-path and closed-path instruments or observed cold-season uptakes are much larger than these shown examples, they are likely not related to the heating effects.

Such differences need to be carefully examined to determine which flux (open-path or closed-path) has the error, what is the cause of the error and how such error can be corrected. It is also important to make sure that there is not a natural phenomenon present which causes uptakes during cold-season periods (such as algae, chemical reactions, evergreen canopy, etc.)

IMPACT OF HEATING ON LONG-TERM BUDGET



- Accounting for added heat may be less important for hourly fluxes and may be more important for long-term CO_2 budget
- In the case of CO_2 flux, release (winter or night) is ultimately subtracted from uptake (summer or day)
- So two large, similar numbers subtracted from each other result in a small number
- Accounting for heating effect by any of the proposed methods helps to make OP budgets similar to CP budgets
- Similar to hourly scale, long-term impact from heating was about 10-15 times less than impact of traditional WPL term, and similar to OP frequency response correction

The figures above shows cumulative fluxes measured in three field experiments with the closed path LI-6262 and with the open path LI-7500, which was either enclosed, or corrected using four various correction methods. Details on these methods can be found in Burba *et al* (2008).

During 4 weeks in winter over dormant ryegrass, flux measurements made with the open-path analyzer and not corrected for surface heating underestimated CO_2 release by 12 g C m^{-2} compared to the closed path reference. In contrast, when a heating correction was computed the error was reduced from 12 to 2 g C m^{-2}.

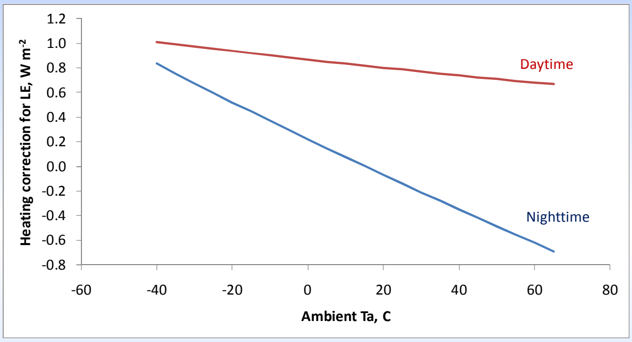
Over a forest clear-cut, use of uncorrected flux led to a 3 g C m^{-2} underestimate of CO_2 release during two weeks in October. Meanwhile, the heating correction led to a considerably better match with closed-path references to within 1 g C m^{-2}.

The yearly CO_2 uptake measured with open-path instrument over maize field was overestimated by 14% as compared to closed-path fluxes. Yet cumulative fluxes from an open-path sensor corrected for heating were consistently similar to closed-path fluxes, matching the closed-path reference within 1%.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

IMPACT OF HEATING ON H_2O AND OTHER FLUXES

- At normal atmospheric pressure, H_2O flux is affected by heating by less than 1 W m^{-2} in LI-7500 for most conditions on Earth, and by less than 3 W m^{-2} in principle, from WPL propagation and available energy



- Long term budgets of H_2O and other non-CO_2 *"primarily one-way fluxes"* are not affected much by heating, because two large numbers are not subtracted from each other in the end, as it was with CO_2 flux

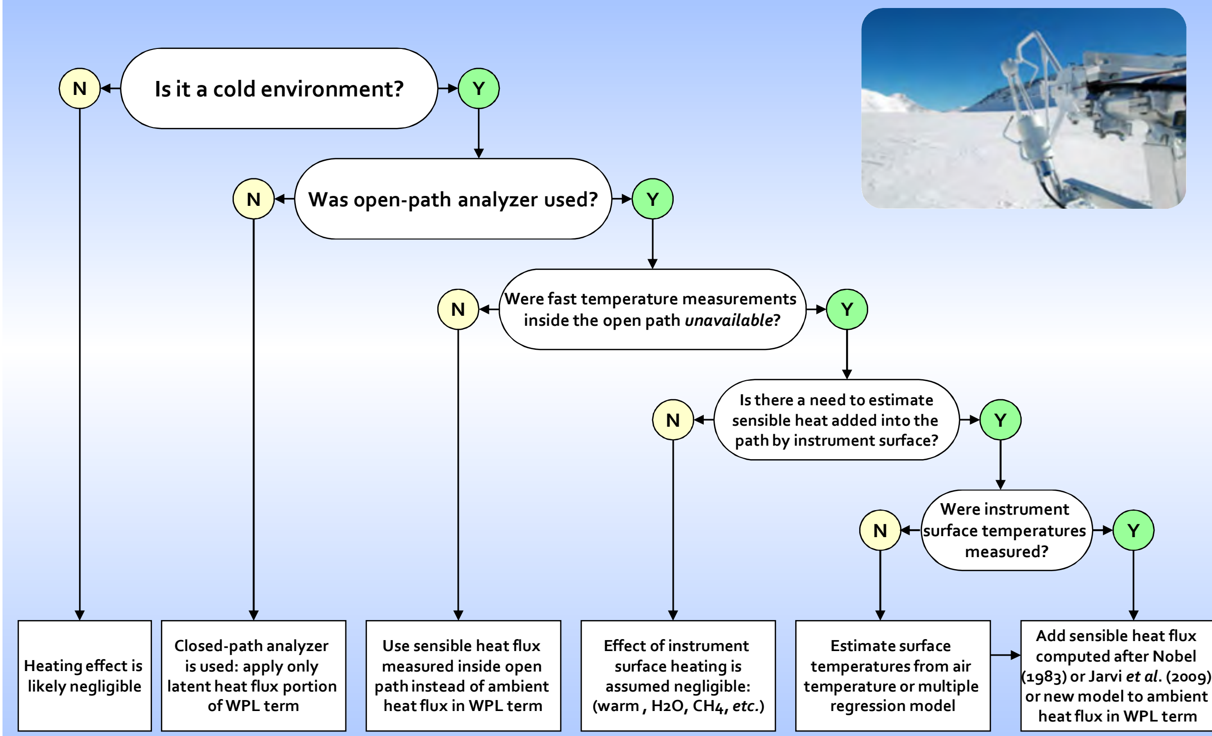
- Also, most non-CO_2 gases are affected little, because WPL term scales with concentration, so a few W m^{-2} of added heat translate into a single percentage of the flux

It is also important to note that, unlike CO_2 exchange, the ecosystem exchange of water vapor, methane, and other gases does not usually have a chronological sequence of emissions and uptakes of similar magnitudes.

Therefore, the percentage-error incurred during water vapor or methane flux measurements is similar to percentage-error in long-term water or methane budget. This is a small number, usually positioned well inside the error bars of the measurements.

With CO_2 flux, long-term budget is often close to zero, and percentage-error in hourly fluxes may translate into a much larger error in long-term budget.

DEALING WITH PAST CO_2 DATA



In warm environments for CO_2, and in all cases for H_2O, or for any one-way gas fluxes, no corrections are usually needed for the past data. In cold environments, there are several techniques to correct the past open-path CO_2 data for sensor heating.

Past open-path CO_2 data can be corrected using ambient heat flux and adding the additional heat exchange by the instrument surface estimated from measured Ts, or computed from Ts estimated via linear regression with air temperature. Added heat also can be computed from Ts estimated via multiple regression with key weather variables.

Closed-path measurements with LI-6262 and LI-7000, if available even part-time, can be used to establish the relationship with open-path measurements and correct the data following Jarvi et al, (2009).

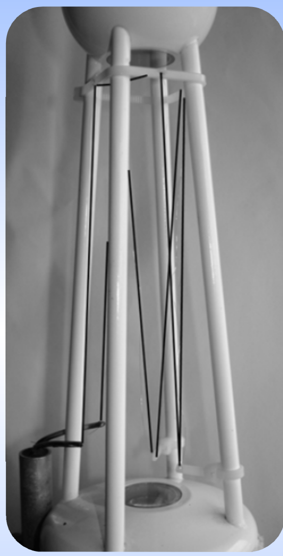
Scheme above summarizes these and other techniques in a decision tree to help determine the best method to correct a specific set of open-path CO_2 flux data based on which auxiliary measurements are available.

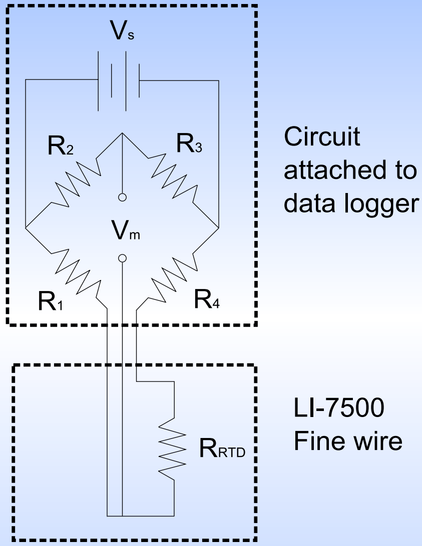
Jarvi, L., I. Mammarella, W. Eugster, A. Ibrom, E. Siivola, E. Dellvik, P. Keronen, G. Burba, and T. Vesala, 2009. Comparison on net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment. Boreal Environment Research, ISSN 1239-6095 (14): 14pp.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

In addition, LI-COR has an information packet to help deal with past data. It was written based on questions generated by the community 2005-2008, and contains many additional explanations, an Excel worksheet computing the correction for vertical sensors, and relevant papers on the topic. Please e-mail "george.burba@licor.com" for this information.

DEALING WITH FUTURE CO_2 DATA: OLD LI-7500





- Fine-wire thermometer performs very well (Grelle and Burba, 2007)
- Thermocouple profile is also as effective (Massman, *et al.*, 2009)
- Detailed instructions on fine-wire thermometer can be found here:

http://www.licor.com/env/Products/GasAnalyzers/7500/heating_articles/using_fine-wire_thermometer_solution.pdf

In warm environments for CO_2, in all cases for H_2O, and for one-way gas fluxes, no heating correction is usually required. In cold environments for CO_2, there are several ways of dealing with future data collection.

One way is to use closed path instruments, or open path instruments designed with less power dissipation near the optical path. The latter are novel instruments described in detail on the next 6 pages. Another way is to develop open path to closed path relationship for a given site and make correction based on this site-specific relationship (Jarvi, et al., 2009).

Finally, one can measure the heating in the path directly with a fine-wire thermometer or with several thermocouples. In fine-wire thermometer technique, sensible heat flux inside the open path is measured directly by fine-wire thermometer, and used instead of ambient sensible heat flux measured in the open air in WPL equation.

In order to compute the sensible heat flux in the open path from vertical wind speed fluctuations, w', and wire temperature fluctuation, $T_{wire'}$, with minimal errors, the following steps should be taken:

1) De-spike instantaneous time series of w and T_{wire}; the criteria for de-spiking would depend on the specific conditions at the site (insects, mist, *etc.*)

2) Convert voltages for instantaneous T_{wire} to °K

3) Run circular correlation between w' and $T_{wire'}$ during periods with good turbulence to establish best time delay and minimize S flux loss due to time delay

4) Apply time delays to these and other periods accordingly. Since thermometer wire can change time response with the wind speed, it may be a good idea to estimate time delay for each averaging period (e.g., half-hour or hour).

5) Compute raw sensible heat flux using time delay-corrected w and T_{wire} time series

6) Apply frequency response corrections to S using Kaimal curves or non-dimensionalized sonic T_a co-spectra as reference. Routinely, this step is ignored for sensible heat flux. However, in the case of a long thermometer wire with variable time constant located away from sonic anemometer, it is important to compare non-dimensional co-spectra from $w'T_{wire'}$ with reference curves to make sure that path averaging, variable delay, and sensor separation are adequately corrected for.

Please also note that this sensible heat flux should not be used for computing sensible heat flux from the study site for the purposes of energy budget closure or other site-wide computations, because inside the open path it may be different from that generated by the study site.

NEW OPEN-PATH INSTRUMENTS

New open-path instruments must be:

- Very fast and low power
- Stable, and require low-attendance
- Dissipate much less heat in path
- Minimize/eliminate heating effect
- Possibly address the real big item – precipitation/spray/icing data losses

Is the open-path approach still useful for flux studies? Yes, absolutely. For more than 10 years the open-path approach was the best low-power remote unattended solution available.

The heating impact is much smaller than other well-known and accepted errors in Eddy Covariance flux measurements. Many warm ecosystems and seasons are not affected by this phenomenon due to very large fluxes and very small heating corrections.

Many moderate ecosystems and seasons are affected very little, because of large fluxes and small heating corrections.

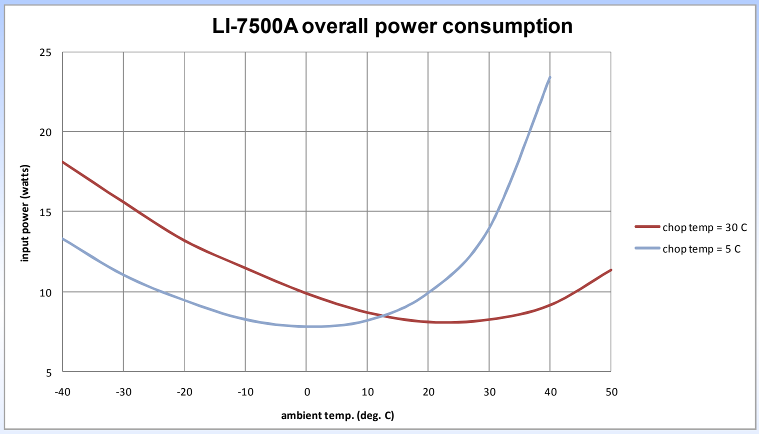
Cold ecosystems and seasons below -10 °C, and places with near-zero flux (parking lots, unvegetated deserts, airstrips) are affected. However, a set of solutions and a number of new instruments are available to address this.

For example, three new analyzers are available now, which are very fast, low-power, stable, require little attendance, and dissipate much less heat in the path, minimizing and eliminating the heating effect.

Two out of the three also address the significant challenge of open-path measurements – data losses due to precipitation, fog, spray, and icing.

These three instruments are LI-7500A, LI-7700, and LI-7200. Their technical aspects and specifications are described in detail in Instruments section. Following is a brief summary for each of these instruments focused on the surface heating effects.

OPEN PATH INSTRUMENT WITH REDUCED POWER DISSIPATION



- The two temperature settings help to always keep power dissipation from the instrument in single Watts
- This is because electronic heating of the window surfaces is a small fraction of total power coming to the instrument

A new, low power dissipating, open-path CO_2/H_2O analyzer, the LI-7500A, allows user to set chopper housing temperature at two settings: low temperature setting of 5 °C and regular setting of 30 °C. Low temperature setting was added for studies in cold climates to reduce energy use and heat dissipation in extremely cold environments.

In our field tests, both external heat dissipation and the system power demand were significantly reduced when 5 °C setting was activated under extremely cold conditions. Please see previous discussion on Surface Heating Correction for details.

LI-COR recommends changing to 5 °C setting only when the average ambient temperature drops below 5 °C; you can change the setting again to 30 °C when the average ambient temperature is above 5 °C.

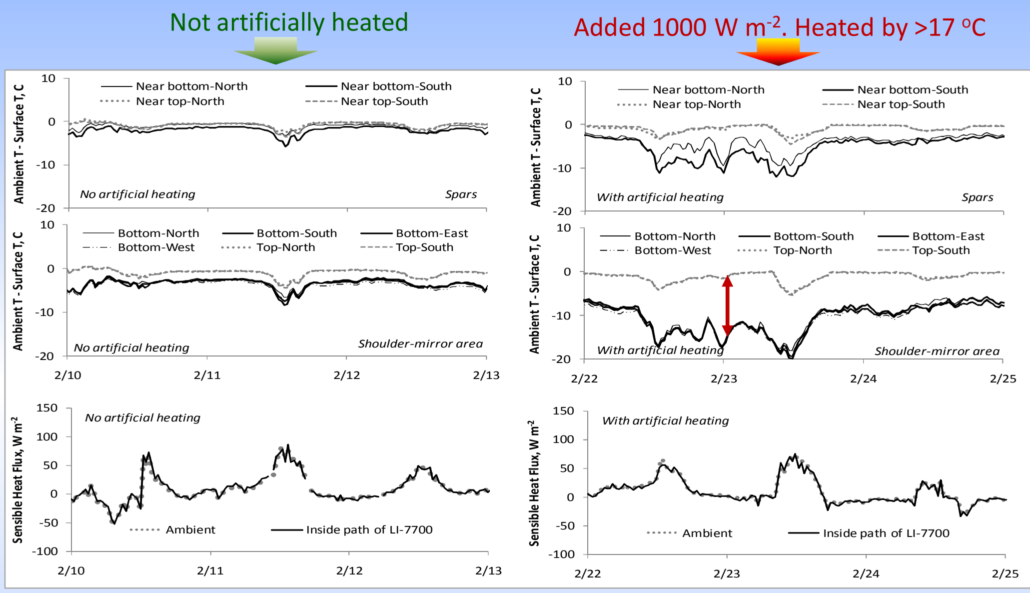
Note, however, that the instrument will still function properly when the chopper motor housing temperature is set to 30 °C, even when temperatures are below 5 °C.

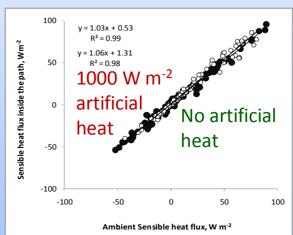
⚠ Do not set the chopper housing temperature to 5 °C when ambient temperatures are above 5 °C, however, as the instrument will not function properly.

ftp://ftp.licor.com/perm/env/LI-7500A/LI-7500A_Manual.pdf

http://www.licor.com/env/2010/products/gas_analyzers/LI-7500A/LI-7500A.jsp

OP INSTRUMENT WITH NO OBSERVED HEATING EFFECT





In a field experiment with artificial heater, the surface heating was not seen in LI-7700 open-path CH4 gas analyzer, even when mirrors were heated by over 17 °C above ambient

A new, fast open-path CH_4 analyzer was tested vigorously for surface heating in winter of 2008.

High-speed air temperature fluctuations inside the LI-7700 sampling path and resulting sensible heat fluxes were measured during field experiments in February and March near Mead, Nebraska. The Eddy Covariance approach with normal and with strongly heated LI-7700 was used in this worst-case scenario for instrument heating effects.

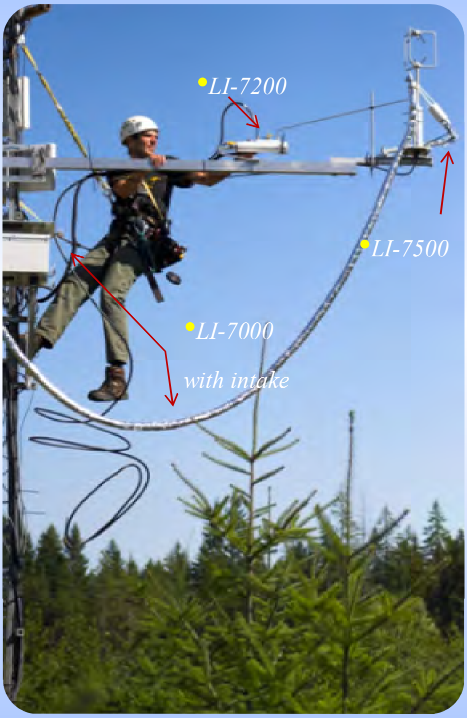
An array of 5 fine-wire thermocouples (0.002", CSI, Logan Utah) was installed inside the LI-7700 path, 5 mm, 14 cm and 24.5 cm above the bottom mirror, and 14 cm and 5 mm below the top mirror. Figures above show that sensible heat flux integrated over the path of LI-7700 was within 2% of ambient sensible heat flux both during periods with no artificial mirror heating and when 5 W of artificial heating was applied to the bottom mirror (resulting in equivalent of over 1000 W m^{-2} artificial heat flux to the mirror).

LI-7700 displayed very little or no effect of instrument surface heating on the sensible heat flux measured inside the path. This is different in the LI-7700 from that of the older LI-7500. The latter had 10-20 W m^{-2} larger sensible heat flux inside the instrument path as compared to an ambient air outside the path (Grelle and Burba, 2007; Burba et al, 2008; Clement et al, 2009).

The small-to-negligible effect of surface heating in LI-7700 is likely related to instrument design of LI-7700, which is different from the LI-7500. The LI-7700 has much larger spacing between mirrors, smaller mirror-to-path ratio, spars are positioned further away from the cell, virtually no warm air is moving from the instrument surface into the optical path of LI-7700, and the spars are made of carbon fiber. The LI-7700 has only three widely spaced spars, and the bottom mirror has been separated from the underlying electronics. As a result, the LI-7700 has a more open sampling cell as compared to the LI-7500, which is closely surrounded by variably heated elements.

http://www.licor.com/env/2010/products/gas_analyzers/LI-7700/LI-7700.jsp

ENCLOSED SHORT-TUBE LOW-POWER SOLUTION



- LI-7200 - fast T and P in the cell:
  - can work with short tube
  - nearly as low power as open-path
- Strengths similar to closed-path analyzers (such as LI-7000/6262):
  - little/no data loss due to precipitation
  - no surface heating issues
- Strengths similar to open-path analyzers (such as LI-7500/7500A) :
  - small easy-to-correct attenuation
  - infrequent calibration requirements
  - minimum maintenance
  - low power with short tube
  - small, light, and weather-proof

The new LI-7200 utilizes a new concept of the enclosed concept of a gas analyzer. When used with long intake tube, the analyzer behaves identical to traditional closed-path analyzers. Yet when used with very short intake tube, the analyzer has some features of open-path gas analyzers. In both cases it is not susceptible to the surface heating effects because fluctuations of the fast temperature in the sampling cell are mostly eliminated and a remainder is measured directly.

LI-7200 is specifically designed for Eddy Covariance measurements, intended to maximize strengths and to minimize weaknesses of both traditional open-path and closed-path designs, but it also can be used with any other flux measurement techniques.

The LI-7200 is based on the absolute NDIR design of the LI-7500; however, it uses a closed-path sampling cell, similar to the LI-7000 and LI-6262. Unlike any previous closed path instrument, the LI-7200 can be used with a short intake tube because the analyzer is weatherproof and it can be mounted on the tower, not on the ground.

Fast temperature and fast pressure of the gas stream are measured at the sampling cell. Fast temperature is measured in two places: just before gas entry into the cell and just after the gas exits from the cell. Fast pressure is measured in the middle of the sampling cell.

Burba, G., D. McDermitt, D. Anderson, M. Furtaw, and R. Eckles, 2010. Novel design of an enclosed CO_2/H_2O gas analyzer for Eddy Covariance flux measurements. Tellus B: Chemical and Physical Meteorology. *Accepted*

ftp://ftp.licor.com/perm/env/LI-7200/LI-7200_Manual.pdf

http://www.licor.com/env/Products/GasAnalyzers/li7200/7200.jsp

SUMMARY

- Open-path heating does not pose a problem for CO_2 in warm environments
- It is unlikely to cause problems for H_2O in any environment
- It is unlikely to cause problems for any one-way fluxes in any environment
- In cold environment, impact of heating on CO_2 flux is quite small
- The heating impact is typically about 0.025 mg CO_2 m^{-2} s^{-1}, 10-100 times smaller then most typical CO_2 fluxes
- It is also much smaller than other well-known effects, such as precipitation losses, standard WPL, and frequency response corrections
- Solutions for old instruments are available: empirical and directly measured
- New instruments are available that resolve the heating phenomenon

Open-path approach provides serious advantages for measurements of gas fluxes in spite of susceptibility to precipitation, and sometimes, heating. And in many cases, open-path measurements provide data coverage that would not be possible using traditional closed-path approach.

Heating effect does not pose a problem for CO_2 flux in warm environments, and is unlikely to cause problems for H_2O and other one-way fluxes in any environment. In cold environments, the impact of heating on CO_2 flux is much smaller than other well-known effects, such as precipitation losses, standard WPL and frequency response corrections.

Heating effect in older open-path analyzers needs further studies for dealing with *past* data, but it is not a major threat to *future* open-path flux measurements.

For *past* open-path data, surface heating correcting should be treated similar to other corrections such as frequency response corrections and WPL terms:

(1) Study and understand the effect
(2) Evaluate its magnitude
(3) Make appropriate corrections

The corrections can be applied via developing site-specific open-path/closed-path relationship (Jarvi, et al., 2009), or by using semi-empirical relationships (Burba, et al., 2008), or by deriving new relationship based on the concept of the surface heating.

For *future* data, a number of confident approaches are available:

(1) In extremely cold weather , use newer open-path analyzers with low heat dissipation, or use closed-path analyzers (power and error tolerance permitting), or use an new enclosed analyzer
(2) Measure heating using fine-wire thermometer (Grelle and Burba, 2007) or fine-wire thermocouples (Massman, 2009)
(3) Use site-specific open-path/closed-path relationship following Jarvi, et al. (2009)

The low-power low-maintenance instruments addressing the heating effect are already available (e.g., LI-7500A, LI-7200, and LI-7700).

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 5. Quality Control of Eddy Covariance Flux Data

QUALITY CONTROL

Bad data are removed for these key reasons:

- Instrument malfunctions
- Processing/mathematical artifacts
- Ambient conditions not satisfying EC method
- Winds are not from the footprint of interest
- Heavy precipitation

Removing bad data is an important part of the data quality control process. It ensures that results do not have a bias or errors due to some obvious or common reasons. As a first step, bad data are usually removed for one of the following causes: instrument malfunctions, processing/mathematical artifacts, ambient conditions not satisfying Eddy Covariance method, winds are not from the footprint of interest, and heavy precipitation.

Among these, ambient conditions not satisfying the Eddy Covariance method include: conditions when turbulent transfer does not prevail, non-stationary conditions, periods with significant convergence or divergence, periods with wind directions not from the footprint of interest, etc.

Some particularly good sources of information on Eddy Covariance quality control are available from the web-sites listed in the Note section of this page:

http://public.ornl.gov/ameriflux/measurement_standards_4.doc [Munger J.W. and H. W. Loescher. Guidelines for making Eddy Covariance flux measurements]

http://www.geo.uni-bayreuth.de/mikrometeorologie/ARBERG/ARBERG26.pdf - Mauder, M. and T. Foken. 2004. Documentation and Instruction Manual of the Eddy Covariance Software Package.

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf- Fluxnet-Canada Measurement Protocols. Working Draft. Version 1.3. 2003

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O., 2008. Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software, Biogeosciences, 5, 451-462

QUALITY CONTROL (cont.)

- The variety of algorithms and protocols that are used by different groups/networks (*e.g.*, Carboeurope, FluxNet-Canada, AmeriFlux) have these features in common:

  Ranges of tolerance established for each variable
  Data outside tolerance ranges removed or flagged
  Precipitation events flagged
  U, u*, and/or stationarity tests conducted
  Non-stationary periods removed
  Data validated via energy budget closure, co-spectral models, *etc.*
  Data gaps filled with back-up instruments, regressions, models
  Gas storage below measurement height computed from profiles
  Data integrated, uncertainties computed

- Quality control is very much a site- and instrument-specific activity

Various algorithms and protocols are used by different groups and/or networks (*e.g.*, CarboEurope, Fluxnet-Canada, Ameriflux, *etc.*) to automate the bad data removal procedure. These protocols are somewhat different from each other, but they have a number of commonalities.

In general, however, the quality control procedure is very much a site-specific and instrument-specific activity, except for these common steps. Thus, it is important not to overdo bad data removal at one study site based on past experience with a different study site.

For example, the tolerance thresholds for sensible heat flux data will differ greatly between an open-water flux measurement over a lake (which will have generally small sensible heat fluxes), and a desert measurement that has high heat fluxes. Thus, applying criteria developed for open water fluxes would probably eliminate many good data points if applied to measurements taken over the desert.

This is why it is generally recommended to collect a good amount of data and establish a baseline for a specific site before the removal criteria are established and applied to the original data.

Foken, Th. and B. Wichura. 1995. Tools for quality assessment of surface-based flux measurements', Agricultural and Forest Meteorology, 78, 83-105

Vickers, D. and Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526

Another important part of the quality analysis is making sure that the data have come from the footprint of interest. Examples describing this part of the quality control are given below.

Gash, J.H.C. 1986 A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary Layer Meteorology 35: 409-413

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., et al. 2008. Quality control of CarboEurope flux data – Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5, 433-45

http://public.ornl.gov/ameriflux/measurement_standards_4.doc - Munger J.W. and H. W. Loescher. Guidelines for making Eddy Covariance flux measurements

QUALITY CONTROL DURING NIGHTTIME

- Fluxes are small
- Winds may be low, co-spectra bad
- Conditions may be stable
- Turbulence may not prevail
- Storage may be significant
- Advection of the flux, drainage flows
- Divergence, convergence

Nighttime is usually a separate case for quality control. Special care is required at night, because the winds are usually low, stratification is stable, and turbulence may not be developed. With slow winds and temperature inversions, flow may become non-stationary and advection, drainage, flow convergence and divergence may become dominant.

The footprint may also increase dramatically due to the stable conditions. With a larger footprint the tower instrumentation then would measure some of the fluxes outside the territory of interest.

As a result of these processes, data loss usually increases at night, especially during calm nights and under tall canopies.

A stationarity test is one of the more reliable tests for cleaning nighttime data. This test sets criteria for the behavior of the air flow in such a way that non-stationary periods can be flagged and removed.

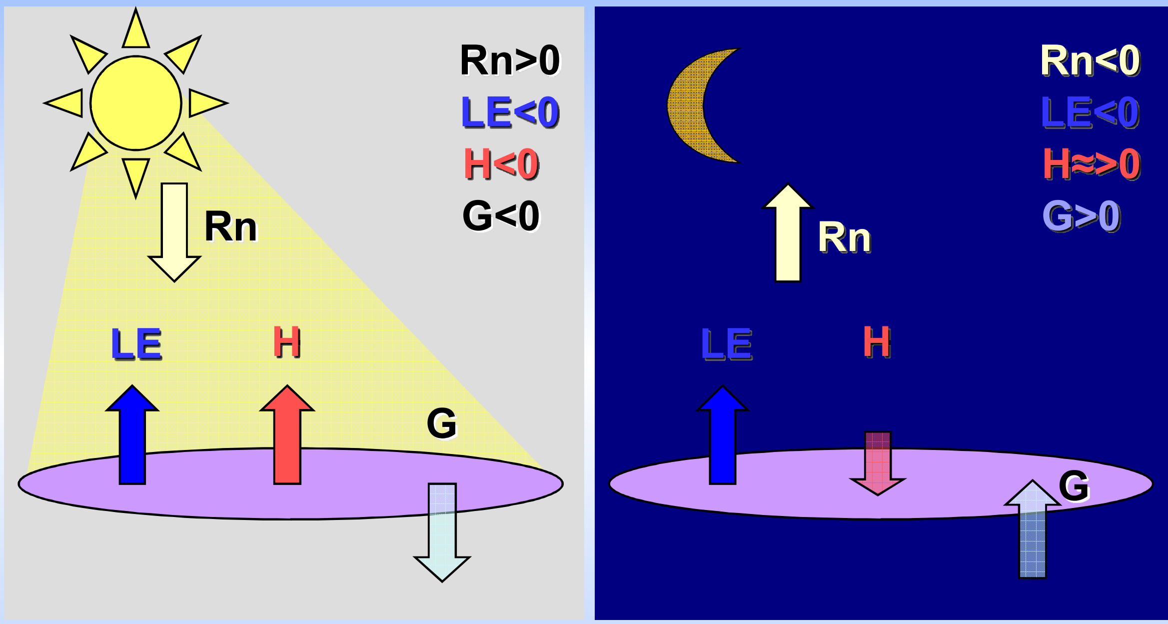
Foken, T, and B. Wichura, 1996. Tools for quality assessment of surface-based flux measurements, Agric. Forest Meteorology (78): 83-105

Vickers, D. and L. Mahrt, 1997, Quality control and Flux sampling problems for tower and aircraft data, J. Atmos. Ocean.Technology (14): 512-526

http://nature.berkeley.edu/biometlab/espm228 Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

Gash, J.H.C. 1986, A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary Layer Meteorology 35: 409-413

VALIDATION: ENERGY BUDGET



Short Equation: $Rn+H+LE+G \approx 0$

One way to validate fluxes measured with Eddy Covariance is to construct an energy budget for the study site. Two traditional examples (daytime and nighttime) with key components of the energy budget are shown on this page. Rn is net radiation; LE is latent heat flux; H is sensible heat flux, and G is the sum of soil heat flux and soil heat storage.

These examples also illustrate a short, 4-component, equation for an energy budget where: net radiation is usually measured with net radiometers, or with other radiation sensors, soil heat flux is usually calculated from heat flux plates and soil temperature, and latent and sensible heat fluxes are measured with Eddy Covariance technique.

The idea of validation with an energy budget is simply that if all of these key components sum to zero as required by conservation of energy, then all energy transfers have been successfully accounted for and sensible and latent heat fluxes were measured correctly. Since the latter was measured correctly, the CO_2 or other trace gas fluxes were most likely measured correctly as well.

It is important to realize, however, that a good (closed) energy budget would not necessarily indicate good measurements of the trace gas flux, while a "non-closing" energy budget would almost certainly indicate a problem in measuring the flux.

A challenge in using energy budget to validate closure is that a good measurement of latent heat flux does not automatically mean a good measurement of the trace gas, because heat transfer for water and for the gas of interest may differ, especially if gases are reactive (such as volatile organic compounds) or have significantly different sources and sinks as compared to water vapor.

Another challenge in using energy budget is often related to the difficulty in measuring soil heat flux, especially in soil with relatively rapid change in water content, and in non-uniform patchy soils or terrains.

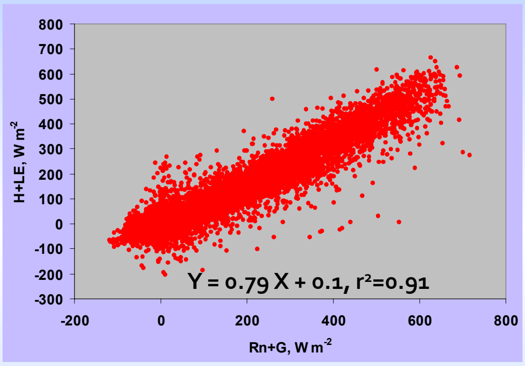
In spite of these difficulties, and with proper precautions, surface energy budget remains one of the most convincing ways to assess the quality of Eddy Covariance results, and is widely used in the flux communities.

Wilson, K. et al., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1-4): 223-243.

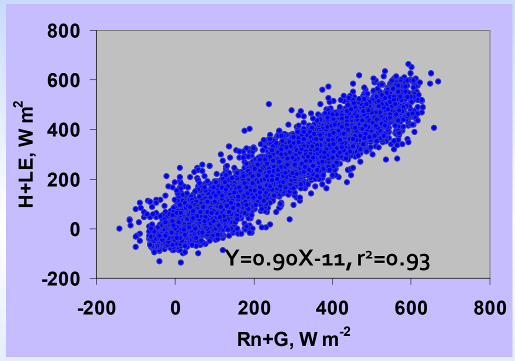
Rosset, M., Riedo, M., Grub, A., Geissmann, M., and J. Fuhrer, 1997. Seasonal Variations in radiation and energy balances of permanent pastures at different altitudes. Agricultural and Forest Meteorology, 86: 245-258.

VALIDATION: FULL EB CLOSURE

Short Equation
Rn+G vs. –(H+LE)



Complete Equation
Rn+G vs. –(H+LE+Ps+M)



Ideal closure (Y=X) is rarely achieved by Eddy Covariance method

Including all members of Energy Budget improves closure substantially

Good closure is not necessarily a validation, but bad closure is a definite problem

Another caveat in energy budget validation of Eddy Covariance flux is that some minor components may be missed in the short energy budget equation shown previously, even if all four key components there were measured properly.

Constructing a complete equation is more difficult, but it may also be more beneficial for quality control or validation of the Eddy Covariance data. The complete equation might include such components as energy spent on photosynthesis by the plants (Ps), and miscellaneous terms (M) such as heat stored in the canopy, heat stored in the mulch and soil water, *etc.*

Ideal closure, when (Rn + G) is equal to - (H + LE), is rarely achieved due to a number of reasons that have been listed before. Still, including all components into an Energy Budget can significantly improve the closure and help avoid unnecessary data removal or corrections to the Eddy Covariance data.

To illustrate this point, here are two plots with actual field data collected in maize near Mead, Nebraska over an entire year. The ideal closure on these plots would have been indicated by the regression slope of 1 (or 100%) and offset of zero. With the short equation, there is only 79% closure. That means that 21% of the energy is missing somewhere. But using a more complete equation leads to a closure of 90%, which is better than most typical values for Eddy Covariance study sites.

Wilson, K. et al., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1-4): 223-243.

Kim, J., and S.B. Verma, 1990. Components of surface energy balance in a temperate grassland ecosystem. Boundary-Layer Meteorology, 51: 401-417

VALIDATION: OTHER METHODS

- There are many other ways to validate Eddy Covariance flux:

  Quality and shape of daytime co-spectra

  Similarity theory models (vs. z/L)

  Verification with biological data (NEP)

  Upscaled from leaf level (leaf chamber measurements)

  Upscaled from soil level (soil chamber measurements)

- None of these methods could guarantee correct data, but all of them combined could help identify problems or to help defend the flux data

There are many other ways to validate Eddy Covariance flux.

Quality and shape of daytime gas flux co-spectra in comparison with sensible heat flux co-spectra or with ideal Kaimal-Moore co-spectra helps to understand at what frequencies gas flux may be missed or measured incorrectly. For example, ship-borne and airborne Eddy Covariance studies may find unusual co-spectra shapes for their gas fluxes at the frequencies of ship heave and airplane vibration, and may need to counter these interferences with different sensor arrangements.

Similarity theory models involving Monin-Obukhov stability parameter may help to assess if flux covariances or momentum characteristics behave in a predictable way and fit established meteorological models.

Verification of tower data with data collected by other techniques (for example, net ecosystem production computations from biomass data, leaf chamber measurements or soil chamber data) can help all the compared techniques reveal inconsistencies and to find their cause.

None of these methods alone will guarantee the correct data, but all of them combined can help to find hidden problems or to defend the flux data.

FILLING IN MISSING DATA

- After bad data have been removed, data gap inventory and data filling need to be performed
- Inventory is important for getting an idea of the quality of results and may be useful for computing uncertainties for integrated values
- Filling-in the data is not a trivial process in the Eddy Covariance method – there is always a danger of bias
- Some of established strategies to fill-in missing data are:

  Regressions with backup instruments
  Regressions with nearby sites (when appropriate)
  Physical restrictions (energy budget, mass budget, etc.)
  Lookup tables and Ameriflux gap filling strategies
  CO_2 daytime – light response curves for different GFAI
  CO_2 nighttime – temperature, moisture, for diff GFAI, Q10

After bad data have been removed, one has to perform data gap inventory and fill in the missing periods in order to construct a seasonal or yearly picture of ecosystem exchange.

Bad data inventory is important for getting an idea on the quality of results, and may also be useful for computing uncertainties for integrated values.

Filling-in the data is not a trivial process in the eddy covariance method – there is always a danger of adding bias to the data. Some of the established strategies for "filling in" missing data are: regressions with backup instruments; regressions with nearby sites; physical restrictions (energy budget, mass budget, etc.); lookup tables and Ameriflux gap filling strategies; CO_2 daytime (light response curves for different green leaf area index, GFAI); CO_2 nighttime (temperature, moisture, respiration-temperature dependence, Q10, for different green leaf area index).

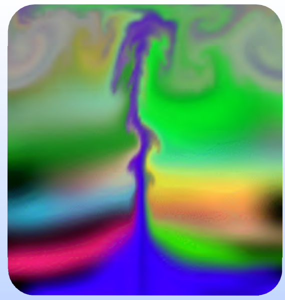
It is also important to note that nighttime data often need to be filled in separately from the daytime data for physiological reasons (for example, a different set of processes is responsible for CO_2 release/uptake during day than during the night), and because of turbulent exchange problems (see page 115 of this guide)

Falge, E.; D. Baldocchi; R. Olson; P. Anthoni; M. Aubinet; C. Bernhofer; G. Burba; R. Ceulemans; R. Clement; H. Dolman; A. Granier; P. Gross; T. Grunwald; D. Hollinger; N. O. Jensen; G. Katul; P. Keronen; A. Kowalski; C. T. Lai; B. E. Law; T. Meyers; J. Moncrieff; E. Moors, 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1), 43-69.

Falge, E.; D. Baldocchi; R. Olson; P. Anthoni; M. Aubinet; C. Bernhofer; G. Burba; G. Ceulemans; R. Clement; H. Dolman; A. Granier; P. Gross; T. Grunwald; D. Hollinger; N. O. Jensen; G. Katul; P. Keronen; A. Kowalski; C. T. Lai; B. E. Law; T. Meyers; J. Moncrieff; E. Moors, 2001. Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology, 107(1), 71-77.

STORAGE

- Eddy Covariance instruments record flux at certain measurement height
- Below this measurement height, concentration could build up or decrease especially during calm periods (for example, CO2 build up on calm night)
- Gusts of wind could move this build-up sideways or upward very quickly, so this flux is either undetected or partially detected
- Gas concentration profile measurements allow for a detection of most of such buildups
- Storage term could be calculated from the temporal changes in gas concentration profiles, and incorporated in the final flux
- Storage calculations are especially important during conditions with low wind, stable stratification, in high canopies, or in any case when air mixing is significantly reduced or/and atmosphere-surface are decoupled



Eddy Covariance instruments record flux at a certain measurement height. Below this height, gas can build up or get depleted especially during calm periods or within a tall canopy (for example, CO_2 build up on a calm night or CO_2 depletion on a calm day).

Depending on the canopy and terrain, wind gusts can move such a build up sideways below the tower, or upward next to the tower very fast, so this flux is either undetected or partially detected, especially in tall canopies or in complex terrains. On flat uniform terrains with short canopies and with good turbulent mixing these processes are either small or eventually even themselves out over the long term, but they still can significantly affect hourly data.

Gas concentration profile measurements allow detection of the majority of these buildups by providing data for computing a storage term below measurement height. The storage term is usually calculated from the temporal changes in the integrated gas concentration profile, and is added to the Eddy Covariance flux to come up with final flux number.

Storage calculations are especially important during conditions with: low wind, stable stratification, high canopies, or in any case when air mixing is significantly reduced or when the atmosphere and surface are decoupled from each other. Storage calculations are not measurements of turbulent fluxes, but they are important for the final flux number, especially when net ecosystem exchange is the focus of the study.

http://nature.berkeley.edu/biometlab/espm228/ - Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

http://nigec.ucdavis.edu/publications/ar/annual2004/sc/SC04_Heilman.pdf - Heilman, J., McInnes, K., and M. Owens. 2003. Net Carbon Dioxide Exchange in Live Oak-Ashe Juniper Savanna and C4 Grassland Ecosystems on the Edwards Plateau, Texas: Effects of Seasonal and Interannual Changes in Climate and Phenology

Finnigan, J.J, 2006. The storage term in eddy flux calculations. Agricultural and Forest Meteorology Volume 136, 3-4: 108-113

Bradford W., Berger, B., Davis, K., and C. Yi, 2001. Long-Term Carbon Dioxide Fluxes from a Very Tall Tower in a Northern Forest: Flux Measurement Methodology. Journal of Atmospheric and Oceanic Technology, 18(4): 529–542

INTEGRATION

- Integrations should be done after the data has been processed, corrected, quality controlled, validated, and storage term has been added to a gas flux
- Yearly CO_2 integrations are especially unforgiving, because two similar quantities (photosynthesis/uptake and respiration/release) are subtracted from each other
- Result is a relatively small number with relatively large uncertainties:

  instrumental   EC methodology   gap filling
- Error analysis should be conducted to estimate uncertainties and results should be presented as a range, and not as a single number

Integration should be done after data has been processed, corrected, quality controlled, validated, and a storage has been added.

Yearly CO_2 integrations are especially unforgiving, because two large, similar quantities (photosynthesis/uptake and respiration/release) are subtracted from each other. As a result, uncertainties due to instrument performance, EC methodology, quality control and gap filling which seemed small or negligible in comparison with hourly fluxes, now become relatively large in comparison with the integrated seasonal flux number.

Error analysis is highly advisable at this stage. It can help to quantitatively estimate the impact of these uncertainties, and to present resultant integrated flux as realistic range rather than as a single number.

Falge, E.; D. Baldocchi; R. Olson; P. Anthoni; M. Aubinet; C. Bernhofer; G. Burba; R. Ceulemans; R. Clement; H. Dolman; A. Granier; P. Gross; T. Grunwald; D. Hollinger; N. O. Jensen; G. Katul; P. Keronen; A. Kowalski; C. T. Lai; B. E. Law; T. Meyers; J. Moncrieff; E. Moors, 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1), 43-69

PART II. TYPICAL EDDY COVARIANCE WORKFLOW

Section 6. Eddy Covariance Workflow Summary

WORKFLOW: SUMMARY

- Each experimental site is different and requires unique treatment
- Eddy Covariance is, to a large extent, a site-specific method
- The entire process of experimental design, implementation and data processing should be tailor-made for specific purpose at specific site

Overall, perhaps the most important point about Eddy Covariance workflow is the necessity for an individualized and customized approach to each experiment, because Eddy Covariance, to a large extent, is a site-specific method.

Each study site is different and requires unique treatment in terms of experimental design, tower placement, instrumental set up, data collection, and processing and analysis.

Built-in flexibility of the Eddy Covariance method, in conjunction with user knowledge and understanding of the method and the study site, will allow for successful implementation of site-specific arrangements that are tailor-made for a specific scientific purpose under specific ambient conditions.

WORKFLOW: SUMMARY

- ***Experiment design:*** establish purpose, variables, instruments, software, location, maintenance plan
- ***Implementation:*** place tower and instruments, test data collection and retrieval, test processing program on the standard file, keep up maintenance throughout the experiment
- ***Process instantaneous data:*** convert units, determine best averaging period, de-spike, correct for time delay, apply calibrations, compute rotation coefficients and frequency response corrections, average data
- ***Process averaged data:*** apply rotation coefficients, frequency response and other corrections, quality control, fill-in, integrate, compute storage
- ***Validate data:*** validate with Energy Budget closure, co-spectra, alternative methods, back-up instruments, biomass data, and light-response curves
- ***Pre-analyze data:*** check carefully nighttime data, advection periods, calculate uncertainties for integrated flux numbers

The main elements of the Eddy Covariance workflow are: experiment design, implementation, data processing, validation and analysis.

Experiment design consists of establishing purpose, variables, instruments, software, location, and a maintenance plan.

Implementation involves placing the tower and instruments, testing data collection and retrieval, testing the processing program, and keeping up maintenance throughout the experiment.

The main steps in processing of instantaneous data are: unit conversions, determining best averaging period, de-spiking, correcting for time delay, applying calibrations, computing rotation coefficients and frequency response corrections, and averaging the instantaneous data. Further processing includes: applying rotation coefficients, frequency response and other corrections, conducting quality control and gap filling, computing storage term, and integrating long-term data.

Data validation can be done in a number of different ways including: Energy Budget closure, co-spectra, alternative methods, back-up instruments, biomass data, and light-response curves.

Initial data analysis involves careful checks of data, especially during night, calm and advection periods, and calculating uncertainties for integrated flux numbers.

PART III. ALTERNATIVE FLUX METHODS

ALTERNATIVE FLUX METHODS

- Environmental conditions may prevent using Eddy Covariance
- Instrument system not fast enough for certain gases (ex.: NH_3, VOC, *etc.*)
- Information is needed other than from EC (ex.: soil respiration)
- As a complimentary method to add value, validation, backup to EC
- Below is a quick review of key methods:
  - ❑ Eddy Accumulation
  - ❑ Relaxed Eddy Accumulation
  - ❑ Bowen Ratio
  - ❑ Aerodynamic method
  - ❑ Resistance method
  - ❑ Chamber
  - ❑ Others (modeling: Lagrangian, fenced line, differences b/w mean conc. and emission, *etc.)*

There are a number of situations where the Eddy Covariance method either could not be used to measure fluxes, or is not the best method to do so. These include environmental conditions with a very small area of study, predominantly low winds, complex terrain, point flux sources etc. Also, for some gases, such as ammonia and volatile compounds, the instrument system may not be sensitive enough or fast enough to measure small changes at 10 or 20 Hz frequencies. The focus of the experiment itself may prevent a researcher from using the Eddy Covariance method, for example, when it is narrowed down to only one of the components of the flux, such as soil respiration, or canopy transpiration.

In these situations, other methods become more useful scientific tools. They can also be used as complementary methods to add value, validation or backup to the Eddy Covariance method. The next few pages contain a quick overview of some of these methods. We will briefly look at Eddy Accumulation, Bowen Ratio, and a few other methods. Further details on these and other methods to measure fluxes can be found in the sources listed below:

Rosenberg, N.J., B.L. Blad & S.B. Verma. 1983. Microclimate. The biological environment. A Wiley-interscience publication. New York. 255-257

Verma, S.B., 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. Remote Sensing Reviews, 5: 99-115.

Baldocchi, D.D., B.B. Hicks and T.P. Meyers. 1988. 'Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods', Ecology, 69, 1331-1340

Denmead, O.T. and M.R. Raupach. 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. American Society of Agronomy

Lenschow, DH.1995.Micrometeorological techniques for measuring biosphere-atmosphere trace gas exchange. In: Biogenic Trace Gases: Measuring Emissions from Soil and Water. Eds. P.A. Matson and R.C. Harriss. Blackwell Sci. Pub. Pp 126-163.

Wesely, M.L., D.H. Lenschow and O.T. 1989. Flux measurement techniques. In: Global Tropospheric hemistry, Chemical Fluxes in the Global Atmosphere. NCAR Report. Eds. DH Lenschow and BB Hicks. pp 31-46

EDDY ACCUMULATION

- Updrafts (w'>o) are physically sampled separately from downdrafts (w'<o)
- Sampling is proportional to the strength of updraft and downdraft
- After data has been accumulated over time, one is subtracted from another
- Result is a net flux at the sampling level
- Difficult to sample proportionally
- Difficult to sample small changes

The Eddy Accumulation method is similar to the Eddy Covariance method. The Eddy Accumulation method is based on measuring the turbulence transportation of gases. But unlike Eddy Covariance, Eddy Accumulation samples updrafts and down-drafts separately.

This sampling is proportional to the strength of the updraft and downdraft, and after data has been accumulated over time, the updraft average concentration is subtracted from the downdraft average concentration. As a result, a net flux at the sampling level is obtained.

The main challenge for the Eddy Accumulation method is to make sure that sampling is done proportionally to the strength of the updraft and downdraft, and that small changes in concentrations are measured adequately. More information on this method is available from the literature listed below.

Baker, J.M 2000. Conditional sampling revisited. Agricultural and Forest Meteorology. 104. 59-65.

Baker JM, Norman JM, Bland WL (1992) Field-scale application of flux measurement by conditional sampling. Agricultural and Forest Meteorology 62:31-52

Katul GG, Finkelstein PL, Clarke JF, Ellestad TG (1996) An investigation of the conditional sampling method used to estimate fluxes of active, reactive, and passive scalars. J. Appl. Meteorol. 35:1835-1845.

http://nature.berkeley.edu/biometlab/espm228
Baldocchi, D. 2005. Advanced Topics in Biometeorology and Micrometeorology

RELAXED EDDY ACCUMULATION

- Updrafts (w'>o) are physically sampled separately from downdrafts (w'<o)
- Sampling is not proportional to the strength of updraft and downdraft
- Sampling is at constant flow rate
- After data have been accumulated over time, one is subtracted from another
- Result is a net flux at the sampling level
- Difficult to correctly evaluate empirical coefficient required for calculations
- Number of corrections required; difficult to measure small changes

A modification of the Eddy Accumulation method is the Relaxed Eddy Accumulation method. Similar to Eddy Accumulation, the updrafts are sampled separately from the downdrafts.

However, this sampling is not proportional to the strength of the updraft and downdraft, and is done at a constant flow rate. After data have been accumulated over time, the updraft average concentration is subtracted from the downdraft. As a result, a net flux at the sampling level is obtained.

The main challenge for the Relaxed Eddy Accumulation method is to make sure that empirical coefficients are evaluated correctly, that corrections are properly applied, and that small changes are sampled adequately.

Nie D, Kleindienst TE, Arnts RR, Sickles JE, 1995. The design and testing of a relaxed eddy accumulation system. JGR. 100: 11,415-11,423

Oncley SP, Delany AC, Horst TW, Tans PP (1993) Verification of flux measurement using relaxed eddy accumulation. Atmos. Environ. 27A:2417-2426

Pattey E, Desjardins RL, Rochette P (1993) Accuracy of the relaxed eddy-accumulation technique, evaluated using CO_2 flux measurements. Boundary Layer Meteorology 66:341-355

Pattey E, Desjardins RL, Boudreau F, Rochette P (1992) Impact of density fluctuations on flux measurements of trace gases: implications for the relaxed eddy accumulation technique. Boundary Layer Meteorology 59:195-203

BOWEN RATIO METHOD

- Latent heat flux is computed from surface energy budget components and Bowen Ratio (ratio of sensible to latent heat fluxes)
- Turbulent exchange coefficients for heat/water assumed similar
- Turbulent exchange coefficient for gas assumed similar to water
- Actually, turbulent exchange coefficients are rarely similar
- Difficult to measure gradients without biases
- Bowen Ratio may not hold in evenings and mornings (division by zero)
- Results heavily rely on soil heat flux and storage data: difficult to measure accurately

The Bowen Ratio is a relatively old and well-established technique, initiated in the 1920s. Water or gas fluxes are computed in this method from surface energy budget components, and from a Bowen Ratio (that is, the ratio of sensible and latent heat fluxes, and assumed to be proportional to the ratio of temperature and humidity gradients between two measurement levels). The Bowen Ratio Method usually requires assumptions that the turbulent exchange coefficients for heat/water/gases are similar, or easily predictable.

The method was wide-spread in agricultural and flux studies for many years, and has accumulated both positive and negative reviews. The method is easy to implement in the field, data processing is relatively simple, and equipment is not expensive, yet the method has a number of significant challenges.

One of the main challenges of the Bowen Ratio method is related to the fact that the exchange coefficients are often not similar between temperature, water vapor and other gases, but rather gas-specific and may change dynamically. Another challenge is that it is difficult to measure gradients without biases. To minimize errors, the method often requires physical exchange of the two sensors between two levels. Computations may not hold in evenings and mornings, when the humidity gradient is near-zero (leading to a division by 0), or at any time of the day when temperature or humidity profiles are not consistent and have kinks. Additionally, results of the method heavily rely on soil heat storage data, which is difficult to measure correctly over a large footprint of the flux.

To avoid confusion please note that what has been described so far is the classic Bowen Ratio Method and not the recently popular Modified Bowen Ratio method. The Modified Method is a combination of the Eddy Covariance and traditional Bowen Ratio methods. This technique is explained well in Liu, H. and T. Foken, 2001 (A modified Bowen ratio method to Determine sensible and latent heat fluxes. Meteorologische Zeitschrift, Vol. 10, No. 1, 71-80).

The original source for the classic Bowen Ratio method is Bowen, I.S., 1926 (The ratio of heat losses by conduction and by evaporation from any water surface, Physics Review, vol. 27, pp. 779-787).

A detailed explanation is given in Rosenberg, N.J., B.L. Blad & S.B. Verma, 1983 (Microclimate. The biological environment. A Wiley-interscience publication. New York. 255-257)

AERODYNAMIC METHOD

- Flux is computed from wind profile and gas concentration profile
- Turbulent exchange coefficients for momentum, gas are assumed similar
- Alternatively, turbulent exchange coefficients have to be known or modeled
- Difficult to determine turbulent exchange coefficient for momentum
- Turbulent exchange coefficient rarely similar, especially for rare gases
- Atmospheric stability significantly affects calculation

In the Aerodynamic method, or family of methods, flux is computed from the vertical profiles of wind speed and gas concentration. Turbulent exchange coefficients for momentum and the gas of interest are either assumed to be similar, measured, or modeled.

The main challenges are related to difficulties in determining the turbulent exchange coefficient for momentum, and the fact that the turbulent exchange coefficient between momentum and gases are not always similar, and may in fact, be gas-specific.

Atmospheric stability can also significantly affect the flux calculated using the aerodynamic method.

Pruitt, W.O., 1963. Application of several energy balance and aerodynamic evaporation equations under a wide range of stability. Final report to USAEPG, Univ. of California-Davis. pp 107-124

Thornthwaite N, Holzman B. 1942. Measurement of evaporation from land and water surfaces, USDA Tech. Bull., No. 817 Webb, E. K.: 1965, 'Aerial Microclimate', in. Agricultural Meteorology, Meteor. Monographs, Vol. 6, 28, 27-58

RESISTANCE APPROACH

- Could be considered a version of aerodynamic method
- Computes flux from gradient and resistances to transport
- Need to know aerodynamic and stomatal resistances
- May need to know soil surface resistance
- Resistances are difficult to measure

The Resistance approach is considered, by some, to be a version of the aerodynamic method. Fluxes in the resistance approach are computed from gradients and resistances to transport.

Both aerodynamic and stomatal resistances are usually needed to measure fluxes over live canopies. The soil surface resistance is often required as well, especially in sparse canopies.

With well-developed and tested models (such as Shuttleworth-Wallace and Penman-Montieth) and a good understanding of the processes, the main challenge in using the traditional resistance approach is the great difficulties encountered while attempting to accurately measure the resistances.

Rosenberg, N.J., B.L. Blad & S.B. Verma. 1983. Microclimate. The biological environment. A Wiley-interscience publication. New York. 255-257

Montieth, J. L. 1963. Gas exchange in plant communities. pages 95-112 in L. T. Evans, ed. Environmental control of plant growth. Academic Press, New York

CHAMBER MEASUREMENTS

- Computes flux from changes in the concentration in closed volume over time; good for soil and leaf measurements
- Measures soil flux only, leaf flux only, or total in large chambers
- Chambers could alter the environment significantly
- Leaf and soil chambers do not give ecosystem flux
- Requires up-scaling for ecosystem flux assessment

Even though the Chamber method is not a tower measurement, it is an important and widely used technique to measure fluxes over relatively small areas.

The classical chamber method computes flux from changes in the concentration in a closed-volume over time. It is a good tool to measure soil flux or canopy flux. Unlike tower flux measurement methods, the chamber method allows measuring soil flux separately from the canopy or leaf fluxes.

Large chambers can also include both soil and canopy, but they alter the environment significantly, and are used less often than small chambers.

While leaf and soil chambers do not give ecosystem flux, they allow process analysis of the sources and sinks at different time and area scales. Such measurements are very useful for deeper understanding and modeling of the factors governing ecosystem gas exchange.

To compare chamber fluxes and tower fluxes requires the chamber fluxes to be up-scaled to the ecosystem level. Successful up-scaling depends on the ecosystem variability, number of chambers and their placement within the ecosystem.

For more details please see Chapter 12 by Rochette and Hutchinson (pages 247-286) in Micrometeorology in Agricultural Systems (2005), published by Soil Science Society of America as Agronomy Monograph no. 47.

OTHER ALTERNATIVE METHODS

- Disjunct Eddy Covariance
- Relaxed Eddy Accumulation with injections
- Mass balance for small areas
- Surface renewal method
- Control volume
- Boundary layer towers
- Virtual towers
- Biological and soil sampling
- Lysimeter

There are a large number of other methods to measure fluxes, in addition to the few methods described in this guide. They include modifications of the described methods (such as, disjunct eddy covariance, relaxed eddy accumulation with injections, etc.) and completely separate methods (such as, sap flow, virtual towers, lysimetry, etc.). Examples of comparison between some of these methods are given below:

Williams, D.G., W. Cable, K. Hultine, J.C.B. Hoedjes, E. Yepez, V. Simonneaux, S. Er-Raki, G. Boulet, H.A.R. de Bruin, A. Chehbouni, O.K. Hartogensis and F. Timouk, 2004. Components of evapotranspiration determined by stable isotope, sap flow and eddy covariance techniques. Agricultural and Forest Meteorology 125:241-258

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute
http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

PART IV. FUTURE DEVELOPMENT

FUTURE DEVELOPMENT

- Scientific disciplines
- Industrial applications
- Gas species
- Terrains
- Scale expansion

The Eddy Covariance method is gaining increased popularity in micrometeorology, and especially, in carbon flux studies. Every year the number of tower sites increases and new experiments are planned.

In the next few pages we will look at several examples of the near-future prospects for the method:

- expansion to scientific disciplines beyond micrometeorology
- expansion into industrial and environmental monitoring and management
- expansion to many gas species beyond CO_2, to dust, and aerosols
- measuring at difficult terrains (hillsides, mountains, urban)
- expansion in geographic scales of measurements

EC EXPANSION: DISCIPLINES

Use of the EC method is currently restricted by complexities with non-uniform terminology and the lack of user-friendly, comprehensive standardized software to give a non-expert user a choice of settings and parameters to handle eddy flux data

Disciplines such as ecology, geo-ecology, entomology, biology, ecosystem science etc., would profit greatly from using standardized methodology, field procedures and equipment

Use of the Eddy Covariance method is often restricted by complexities with non-uniformed terminology and the lack of user-friendly, all inclusive software that would give a non-expert user a choice of settings and parameters to handle eddy flux data.

As these challenges are being successfully resolved by flux networks, scientific and educational institutions, disciplines such as ecology, entomology, biology, ecosystem science, hydrology, oceanography etc., would profit greatly from using the Eddy Covariance method for their specific applications.

These applications can range widely, from studies on the cicada life cycles and related soil aeration to incorporating gas exchange into GIS modeling, and from remote sensing validation to dissipation of methane through ocean waters and related changes in biodiversity.

EC EXPANSION: INDUSTRIAL APPLICATIONS

- Eddy Covariance methodology is now ready to become a valuable tool for applications outside the scientific studies: it is direct, defensible, practical and repeatable method
- It could be quite useful for industrial and environmental monitoring and management, carbon capture and sequestration, landfill management, carbon credit system, *etc.*

As Eddy Covariance method becomes more uniformed and more accessible for usage outside scientific disciplines, it may be of great use for a number of industrial and environmental monitoring and management applications, and may become an important part of carbon credit system.

Some of the relevant advantages of the Eddy Covariance method are:

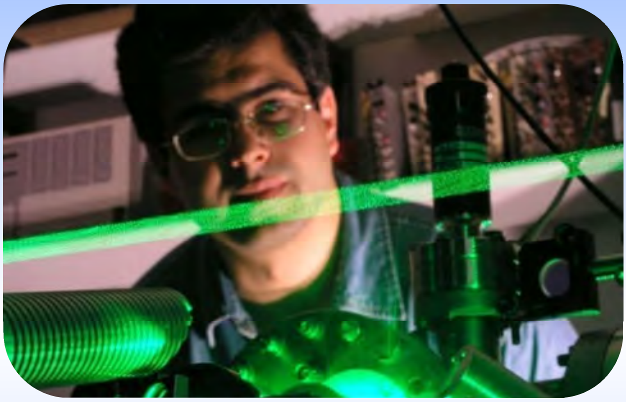
Direct measurement
Reliability and repeatability of the result
Defensible measured value
High temporal resolution
Integrated over an area
Many gas species can be covered
Backed by scientific community
Can be low-power, unattended, continuous

While there are a lot of potential industrial applications which can benefit from using Eddy Covariance method, the more obvious cases would be the following:

Carbon Capture and Sequestration
Landfill Emissions and Gas Budget
Oil and gas industry
Environmental Emission Monitoring
Carbon Credit Budgets at City and State level
Fugitive emissions
Agricultural emission or consumption
etc.

NETL's Carbon Sequestration Program - http://www.netl.doe.gov/technologies/carbon_seq/

EC EXPANSION: GAS SPECIES



- Laser technologies can detect ppb at high frequencies
- Potentially allows multiple gas, fast, and high resolution Eddy Covariance systems

Fluxes of momentum, heat, carbon dioxide and water used to be the prime focus of Eddy Covariance.

With advances in technological development (such as Wavelength Modulation Spectroscopy, fast digital processing, and wireless, low-power solutions, *etc.*) instruments soon will be able to detect several parts per billion at high frequencies for many more gas species, faster, with more accuracy, and consuming little power.

As a result, Eddy Covariance is getting positioned to compute fluxes from rare or multiple gas species in low-power open-path systems, and shed more light on the processes affecting fluxes of volatile components, such as nitrous oxide, methane, ozone, VOCs, isotopes, *etc.*

EC EXPANSION: TERRAINS

- Further understanding the complex flow
- Measure convergence and divergence
- Measure drainage flux, advection, and storage
- Use of control volumes and multiplexed tower, transects, *etc.*

The latest scientific developments have enabled Eddy Covariance to be used in complex terrains (on hills, in cities, and under conditions of various flow obstructions).

Success of these applications has been intermittent, but progress in this direction is very promising. Several groups in Fluxnet work specifically in complex terrains, and have become experts in this application of the method.

Eddy covariance studies in complex terrains rely on further understanding the complex flow, measurements of flow convergence and divergence, drainage flux, advection, and storage. They also rely on the use of control volumes and multiplexers, and other instrument-intensive techniques.

Such developments are especially important for understanding and quantifying fluxes in ever-expanding urban territories and in sparsely studied mountain regions. Both of these areas are vast, and have a very large impact on global fluxes of carbon, water, and aerosols.

McMillen, R.T. 1988. 'An eddy correlation technique with extended applicability to non-simple terrain', Boundary Layer Meteorology, 43, 231-245

Raupach, MR, Finnigan, JJ. 1997. The influence of topography on meteorological variables and surface-atmosphere interactions. Journal of Hydrology, 190:182-213

EXPANSION IN SCALE: LIDAR, SCINTILLOMETER…

- LIDAR – LIght Detection and Ranging ("laser radar")
  - Differential absorption lidars can measure gas concentrations
  - Could potentially be used to measure & compute fluxes
- Scintillometer
  - Detects fluctuations of refractive index due to T, humidity, and pressure
  - Could be used to measure sensible and latent heat fluxes

Classical tower flux measurements cover upwind footprints on the order of thousands of square meters.

New technologies, such as LIDAR, Scintillometers, long-distance FTIR instruments can potentially be used to measure and compute gas fluxes from areas of many square kilometers, and from all wind directions.

Based on Eddy covariance principles and these technologies, new methods can potentially be developed to be both fast and accurate, similar to Eddy Covariance, and have large spatial averaging independent of wind speed and direction, similar to the LIDAR or Scintillometery.

LIDAR is an abbreviation for LIght Detection and Ranging, alternatively called 'laser radar'. The main types of LIDAR are:

range finders – measure distances
differential absorption – gas concentrations
dopplers – measure velocity of a target

In addition to flux measurement potential, LIDAR can also be used to measure average concentration of the entity of interest in the vertical column in the lower atmosphere, and can measure average concentrations over two-dimensional planes above the surface.

Scintillometers have recently been used for detection of sensible heat flux over large territories, with reasonable success, and for detection of water vapor flux, with limited success.

These and other long-range methods currently require substantial amount of modeling and empirical calibration and adjustment of the calculations, but they have a good potential in the future, when directness and resolution challenges can be successfully addressed through technology.

EXPANSION IN SCALE: AIRBORNE

Flux measurements done from airplanes and helicopters are expanding their scope and frequency, and may cover areas of hundreds to thousands of square kilometers. Fluxes, concentration gradients and transects can all be measured airborne with modern instrumentation.

Special networks are being formed, such as NAERS, the Network of Airborne Environmental Research Scientists (http://www.naers.org/) to advance this type of environmental research.

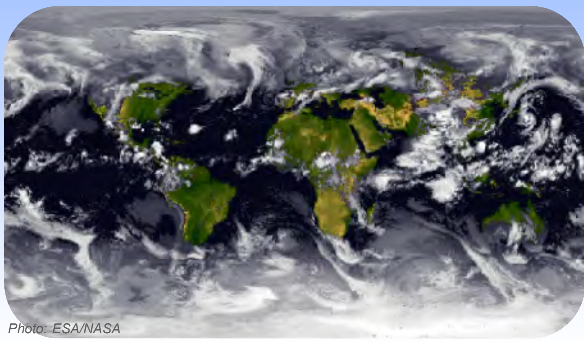
In conjunction with newly developed instrumentation and data from tower networks, airborne measurements will help the tower measurements to be scalable to a regional level.

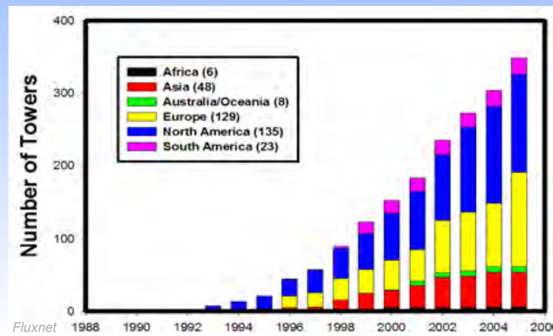
Crawford, TL, RJ Dobosy, RT McMillen, CA Vogel and BB Hicks. 1996. Air-surface exchange measurements in heterogeneous regions: extending tower observations with spatial structure observed from small aircraft. Global Change Biology. 2,275-286

Mahrt L., 1998. Flux sampling errors for aircraft and towers JAOT, 15: (2) 416-429 APR8

Vickers, D. and Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526

EXPANSION IN SCALE: GLOBAL NETWORKS





- Need for spatial resolution at all scales
- Local: multiplex systems for soil, multiple towers, field remote sensing
- Regional: regional networks (ICOS, NEON, Ameriflux, Fluxnet-Canada, *etc.*)
- Global: global network (iLEAPs/FLUXNET), standardized databases, modeling
- Earth observations intranet

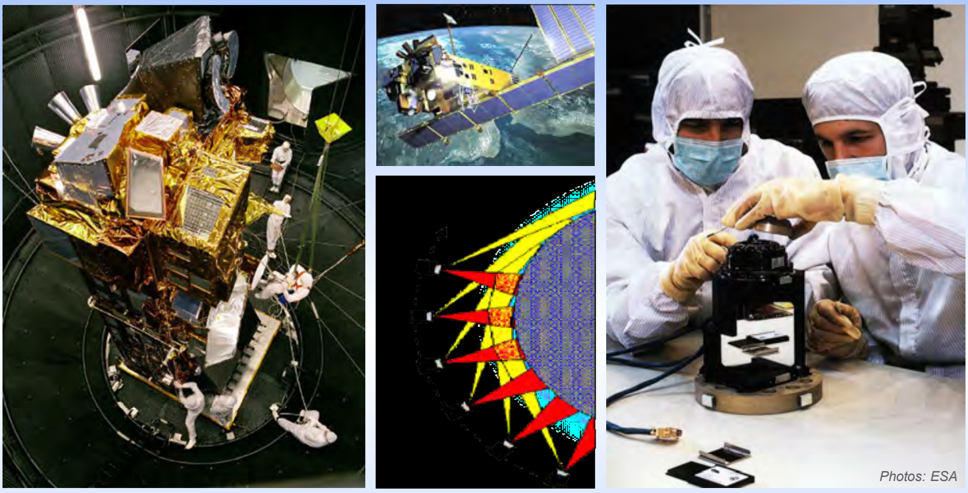
Flux networks unite EC research with various spatial resolution and coverage. Data from many sites are collected in a single archive. They are collected with uniformed collection and reduction methods and stored and maintained with consistent formats. Such data are invaluable for carbon cycle and global climate modeling, and may have multiple uses in other disciplines.

Networks' archives cover ecosystem flux and related parameters on a variety of scales from: field scale (e.g., short tower data, multiplex systems for soil, field-size remote sensing), to regional scale with networks such as: ICOS, NEON, Ameriflux, Fluxnet-Canada, *etc.*, and finally globally with networks like: iLEAPs/FLUXNET.

Web-pages of global and regional flux networks listed below are helpful for access to general network descriptions, recent publications, field data sets, and other useful information:

Fluxnet - http://daac.ornl.gov/FLUXNET/
Ameriflux - http://public.ornl.gov/ameriflux/
AsiaFlux - http://asiaflux.yonsei.kr/
Biosphere-Atmopsphere Stable Isotope Network - http://basinisotopes.org
NEON - http://www.neoninc.org
NitroEurope - http://www.nitroeurope.eu/
FluxNet-Canada- http://www.fluxnet-canada.ca/
Carbo-Africa - http://www.carboafrica.net
CarboEurope IP - http://www.carboeurope.org/
Carbomont - http://www.uibk.ac.at/carbomont/
ChinaFlux - http://www.chinaflux.org
ICOS - http://www.icos-infrastructure.eu
JapanFlux - http://www.japanflux.org/
KoFlux - http://koflux.yonsei.ac.kr/
LaThuile Data Set - http://www.fluxdata.org
OzFlux - http://www.cmar.csiro.au/ozflux/
ThaiFlux - http://compete.center.ku.ac.th/HomeFlux.htm
Urban Fluxnet- http://www.kcl.ac.uk/projects/muhd/

EXPANSION IN SCALE: PLANETARY



- Spectral measurements from space could potentially observe dynamic content of entire atmosphere – the ultimate goal of tower networks
- The working example is SCIAMACHY – orbital imaging spectrometer

Spectral measurements done from space can potentially observe dynamic content of the entire atmosphere – the ultimate goal of tower networks. Future satellite measurements require development and testing of instruments and data collection systems on the ground, which later could be used for remote sensing. Comparison of field and satellite data (called ground truthing) is very important for developing this approach. With time, satellite instrument systems could reliably determine the dynamics of gases, aerosol and dust for the planet as a whole.

One of the pioneering examples of such a system is the orbital imaging spectrometer SCIAMACHY – Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY.

Although not using Eddy Covariance, such observations and measurements could be used together with tower measurements to compute fluxes at both high temporal resolution (from Eddy Covariance) and spatial coverage (satellite data) at the same time.

Sellers, P.J., Hall, F.G, Asrar, G., Strebel, D.E. and R.E. Murphy, 1992. An Overview of the first international satellite land surface climatology project (ISLSCP) field experiment (FIFE). Journal of Geophysical Research, 97: 18345-18371

Gitelson, A.; S.Verma; A.Viña; D. Rundquist; G. Keydan; T. Arkebauer; G. Burba; A. Suyker, 2003. Novel Technique for Remote Estimation of Landscape-level CO_2 flux. GRL, 30 (9), 1-4

PART V. EDDY COVARIANCE REVIEW SUMMARY

EC REVIEW SUMMARY

- Micrometeorological technique to measure vertical turbulent fluxes in the atmospheric boundary layer: nearly-direct, theoretically solid and proven, very flexible in applications, verifiable by other techniques
- Widely used in micrometeorology to measure H_2O, CO_2, heat, momentum, increasingly being used to measure CH_4, O_3, NO_3, isotopes, bVOCs and other gases
- Requires a number of assumptions/corrections, demands careful design, execution and processing custom-fitted to the specific purpose at the specific experimental site
- Continuously develops on conceptual and instrumental levels to allow wider applications in more environments

In this guide we put together simple guidelines to help a non-expert to understand the general principles, requirements, applications, and processing steps of the Eddy Covariance method. Its goal is to promote further understanding of the method via more advanced sources (e.g., textbooks, papers), and to help design the experiment for specific scientific needs.

In summary, Eddy Covariance is a micrometeorological technique to measure vertical turbulent fluxes in the atmospheric boundary layer. It is: nearly-direct, theoretically solid, proven, very flexible in applications, and verifiable by other techniques.

It is widely used in micrometeorology to measure H_2O, CO_2, heat, and momentum, and has started being used to measure CH_4, O_3, NO_3, volatile organic components and other gases.

The method requires a number of assumptions and corrections. It demands careful design, execution and processing that is fit to the specific purpose at the specific experimental site.

Eddy Covariance continues to develop on conceptual and instrumental levels. It is expanding in application scope and is being used in more diverse environments.

EC REVIEW: SUMMARY (cont.)

- Potentially of great use to many non-meteorological sciences, industry, carbon capture and sequestration, environmental management and monitoring *etc.*, when energy, water or gas exchanges and balances are of interest

- Major flux measurement networks already exist to provide global synthesis, allow interpretation of one particular EC experiment in the context of world-wide observations – new and invaluable scientific tool

Eddy covariance is potentially of great use to many non-meteorological sciences, industrial monitoring, carbon storage and sequestration, landfill and environmental management, and any type of monitoring of actual emission rates when energy, water or gas exchanges and balances are of interest.

Major flux measurement networks already provide open-access uniformed experimental data from hundreds of tower sites to a variety of natural sciences.

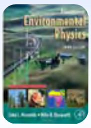
Such network observations are an invaluable global scientific tool which did not exist 20 years ago. Today, it provides modelers and field researches with a wide range of opportunities: from interpretation of one particular Eddy Covariance experiment in the context of world-wide observations to a global synthesis of local and regional flux processes.

PART VI. USEFUL RESOURCES

PRINTED BOOKS

Micrometeorology, 2009. By T. Foken. Springer-Verlag.

Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, 2008. By X. Lee; W. Massman; B. Law (Eds.). Springer-Verlag.



Principles of Environmental Physics, 2007. By J. Monteith and M. Unsworth. Academic Press.

Microclimate: The Biological Environment. 1983. By N. Rosenberg, B. Blad, S. Verma. Wiley Publishers.

Introduction to Micrometeorology (International Geophysics Series). 2001. By S. Pal Arya. Academic Press.

Field Measurements for Forest Carbon Monitoring: A Landscape-Scale Approach, 2008. By C.M. Hoover (Ed.). Springer-Verlag.

Useful books and dissertations on the topics of Eddy Covariance methodology and underlying principles also include:

An Introduction to Boundary Layer Meteorology, 1988. By R.G. Stull, Springer

An Introduction to Environmental Biophysics, 2007. By G. Campbell. Springer

Atmospheric Boundary Layer Flows: Their Structure and Measurement, 1994. By C. Kaimal and J. Finnigan. Oxford University Press

Boundary Layer Climates, 1988. By T.R. Oke. Routledge

Ecological Climatology: Concepts and Applications, 2008. By G. Bonan. Cambridge University Press

Fluxes of Carbon, Water and Energy of European Forests, 2003. By R. Valentini (Ed). Springer

Mass and Energy Exchange of a Plantation Forest in Scotland Using Micrometeorological Methods, 2004. By R.J. Clement. PhD Dissertation, University of Edinburgh, UK - http://www.geos.ed.ac.uk/homes/rclement/PHD/

Micrometeorology in Agricultural Systems,2005. By J. Hatfield (Ed.). American Society of Agronomy-Crop Science Society of America-Soil Science Society of America

Transport at the Air-Sea Interface: Measurements, Models and Parametrizations, 2007. By C.S. Garbe R.A. Handler, B. Jahne (Eds). Springer

Long term atmosphere/biosphere exchange of CO_2 in Hungary, 2001. By Z. Barcza. PhD Dissertation, Eötvös Loránd University, Hungary - http://nimbus.elte.hu/~bzoli/thesis

ELECTRONIC BOOKS, LECTURES, AND GUIDES

Advanced topics in Biometeorology and Microclimatology, 2006. By D. Baldocchi, Department of Environmental Science, UC-Berkeley - http://nature.berkeley.edu/biometlab/espm228/

AmeriFlux Guidelines For Making Eddy Covariance Flux Measurements, by Munger and HW Loescher, AmeriFlux - http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

Fluxnet-Canada Measurement Protocols, by Fluxnet-Canada Network Management Office - http://www.fluxnet-canada.ca/pages/protocols_en/ measurement protocols_v.1.3_background.pdf

Practical Handbook of Tower Flux Observations, by Forest Meteorology Research Group of the Forestry and Forest Products Research Institute - http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

Also instructive are the following:

Corrections to Sensible and Latent Heat Flux Measurements, 2003. By T.W. Horst http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/

Documentation and Instruction Manual of the Eddy Covariance Software Package, 2004. By M. Mauder, and T. Foken http://132.180.112.26/mikrometeorologie/ARBERG/ARBERG26.pdf

EdiRe Access and Tutorial, 2006. By R. Clement http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/

Introduction to the Eddy Covariance Method: General Guidelines and Conventional Workflow: Lectures, 2007. By G. Burba and D. Anderson, read by J. Amen, LI-COR Biosciences

Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH20, 2004-2006. By CSI, Inc. http://www.campbellsci.com/documents/manuals/opecsystem.pdf

Summary and Synthesis of Recommendations of the AmeriFlux Workshop on Standardization of Flux Analysis and Diagnostics, 2002. By B. Massman , L. Finnigan and D. Billesbach http://public.ornl.gov/ameriflux/workshops/workshop-20020827-CorvallisOR-summary.doc

WEB-SITES

FLUXNET - http://daac.ornl.gov/FLUXNET/

GCP - http://www.globalcarbonproject.org/

ICOS - http://www.icos-infrastructure.eu/

IGOS - http://www.ioc.unesco.org/igospartners/carbon.htm

iLEAPs - http://www.ileaps.org/

NEON - http://www.neoninc.org/

In addition to the global and large-scope projects shown above, below is a recently compiled list of regional flux networks and specialized ecosystem study networks involving Eddy Covariance flux measurements:

Ameriflux - http://public.ornl.gov/ameriflux/
AsiaFlux - http://asiaflux.yonsei.kr/
Biosphere-Atmosphere Stable Isotope Network - http://basinisotopes.org
NitroEurope - http://www.nitroeurope.eu/
FluxNet-Canada - http://www.fluxnet-canada.ca/
Carbo-Africa - http://www.carboafrica.net
CarboEurope - http://www.bgc-jena.mpg.de/bgc-processes/carboeur/projects/index_p.html
CarboEurope IP - http://www.carboeurope.org/
Carbomont - http://www.uibk.ac.at/carbomont/
ChinaFlux - http://www.chinaflux.org
EuroFlux - http://www.unitus.it/dipartimenti/disafri/progetti/eflux/euro.html
GreenGrass - http://www2.clermont.inra.fr/greengrass/
IANABIS - http://www.ipicyt.edu.mx/IANABIS/
JapanFlux - http://www.japanflux.org/
KoFlux - http://koflux.yonsei.ac.kr/
OzFlux - http://www.cmar.csiro.au/ozflux/
ThaiFlux - http://compete.center.ku.ac.th/HomeFlux.htm
Urban Fluxnet - http://www.kcl.ac.uk/projects/muhd/

PART VII. REFERENCES AND FURTHER READING

Ameriflux (2006) Ameriflux Sites Information. http://public.ornl.gov/ameriflux/site-select.cfm

Amiro B, Orchansky A, Sass A (2006) A perspective on CO_2 flux measurements using an open-path infrared gas analyzer in cold environments. Proceedings of 27th Annual Conference of Agricultural and Forest Meteorology, San Diego, California, 5 pp.

Aubinet, M., A. Grelle, A. Ibrom, U. Rannik, J. Moncrieff, T. Foken, A. Kowalski, P. Martin, P. Berbigier, Ch. Bernhofer, R. Clement, J. Elbers, A. Granier, T. Grunwald, K. Morgenster, K. Pilegaard, C. Rebmann, W. Snijders, R. Valentini and T. Vesala. 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology, Advances of Ecological Research. 113-174

Baldocchi, D., 1994, A comparative study of mass and energy exchange over a closed C3 (wheat) and an open C4 (corn) canopy: I. The partitioning of available energy into latent and sensible heat exchange, Agricultural and Forest Meteorology 67, 191-220

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biol, 9: 479-492

Baldocchi, D.D., B.B. Hicks and T.P. Meyers. 1988. 'Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods', Ecology, 69, 1331-1340

Bremer, D.J. and J.M. Ham, 1999. Effects of spring burning on the surface energy balance in a tall grass prairie. Agricultural and Forest Meteorology, 97: 43-54

Billesbach DP, Fischer ML, Berry JA, Torn MS (2001) A highly portable, rapidly deployable system for eddy covariance measurements of CO_2 fluxes. Journal of Atmospheric & Oceanic Technology, 21, 4 29 pp.

Brut A., Legain D., Durand P. and Laville P. 2004 A relaxed eddy accumulator for surface flux measurements on ground-based platforms and aboard research vessels, Journal of Atmospheric & Oceanic Technology, 21: 411-427

Burba, G.G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K.G. Hubbard and M.V.K. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland, 77-87

Burba G. G., Anderson D. J., Xu L., and D. K. McDermitt. 2005a. Solving the off-season uptake problem: correcting fluxes measured with the LI-7500 for the effects of instrument surface heating. Progress report of the ongoing study. PART I: THEORY. Poster presentation. AmeriFlux 2005 Annual Meeting, Boulder, Colorado.

Burba G. G., Anderson D. J., Xu L., and D. K. McDermitt. 2005b. Solving the off-season uptake problem: correcting fluxes measured with the LI-7500 for the effects of instrument surface heating. Progress report of the ongoing study. PART II: RESULTS. Poster Presentation. AmeriFlux 2005 Annual Meeting, Boulder, Colorado.

Burba, G. D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

Burba, G., D. McDermitt, D. Anderson, M. Furtaw, and R. Eckles, 2010. Novel design of an enclosed CO_2/H_2O gas analyzer for Eddy Covariance flux measurements. Tellus B: Chemical and Physical Meteorology. Accepted

Burba, G.G.; S. B. Verma, 2001. Prairie growth, PAR albedo and seasonal distribution of energy fluxes. Agricultural and Forest Meteorology, 107(3), 227-240.

Burba, G.G.; S. B. Verma; J. Kim, 1999. Surface energy fluxes of Phragmites australis in a prairie wetland. Agricultural and Forest Meteorology, 94(1), 31-51.

Businger, J.A. 1986. Evaluation of the accuracy with which dry deposition could be measured with current micrometeorological techniques. Journal of Climate and Applied Meteorology. 25: 1100-1124

Clement, R., G. Burba, A. Grelle, D. Anderson, and J. Moncrieff, 2009. Improved trace gas flux estimation through IRGA sampling optimization. Agricultural and Forest Meteorology, 149 (3-4): 623-638

Crago R, Brutsaert W. 1996. Daytime evaporation and the self-preservation of the evaporative fraction and the Bowen ratio. Journal of Hydrology 178: 241–2551

Crawford, TL, RJ Dobosy, RT McMillen, CA Vogel and BB Hicks. 1996. Air-surface exchange measurements in heterogeneous regions: extending tower observations with spatial structure observed from small aircraft. Global Change Biology. 2,275-286

Denmead, O.T. 1983. Micrometeorological methods for measuring gaseous losses of nitrogen in the field. In: Gaseous Loss of Nitrogen from plant-soil systems. eds. J.R. Freney and J.R. Simpson. pp 137-155.

Denmead, O.T. and M.R. Raupach. 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. American Society of Agronomy.

Falge, E.; D. Baldocchi; R. Olson; P. Anthoni; M. Aubinet; C. Bernhofer; G. Burba; R. Ceulemans; R. Clement; H. Dolman; A. Granier; P. Gross; T. Grunwald; D. Hollinger; N. O. Jensen; G. Katul; P. Keronen; A. Kowalski; C. T. Lai; B. E. Law; T. Meyers; J. Moncrieff; E. Moors, 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1), 43-69.

Falge, E.; D. Baldocchi; R. Olson; P. Anthoni; M. Aubinet; C. Bernhofer; G. Burba; G. Ceulemans; R. Clement; H. Dolman; A. Granier; P. Gross; T. Grunwald; D. Hollinger; N. O. Jensen; G. Katul; P. Keronen; A. Kowalski; C. T. Lai; B. E. Law; T. Meyers; J. Moncrieff; E. Moors, 2001. Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology, 107(1), 71-77.

Falge, E.; D. Baldocchi; J. Tenhunen; M. Aubinet; P. Bakwin; P. Berbigier; C. Bernhofer; G. Burba; R. Clement; K. J. Davis; J. A. Elbers; A. H. Goldstein; A. Grelle; A. Granier; J. Guomundsson; D. Hollinger; A. S. Kowalski; G. Katul; B. E. Law; Y. Malhi; T. Meyers; R.K. Monso, 2002. Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. Agricultural and Forest Meteorology, 113(1-4), 53-74.

Falge, E.; J. Tenhunen; D. Baldocchi; M. Aubinet; P. Bakwin; P. Berbigier; C. Bernhofer; J. M. Bonnefond; G. Burba; R. Clement; K. J. Davis; J. A. Elbers; M. Falk; A. H. Goldstein; A. Grelle; A. Granier; T. Grunwald; J. Gudmundsson; D. Hollinger; I. A. Janssens; P. Keronen, 2002. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. Agricultural and Forest Meteorology, 113 (1-4), 75-95.

Finkelstein, P.L. and Sims. P.F. 2001. Sampling error in eddy correlation flux measurements, Journal of Geophysical Research. 106, 3503-3509,

Finnigan, J.J., Clement, R., Malhi, Y., Leuning, R. and Cleugh, H.A., 2003. A Re-Evaluation of Long-Term Flux Measurement Techniques Part I: Averaging and Coordinate Rotation. Boundary Layer Meteorology, 107: 1-48.

Flint, A.L., Childs, S.W., 1991. Use of the Priestley-Taylor evaporation equation for soil water limited conditions in a small forest clear cut. Agricultural and Forest Meteorology 56: 247-260.

Foken, Th. and B. Wichura. 1995. Tools for quality assessment of surface-based flux measurements, Agricultural and Forest Meteorology, 78, 83-105.

Frank AB (2002) CO_2 fluxes over a grazed prairie and seeded pasture in northern Great Plains. Environmental Pollution, 116, 397–403

Fuehrer, P.L. and Friehe, C.A., 2002. Flux corrections revisited. Boundary Layer Meteorology, 102: 415-457

Gilmanov, T.G.; S. B. Verma; P. L. Sims; T. P. Meyers; J. A. Bradford; G. G. Burba; A. E. Suyker, 2003. Gross primary production and light response parameters of four Southern Plains ecosystems estimated using long-term CO_2-flux tower measurements. Global Biogeochemical Cycles, 17(2), 401-415

Gitelson, A.; S.Verma; A.Viña; D. Rundquist; G. Keydan; T. Arkebauer; G. Burba; A. Suyker, 2003. Novel Technique for Remote Estimation of Landscape-level CO_2 flux. GRL, 30 (9), 1-4

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J. M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I. A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.-M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M. J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J. F., Valentini, R., Vesala, T., Verbeeck, H., and

Yakir, D. 2008. Quality control of CarboEurope flux data – Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5, 433-45

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C. and Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy. Global Change Biology, 2(3): 169-182

Grelle, A., and G. Burba, 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agricultural and Forest Meteorology, 147: 48–57

Ham, J.M. and Heilman, J.L., 2003. Experimental Test of Density and Energy-Balance Corrections on Carbon Dioxide Flux as Measured Using Open-Path Eddy Covariance. Agron J, 95(6): 1393-1403

Hanan, N.; G. Burba; S. B. Verma; J. A. Berry; A. Suyker; E. A. Walter-Shea, 2002. Inversion of net ecosystem CO_2 flux measurements for estimation of canopy PAR absorption. Global Change Biology, 8(6), 563-574

Hanan, N.; J.A. Berry; S.B. Verma; E.A. Walter-Shea; A.E. Suyker; G.G. Burba; A. Scott Denning, 2005. Testing a model of CO_2, water and energy exchange in Great Plains tall-grass prairie and wheat ecosystems. Agricultural and Forest Meteorology,131: 162-179

Heijmans, M.P.D, W.J. Arp, and F.S. Chapin III, 2004. Carbon dioxide and water vapour exchange from understory species in boreal forest. Agricultural and Forest Meteorology 123:135-147

Hirata R, Hirano T, Mogami J, Fujinuma Y, Inukai K, Saigusa N, Yamamoto S (2005) CO_2 flux measured by an open-path system over a larch forest during snow-covered season. Phyton, 45, 347-351.

Hirata R., Hirano, T., Saigusa, N., Fujinuma, Y., Inukai, K., and Y. Kitamon, 2005. Comparison of eddy CO_2 fluxes measured with open-path and closed-path systems based on a long-term measurement. Proceedings of the 7th International Carbon Dioxide Conference, Sept. 25-30, Boulder, Colorado

Horst, T.W. 1997. A simple formula for attenuation of eddy fluxes measured with first order response scalar sensors. BLM. 82, 219-233

Jarvi, L., I. Mammarella, W. Eugster, A. Ibrom, E. Siivola, E. Dellvik, P. Keronen, G. Burba, and T. Vesala, 2009. Comparison on net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment. Boreal Environment Research, ISSN 1239-6095 (14): 14pp.

Jury, W.A., and C.B. Tanner, 1975. Advection modification of the Priestley and Taylor evapotranspiration formula. Agronomy J. 67: 840–842.

Kaimal, J.C. and J.J. Finnigan. 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, UK. 289 pp

Kim, J., and S.B. Verma, 1990. Components of surface energy balance in a temperate grassland ecosystem. Boundary-Layer Meteorology, 51: 401-417

Kimball, B.A., Jackson, R.D., Nakayama, F.S., Idso, S.B. and R.J. Reginato, 1976. Soil-heat flux determination: Temperature gradient method with computed thermal conductivities. Soil Science, 40: 25-28.

Kristensen, K.J. and Jensen, S.E., 1975. A model for estimating actual evapotranspiration from potential transpiration. Nordic Hydrology. 6, 70 - 88

Launiainen S, Rinne J, Pumpanen J, Kulmala L, Kolari P, Keronen P, Siivola E, Pohja T, Hari P, Vesala T(2005) Eddy covariance measurements of CO_2 and sensible and latent heat fluxes during a full year in a boreal pine forest trunk-space. Boreal Environment Research, 10 569-588

Lee X, Massman W, Law B (2004) Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, 250 pp.

Lee X., T.A. Blacck, and M.D. Novak, 1994. Comparison of flux measurements with open-path and closed-path gas analyzers above an agricultural field and forest floor. BLM, 67: (1-2) 195-202

Lenschow, DH. 1995. Micrometeorological techniques for measuring biosphere atmosphere trace gas exchange. In: Biogenic Trace Gases: Measuring Emissions from Soil and Water. Eds. P.A. Matson and R.C. Harriss. Blackwell Sci. Pub. Pp 126-163.

Lhomme, J.P., 1988. Extension of Penman's formulae to multi-layer models. Boundary-Layer Meteorology, 42: 281-291.

Liu H (2005) An Alternative Approach for CO_2 Flux Correction Caused by Heat and Water Vapour Transfer. BLM, 115, 151-168.

Mahrt L., 1998. Flux sampling errors for aircraft and towers. Journal of Atmospheric & Oceanic Technology, 15: (2) 416-429 APR8

Massman, W.J., 1992. A surface energy balance method for partitioning evapotranspiration data into plant and soil components for surface with partial canopy cover. Water resources research, 28(6): 1723-1732

Massman, W.J. 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agricultural and Forest Meteorology.104, 185-198

Massman, W.J. and Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agricultural and Forest Meteorology, 113(1-4): 121-144.

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O., 2008. Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software, Biogeosciences, 5, 451-462

McAneney, K.J., 1996. Operational limits to the Priestley-Taylor formula. Irrigation Science, 17: 37-43

McMillen, R.T. 1988. 'An eddy correlation technique with extended applicability to non-simple terrain', Boundary Layer Meteorology, 43, 231-245.

Moncrieff, J.B., Y. Mahli and R. Leuning. 1996. 'The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water', Global Change Biology, 2, 231-240

Monteith, J.L., 1963. Gas exchange in plant communities. Environmental control of plant growth. L.T. Evans, ed. Academic Press, New York: 95-112

Moore, C. 1986. Frequency response corrections for eddy covariance systems. Boundary Layer Meteorology. 37, 17-35.

Morgenstern K, Black TA, Nesic Z (2006) Evaluation of uncertainty in eddy covariance measurements within Fluxnet-Canada. Proceedings of 27th Annual Conference of Agricultural and Forest Meteorology, San Diego, California, 4 pp.

Munger J.W., and H. W. Loescher. 2006. Guidelines for making Eddy Covariance flux measurements. http://public.ornl.gov/ameriflux/measurement_standards_4.doc]

Nie D, Kleindienst TE, Arnts RR, Sickles JE, 1995. The design and testing of a relaxed eddy accumulation system. JGR. 100: 11,415-11,423

Nobel, P.S., 1983. Biophysical Plant Physiology. W.H. Freeman and Company, San Francisco: 488 pp.

Ono, K. , A. Miyata1 and T. Yamada, 2008. Apparent downward CO_2 flux observed with open-path eddy covariance over a non-vegetated surface. Theoretical and Applied Climatology, 92 (3-4): 195-208

Pattey E, Desjardins RL, Rochette P (1993) Accuracy of the relaxed eddy-accumulation technique, evaluated using CO_2 flux measurements. Boundary Layer Meteorology 66:341-355

Pattey E, Desjardins RL, Boudreau F, Rochette P (1992) Impact of density fluctuations on flux measurements of trace gases: implications for the relaxed eddy accumulation technique. Boundary Layer Meteorology 59:195-203

Penman, H.L., 1948. Natural evapotranspiration from open water, bare soil, and grass. Proc. R. Soc. London, A. 193, pp.120-145.

Pereira, A.R., 2004. The Priestley-Taylor parameter and the decoupling factor for estimation reference evapotranspiration. Agricultural and Forest Meteorology, 125: 305-313.

Priestley, C.H.B, and R.J. Taylor, 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100: 81–92.

Ripley, E.A., 1979. The fluxes of water and carbon dioxide between a tallgrass prairie grassland and the atmosphere. Bol. Soc. Venez. Cienc. Nat.., XXXV (139): 449-487.

Rosset, M., Riedo, M., Grub, A., Geissmann, M., and J. Fuhrer, 1997. Seasonal Variations in radiation and energy balances of permanent pastures at different altitudes. Agricultural and Forest Meteorology, 86: 245-258.

Sammis, T.W., and L.W. Gay, 1979, Evapotranspiration from an arid zone plant community, Journal of Arid Environment 2: 313-321

Schlichting H, Gersten K, Krause E, Oertel H, Mayes C (2004) Boundary-Layer Theory. Springer-Verlag, Berlin, 801 pp.

Sellers, P.J., Hall, F.G, Asrar, G., Strebel, D.E. and R.E. Murphy, 1992. An Overview of the first international satellite land surface climatology project (ISLSCP) field experiment (FIFE). Journal of Geophysical Research, 97: 18345-18371.

Serrano-Ortiz, P., A. Kowalski, F. Domingo, B. Ruiz, and L. Alados-Arboledas, 2008. Consequences of Uncertainties in CO_2 Density for Estimating Net Ecosystem CO_2 Exchange by Open-path Eddy Covariance. Boundary-Layer Meteorology, 126(2): 209-218

Shuttleworth, W.J., and J.S. Wallace, 1985. Evaporation from sparse crops - an energy combination theory. Quart. J. R. Met. Soc., 111: 839-855.

Slatyer, R. O., and I.C. McIlroy, 1961."Practical Microclimatology with special reference to the Water Factor in Soil-plant-atmosphere Relationships." (Unesco and Csiro, Australia)

Stannard, D.I., 1993. Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. Water Resources Research, 29(5): 1379-1392.

Stewart, R.B., and W.R. Rose, 1977. Substantiation of the Priestley and Taylor parameter a=1.26 for potential evaporation in high latitudes. Journal of Applied Meteorology, 16: 649-650

Schontanus, P., Nieuwstadt, F.T.M. and de Bruin, H.A.R. 1983. Temperature measurements with a sonic anemometer and its application to heat and moisture fluxes. Boundary Layer Meteorology. 26, 81-93

Su, H.-B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S. and Oliphant, A.J., 2004. Spectral Characteristics and Correction of Long-Term Eddy-Covariance Measurements Over Two Mixed Hardwood Forests in Non-Flat Terrain. Boundary Layer Meteorology, 110: 213-253.

Suyker, A.E. and S.B. Verma. 1993. Eddy correlation measurement of CO_2 flux using a closed path sensor: theory and field tests against an open path sensor. Boundary-Layer Meteorology. 64, 391-407.

Suyker, A.E. ; S. B. Verma; G. G. Burba, 2003. Interannual variability in net CO_2 exchange of a native tallgrass prairie. Global Change Biology, 9(2), 255-265.

Suyker, A.E.; S. B. Verma; G. G. Burba; T. J. Arkebauer; D. T. Walters; K. G. Hubbard, 2004. Growing season carbon dioxide exchange in irrigated and rainfed maize. Agricultural and Forest Meteorology, 124(1-2), 1-13

Suyker, A.E., S.B. Verma, G.G. Burba, and T.J. Arkebauer. 2005. Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. Agricultural and Forest Meteorology, 131: 180-190

Swinbank, WC, 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology. 8, 135-145

Swinbank, W.C. 1955. An experimental study of eddy transport in the lower atmosphere. Division of Meteorological Physics Technical Paper, 2. CSIRO. Melbourne. 29pp.

Twine, T.E. et al., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology, 103(3): 279-300.

van Bavel, C.H.M., 1966. Potential evaporation: the combination concept and its experimental verification. Water Resources Research, 2: 455-467

Verhoef, A., Allen, S.J., De Bruin, H.A.R., Jacobs, C.M.J. and B.G. Heusinkveld, 1996. Fluxes of carbon and water vapor from a Sahelian savanna. Agricultural and Forest Meteorology, 80: 231-248.

Verma, S.B., and A. E. Suyker. Personal Communications. 2005-06

Verma, S.B., 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. Remote Sensing Reviews, 5: 99-115.

Verma, S.B., Kim, J., and R.J. Clement, 1989. Carbon dioxide, water vapor and sensible heat fluxes over a tallgrass prairie. BLM, 46: 53-67.

Verma, S.B., Kim, J., and R. J. Clement, 1992. Momentum, water vapor and carbon dioxide exchange at a centrally located prairie site during FIFE. Journal of Geophysical Research, 97: 18629-18639.

Verma, S.; A. Dobermann; K. Cassman; D. Walters; J. Knops; T. Arkebauer; A. Suyker; G. Burba; B. Amos; H. Yang; D. Ginting; K. Hubbard; A. Gitelson; E. Walter-Shea, 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agricultural and Forest Meteorology, 131: 77-96

Webb, E.K., G. Pearman and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer, Quarterly Journal of Royal Meteorological Society, 106, 85-100.

Williams, D.G., W. Cable, K. Hultine, J.C.B. Hoedjes, E. Yepez, V. Simonneaux, S. Er-Raki, G. Boulet, H.A.R. de Bruin, A. Chehbouni, O.K. Hartogensis and F. Timouk, 2004. Components of evapotranspiration determined by stable isotope, sap flow and eddy covariance techniques. Agricultural and Forest Meteorology 125:241-258.

Wesely, M.L. 1970. Eddy correlation measurements in the atmospheric surface layer over agricultural crops. Dissertation. University of Wisconsin. Madison, WI.

Wesely, M.L., D.H. Lenschow and O.T. 1989. Flux measurement techniques. In: Global Tropospheric Chemistry, Chemical Fluxes in the Global Atmosphere. NCAR Report. Eds. DH Lenschow and BB Hicks. pp 31-46

Wilson, K. et al., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1-4): 223-243.

Wyngaard , J.C. 1990. Scalar fluxes in the planetary boundary layer-theory, modeling and measurement. Boundary Layer Meteorology. 50: 49-75.

Yunusa, I.A.M., Walker, R.R., and P. Lu, 2004. Evapotranspiration components from energy budget, sapflow and microlysimetry techniques for an irrigated vineyeard in inland Australia. Agricultural and forest meteorology, 127: 93-107

Text and Illustration Credits:

pages 6-34, 46-61, 69-209: written by George Burba, LI-COR
pages 35-45, 62-68: written by Dan Anderson and George Burba, LI-COR
pages 41-45, 49-51, 55-58, 60-62: used information from, and based on the texts written by Thad Miller and Ron Nelson , LI-COR
pages: 49-66 and everywhere else: all renderings and drawings of LI-COR instruments are done by Thad Miller, Ron Nelson and Jon Gooding, LI-COR

Photo Credits:

cover page and pages 12, 14, 26, 30, 32, 35, 46, 48, 51, 53, 69 (top), 70 (middle), 71, 73, 74 (right), 80, 83, 98-100, 104, 108, 113, 158, 162, 164, 172, 179, 186, 188, 189, 190 (right), 191, 197: photos by George Burba, LI-COR
pages 27, 56, 81, 155: photos by Dayle McDermitt, LI-COR
pages 43, 44, 63, 66, 69 (bottom two), 70 (left and right), 182: photos www.licor.com
page 47: map is compiled from images by NASA and SCHIAMACHY
page 75: photo courtesy of Dr Andrew Suyker, University of Nebraska
page 178: photo courtesy of Centre National de Recherches Météorologiques
page 190 (left): photo courtesy of CarboEurope
page 192: photo courtesy of Dr Roni Avissar, Duke University
page 194: photo courtesy of ESA/ENVISAT

This was an edition of

"Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications"
by
G. Burba and D. Anderson of LI-COR Biosciences

Version 1.0.1

LI-COR Biosciences
4647 Superior Street
P.O. Box 4425
Lincoln, Nebraska 68504 USA
www.licor.com
Email: george.burba@licor.com

Phone: 402.467.3576
Toll Free (USA): 800.447.3576

U.S. $35.00

From the Authors:

A Brief Practical Guide to Eddy Covariance Flux Measurements is an update to the 2005-07 field guide entitled "Introduction to the Eddy Covariance Method: General Guidelines and Conventional Workflow".

This book was written to familiarize beginners with general theoretical principles, requirements, applications, and processing steps of the Eddy Covariance method. It is intended to assist in further understanding the method, and provides references such as textbooks, network guidelines and journal papers. It is also intended to help students and researchers in field deployment of instruments used with the Eddy Covariance method, and to promote its use beyond micrometeorology.

We intend to keep the content of this work dynamic and current, and will be happy to incorporate any additional information and literature references. We welcome your suggestions; please address email correspondence to *george.burba@licor.com* with the subject "EC Guide".

Some of the topics covered in A Brief Practical Guide to Eddy Covariance Flux Measurements include:

- Overview of eddy covariance principles
- Typical eddy covariance workflow
- Alternative flux methods
- Future development
- Eddy covariance review summary
- Useful resources
- References and further reading

LI-COR®
Biosciences

4647 Superior Street • P.O. Box 4425 • Lincoln, Nebraska 68504 USA • www.licor.com
North America: 800-447-3576 • International: 402-467-3576 • FAX: 402-467-2819 • envsales@licor.com • envsupport@licor.com
In Germany and Norway – LI-COR Biosciences GmbH: +49 (0) 6172 17 17 771 • envsales-gmbh@licor.com • envsupport-gmbh@licor.com
In UK and Ireland – LI-COR Biosciences UK Ltd.: +44 (0) 1223 422102 • envsales-UK@licor.com • envsupport-UK@licor.com

8/10 984-11301 Printed in USA.