- Measurements of gas fluxes in and out of an ecosystem, quantifying evaporative water losses from an agricultural field, or monitoring of gas emission rates over a carbon sequestration injection site can be done with a wide variety of techniques
- Of these techniques, the eddy covariance method is one of the most accurate, direct and defensible approaches available to date for determining emission and consumption rates of various gases and water vapor over areas with sizes ranging from a few hundred to millions of square meters
- The method relies on direct and fast measurements of actual gas transport by a 3-dimensional wind in real time *in situ*, resulting in calculations of turbulent fluxes within the atmospheric boundary layer

The eddy covariance method provides measurements of gas emission and consumption rates, and also allows measurements of momentum, sensible heat, and latent heat (*e.g.*, evapotranspiration, evaporative water loss, *etc.*) fluxes integrated over areas of various sizes.

Fluxes of H_2O, CO_2, CH_4, N_2O and other gases are characterized above soil and water surfaces, plant canopies, and urban or industrial areas, from a single-point measurement using permanent or mobile stations.

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

While the applications are quite diverse in scope and requirements, there are many methodological commonalities in using the eddy covariance technique in all of these applications.

This book focuses primarily on these commonalities, and then explains the specific steps needed to tailor the method for a particular application or research project.

Below are a few examples of books that broadly cover and compare various flux measurement methods, including the eddy covariance technique.

References

Monteith, J., and M. Unsworth, 2008. Principles of Environmental Physics. Academic Press, Elsevier, Burlington, San Diego, London, 434 pp.

Hatfield, J., and J. Baker (Eds.), 2005. Micrometeorology in Agricultural Systems. ASA-CSSA-SSSA, Madison, Wisconsin, 588 pp.

Rosenberg, N., B. Blad, and S. Verma, 1983. Microclimate: The Biological Environment. Wiley-Interscience Publishers, 528 pp.

Sala, O., R. Jackson, H. Mooney, and R. Howarth (Eds.), 2000. Methods in Ecosystem Science. Springer-Verlag, New York, USA, 426 pp.

Baldocchi, D., 2013. A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective. FluxLetter, 5(2):1-8

- Modern instruments and software make the eddy covariance method easily available and widely-used in studies beyond micrometeorology, such as ecology, hydrology, environmental and industrial monitoring, agricultural and regulatory applications, *etc.*
- The main remaining challenge of the eddy covariance method for a non-expert is the sheer complexity of system design and implementation, and processing of the large volume of data
- Although modern instrument systems and software take care of most of these complexities, some basic understanding of eddy covariance principles and resulting requirements may still be helpful in successful implementation of the method

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

Thus, there is no one single recipe for using the method, and it is helpful to further study key aspects of the method in relation to a specific measurement site and a specific measurement purpose.

The basic information presented in this book 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 micrometeorology textbooks, flux network guidelines, and journal papers.

Below are a few examples of such sources of information focused specifically on the eddy covariance methodology and field deployment.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Baldocchi, D., B. Hicks, and T. Meyers, 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology, 69: 1331-1340

Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, Germany, 310 pp.

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Yamanoi, K., et al. (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

- To help those new to eddy covariance gain a basic understanding of the 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 (micrometeorology textbooks, scientific papers, *etc.*)
- To help design experiments for the specific needs of a new eddy covariance user for scientific, industrial, agricultural and regulatory applications

In this book, we will try to help those new to eddy covariance understand the general principles, requirements, applications, and processing steps.

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

Each page is divided into a top portion, with key points and summaries, and a bottom portion, with explanations, details, and recommended further reading.

In most cases, the top part of the page describes the concept or formulation, or lists what needs to be done, and how. The bottom part of the page explains the reasoning behind the steps that need to be performed.

For those who prefer to read this book in electronic format on an e-reader, illustrations and text are formatted such that they are easily read in daylight and in black-and-white text. Links throughout the text are hyperlinked, and can be clicked to navigate to other pages in the electronic version of the book.

We intend to keep the content of this book current and easy to use, so please do not hesitate to write with any questions, updates and suggestions to 'george.burba@licor.com' with the subject '2013 EC Book'.

The following icons are used throughout the text to indicate critical moments and key literature:

An exclamation point icon indicates warnings, information of high importance, or describes potential pitfalls related to the topic on a specific page.

A book icon indicates scientific references and other useful sources of information related to the topic on a specific page. These are listed, when possible, in order from most relevant or easy to understand, to broader or more complex.

There are eight main parts in this book. The first part, Overview of Eddy Covariance Principles, explains the basics of the eddy covariance theory, key derivations and assumptions, resulting requirements for the method, and main steps in the workflow to address all of the key requirements.

The second part, Designing an Eddy Covariance Experiment, provides a detailed description of each sequential step in the design of the eddy covariance experiment, highlights the most critical moments in this process and the most important concepts to consider before moving to the field.

Part 3, Implementing an Eddy Covariance Experiment, describes key steps during the field installation of the eddy covariance station.

Part 4, Processing Eddy Covariance Data, explains the data processing steps. These steps are usually done in software, but it is helpful to understand what exactly is being done to the data, and why, in order to make sure that the software is configured correctly and the results make sense.

Part 5, Overview of Alternative Flux Methods, briefly outlines the principles, and the pros and cons of other meteorological methods that can be used in cases where eddy covariance is not suitable or may provide unreliable results.

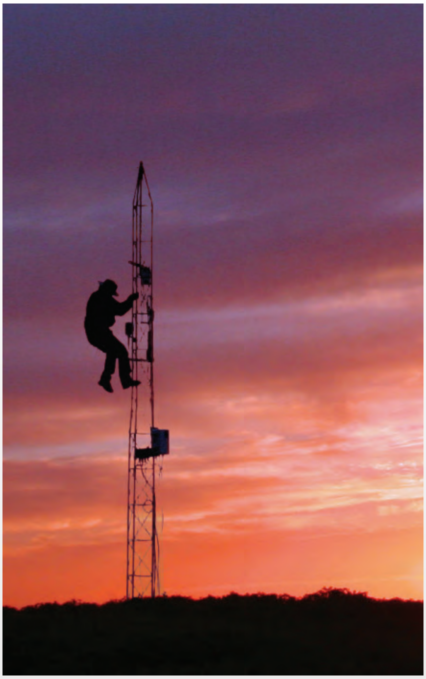
Part 6, Future Developments, describes the very latest upcoming developments of the eddy covariance method, its use, and scope.

Part 7 provides a brief summary of the book, and Part 8 describes further resources on the topic, such as books, lectures, guides, and web-sites.

The Appendix contains a detailed example of a fairly comprehensive eddy covariance field facility at LI-COR Biosciences to give the reader a more practical feel for the method and its implementation.

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

Particularly we thank Drs. Dennis Baldocchi, Dave Billesbach, Christian Bruemmer, Robert Clement, Tanvir Demetriades-Shah, Joe von Fischer, Thomas Foken, Gerardo Fratini, Achim Grelle, Sami Haapanala, Andreas Ibrom, James Kathilankal, Joon Kim, Olaf Kolle, Andrew Kowalski, Beverly Law, Ray Leuning, Anders Lindroth, Hank Loescher, William Massman, Dayle McDermitt, Stefan Metzger, Akira Miyata, William Munger, Taro Nakai, Dario Papale, Elizabeth Pattey, Janne Rinne, Borja Ruiz Reverter, Susanna Rutledge, Russ Scott, Peter Schreiber, HaPe Schmid, Andrew Suyker, Shashi Verma, Timo Vesala, Patrik Vestin, Jon Welles, Georg Wohlfahrt, Sebastian Wolf, Donatella Zona, and many others for their expertise in the area of flux studies.



We thank FluxNet and its regional networks, both past and active (*e.g.*, AmeriFlux, AsiaFlux, CCP and FluxNet-Canada, Carbo-Europe, Japan-Flux, IMECC, OzFlux, *etc.*), as well as ICOS, NEON, InGos, iLEAPS and other organizations, and their members, for providing access to the field data, setup guidelines, collection and processing instructions, and formats for their eddy covariance stations.

We particularly thank Dr. James Kathilankal, and Mr. Israel Begashaw for peer-reviewing the book, Dr. Gerardo Fratini for reviewing parts of the book related to EddyPro® and flux processing, and Mr. Bill Miller for reviewing parts related to analyzer specifications. We would also like to thank Dr. Dayle McDermitt for valuable advice for sections on instrument principles and surface heating.

In addition, we would like to acknowledge valuable input from, and interactions between, teachers and students at LI-COR Eddy Covariance Training Courses, and specifically hard work and input from the teachers: Dave Johnson, Jason Hupp, Peter Martin, and Drs. Liukang Xu, Jiahong Li, Richard Garcia, Tanvir Demetriades-Shah, Frank Griessbaum, and Oliver Marx.

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Also, we 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.

Part One:

Overview of Eddy Covariance Principles

- Flux measurements
- State of the methodology
- Air flow in ecosystems
- How to measure flux
- Derivation of key equations
- Major assumptions
- Major sources of errors
- Use in non-traditional terrains
- Summary of the theory
- Resulting workflow

The first part of this book is dedicated to the basics of the eddy covariance theory.

The following topics are discussed: flux measurements; state of methodology; air flow in ecosystems; surface with and without a flux; how to measure flux; derivation of key equations; major assumptions; major sources of errors; error treatment overview; use in non-traditional terrains; and summary of the resulting workflow when designing the experiment and conducting eddy covariance measurements.

References

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

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

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, Germany, 310 pp.

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

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Hoover, C. (Ed.), 2008. Field measurements for forest carbon monitoring: A landscape-scale approach. Springer, New York, 242 pp.

- Flux measurements are widely used to estimate the exchange of heat, water, and carbon dioxide, as well as methane and other trace gases
- The eddy covariance method 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!*

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

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

Yamanoi, K., *et al.* (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

- Uniform terminology and a single methodology are still being developed for the eddy covariance method
- Much of the effort is being done by networks (*e.g.*, FluxNet, ICOS, NEON, *etc.*) to unify various approaches
- Here we present one of the conventional ways to implement the eddy covariance method

In the past several years, efforts of the flux networks have led to significant progress in unifying the terminology and general standardization of processing steps.

The methodology itself, however, is more 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 gas density corrections may not be necessary.

Meanwhile, if CO_2 and CH_4 emission rates are measured for the purpose of cap-and-trade compliance, 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.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

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Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

- Flux – how much of something moves through a unit area per unit time
- Flux is dependent on:
    1. the number of things crossing the area
    2. the size of the area being crossed
    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.

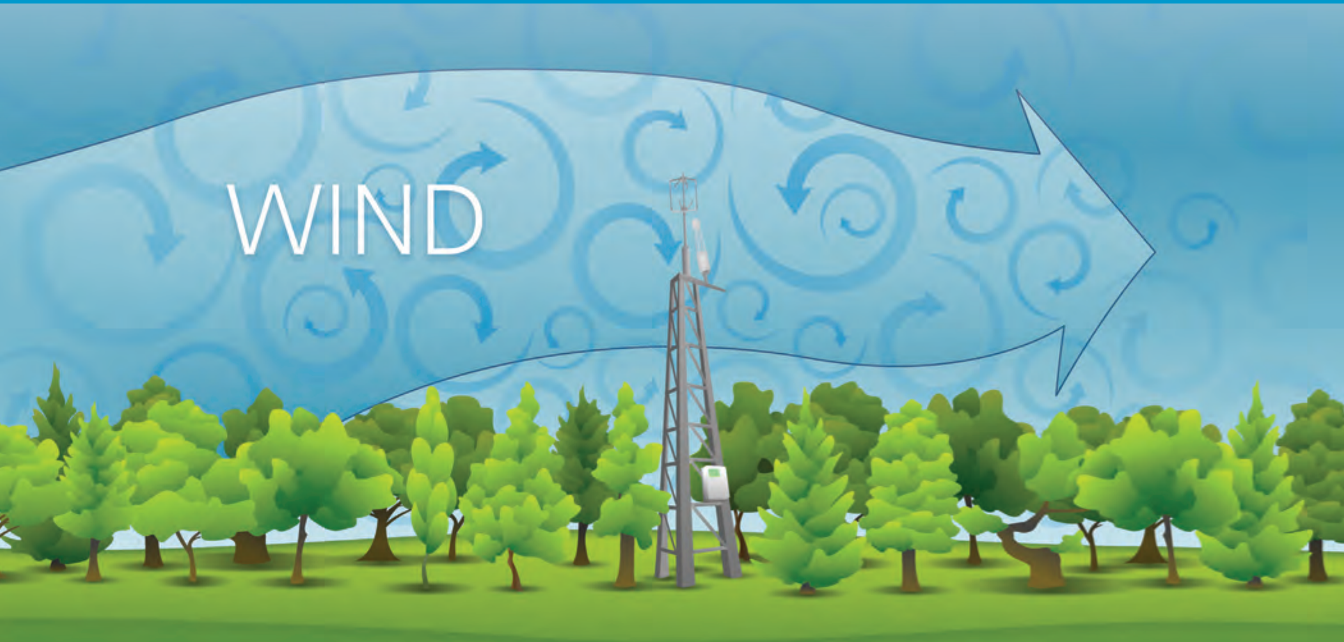
For example, if 100 birds fly through a 1 x 1 meter window each minute – the flux of birds is 100 birds per 1 square meter per 1 minute (100 B m^{-2} min^{-1}). If the window was 10 x 10 meters, the flux would be 1 bird per 1 square meter per 1 minute, because 100 birds/100 sq. meters = 1, so now the flux is 1 B m^{-2} min^{-1}.

Flux is dependent on: (1) the number of things crossing an area, (2) the 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 H_2O released into the atmosphere in the form of water vapor through 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 the day, because green leaves take up CO_2 from the atmosphere through the process of photosynthesis.



- Air flow can be imagined as a horizontal flow of numerous rotating eddies
- Each eddy has 3-D components, including a vertical wind component
- The diagram looks chaotic, but components can be measured from a tower

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 the diagram above, the air flow is represented by the large arrow that passes through the tower, and consists of differently sized eddies.

Conceptually, this is the framework for atmospheric eddy transport.

Closer to the ground, there is a stronger probability of smaller eddies being responsible for the transport of most of the flux. Smaller eddies rotate faster, and hence, more transport is done by higher frequency movements of air.

Further away from the ground, there is a stronger probability of larger eddies being responsible for the transport of most of the flux. Larger eddies rotate slower, and hence, more transport is done by lower frequency movements of air.

In practical terms, there is always a mix of different eddy sizes, so some transport is done at higher frequencies and some at lower ones, covering the whole range of frequencies: from large movements on the order of hours, to small ones on the order of 1/10 of a second.

Closer to the ground, the flux transport is shifted to higher frequencies, and further away from the ground it is shifted to lower frequencies.

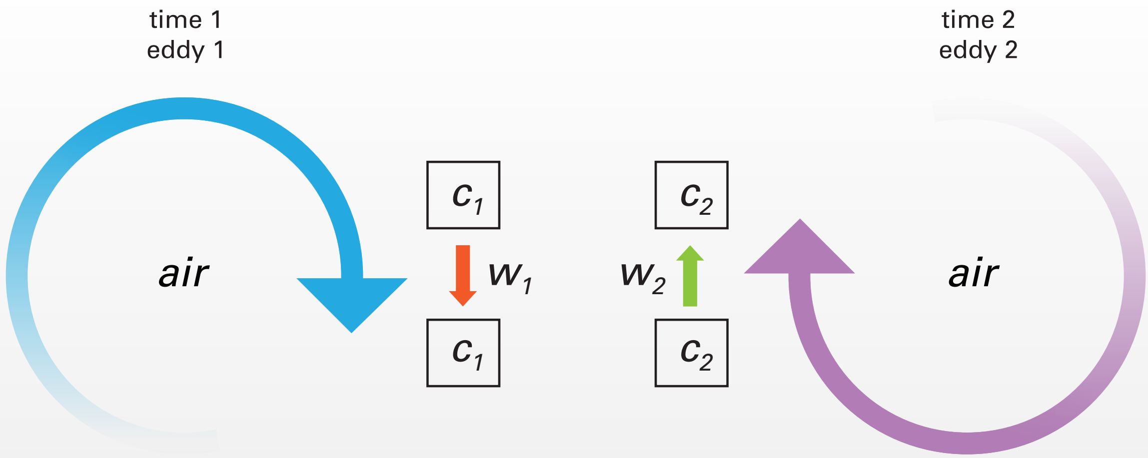
Conceptually, this is the mechanism of atmospheric eddy transport.

References

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

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



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 rotating eddies. Here, let us look closely at the eddies at a single point on the tower.

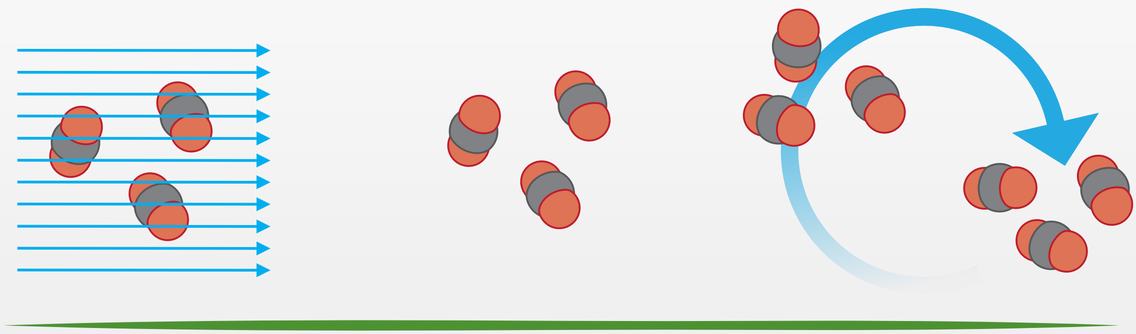
At one moment (time 1), eddy number 1 moves air parcel c_1 downward with the speed w_1. At the next moment (time 2) at the same point, eddy number 2 moves air parcel c_2 upward with speed w_2. Each air parcel has its own characteristics, such as gas concentration, temperature, humidity, *etc.*

If we can measure these characteristics and the speed of the vertical air movement, we will know the vertical upward or downward fluxes of gas and water vapor concentrations, 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.

- The eddy covariance method works by measuring vertical turbulent transport of gas to and from the surface
- With no flux added into the mean flow by the measured area, the eddies move the same number of gas molecules up and down



Another way to visualize the key physical principle behind the eddy covariance measurements is to first imagine an area that adds *no* molecules of the gas of interest to the mean flow, and then compare it to the same area that adds molecules into the flow.

For example, let us imagine a mean flow that carries 3 molecules of CO_2 over the area of interest from left to right, as shown in the diagram above.

Since the area in the middle did not add anything to the flow, the eddy movements at the downwind measurement point on the right would carry, on average, 3 molecules upwards, and 3 molecules downward, with no net flux. Thus, over a long period, such as a half hour or an hour, the eddy covariance station would measure a flux of zero from the area of interest in the middle.

In this example, we make several assumptions to keep the situation simple for now. These assumptions are addressed later in the mathematical expressions for eddy covariance, and are primarily dealt with by proper site selection, installation and flux processing. They do not fundamentally affect the visualization of the main physical principle of how instruments on the station measure the eddy transport of flux.

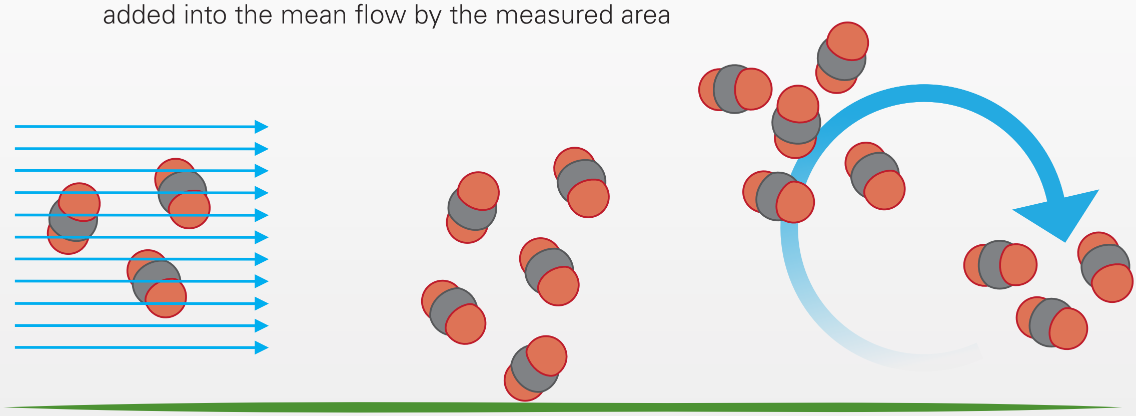
For now, we assume that the surface has the same temperature as the air, such that no temperature flux (*e.g.*, sensible heat flux) is added to the air, and thus, no thermal expansions or contractions affect the density of the air or the CO_2 content.

We also assume that the surface does not add any water molecules to the mean flow, such that no water vapor flux (*e.g.*, latent heat flux) is added to the air, and thus, no water dilution affects the density of the air or the CO_2 content.

Furthermore, we assume that surface does not move with the wind, and does not make air pressure fluctuate in synch with the wind, such that no pressure-related expansions or contractions affect the density of the air or the CO_2 content.

Finally, we assume that no additional air flow or CO_2 injection comes from the sides (*e.g.*, from the direction perpendicular to this page or the picture above) or from above, and there is no convergence of two different flows into one, or divergence of a single flow into multiple flows that occurs over the surface shown.

- With flux added into the mean flow by the measured area, the eddies move more gas up than down, transporting it from the surface into the atmosphere
- If we know the bias between up and down motions, we know how much was added into the mean flow by the measured area



In the previous page, we imagined a mean flow that carried 3 molecules of CO_2 over the area of interest from left to right, and *no* molecules of the CO_2 were added to the mean flow.

Now let us imagine the same situation, but with the surface in the middle adding 2 molecules to the mean flow. Since the area in the middle added 2 molecules to the mean flow, the eddy motions at the downwind measurement point on the right would carry, on average, more molecules upward than downward, with some net CO_2 flux.

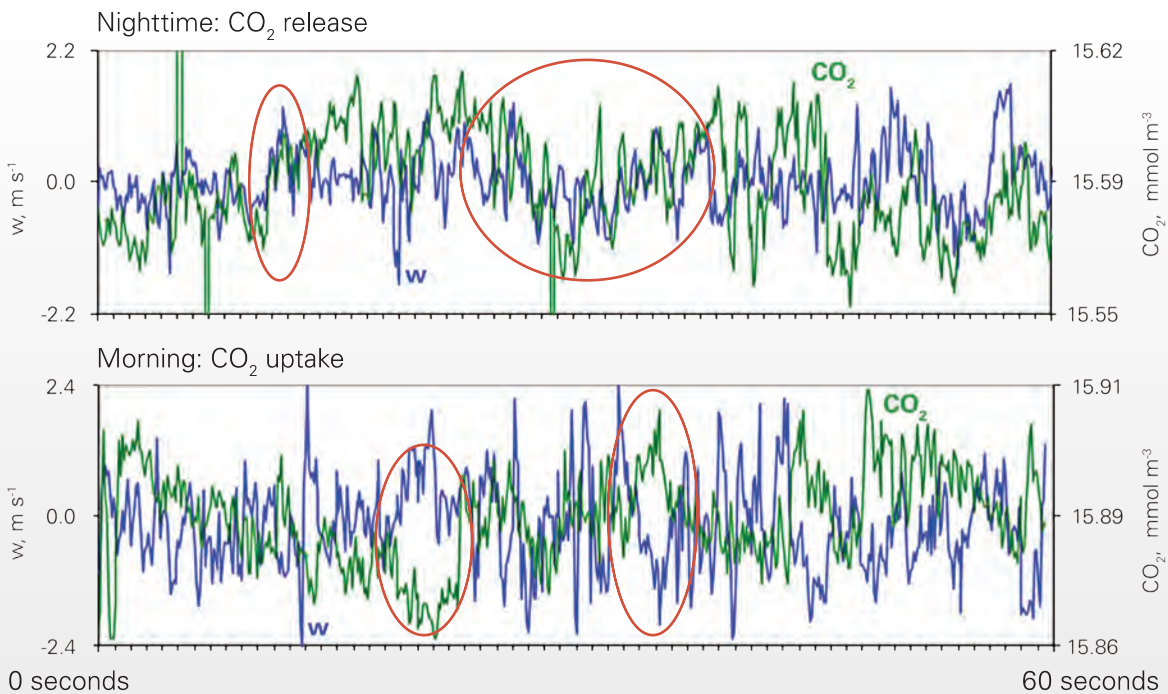
Thus, over a long period, such as 30-60 minutes, the eddy covariance station located on the right would measure some flux from the area of interest in the middle.

Compare the situation when no molecules of CO_2 are added to the mean flow by the area of interest with the situation when such an area adds molecules into the mean flow; this describes the physical essence of eddy covariance measurements. Flux is measured from the area of interest, which adds gas or energy to the mean flow or takes them away.

It is also important to note that in this way we only measure the turbulent transport of the CO_2, and must have well-developed turbulence such that other mechanisms of transport (*e.g.*, molecular diffusion, advection, *etc.*) are negligibly small. This generally is the case during the day, and during nights with wind speeds above 1.0 meter per second or 2.2 miles per hour.

Alternatively, the impact of other mechanisms of transport can be estimated, or measured directly using gas concentration and wind speed profiles and transects.

The ability of the eddy covariance method to provide direct measurements of half-hourly or hourly fluxes integrated over an area of interest, continuously throughout the years, covering most of the days and significant portions of the nights, is an important practical advantage over other present flux measurement methods.



- Actual 10 Hz data from the field – 10 times per second
- Note the difference with CO_2 uptake in the morning

The actual field data look remarkably similar to the thought experiments described on the previous three pages. The picture above shows vertical wind speed (w) and CO_2 measured simultaneously at a fast rate by an eddy covariance station located in the middle of a field covered with green vegetation.

At night, photosynthesis is not occurring, and respiration from the soil and the canopy adds a small CO_2 flux to the atmosphere. This process can be observed in the top plot by looking at what happens to the CO_2 content when wind is moving upwards (positive *w*) and downwards (negative *w*).

On many occasions, the upward movement of the wind carries a higher CO_2 content than the downward movement. The covariance is not very strong due to small nighttime fluxes, but is still visible at higher frequency movements (smaller red oval on the left) and at lower frequency movements (large red oval on the right). In such situations, the covariance of *w* and CO_2 is positive, and the flux of CO_2 is away from the canopy and soil surface.

In the morning, the sun is up and canopy photosynthesis is occurring, overcoming respiration. This process removes CO_2 from the atmosphere, and also can be observed in the bottom plot by watching what happens to the CO_2 content and vertical wind speed.

On many occasions, the upward movement of the wind carries a lower CO_2 content than the downward movement. The covariance is still not very strong due to a small flux rate, but is visible at lower frequency movements (smaller red oval on the left) and at higher frequency movements (large red oval on the right). In such situations, the covariance of *w* and CO_2 is negative, and the flux of CO_2 is directed toward the canopy.

Please notice the scale on the x-axes above, and note how rapidly the turbulent transport happens. This will have significant implications for the experiment and system design described later in the book in Part 2.

The physical 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

The mathematical principle:

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

The instrument challenge:

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

Overall, the general physical principle for eddy flux measurement is to measure how many molecules are moving upward and downward over time, and how fast they travel.

Mathematically such vertical flux can be represented as a covariance between measurements of vertical velocity, the upward and downward movements, and the concentration of the entity of interest.

Such measurements require very sophisticated instrumentation, because turbulent fluctuations happen very quickly, and respective changes in concentration, density or temperature are quite small, and must be measured both very fast and very well.

The traditional eddy covariance method (also known as eddy correlation method, or EC) calculates only turbulent vertical flux, involves a lot of assumptions, and requires high-end instruments. On the other hand, it provides nearly direct continuous flux measurements if the assumptions are satisfied, or corrected for.

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 book. Please refer to the textbook entitled 'Micrometeorology' by T. Foken (2008) for detailed explanations of the differences between these two terminologies.

In turbulent flow, vertical flux can be presented as:
(s is the dry mole fraction of the gas of interest in the air)

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

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

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

Opening the parentheses:

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

averaged deviation from the average is zero

Equation is simplified:

$$F = (\overline{\rho}_d \overline{w}\,\overline{s} + \overline{\rho}_d \overline{w' s'} + \overline{w}\,\overline{\rho'_d s'} + \overline{s}\,\overline{\rho'_d w'} + \overline{\rho'_d w' s'})$$

In very simple terms, when we have turbulent flow, vertical flux can be represented by the equation at the top of this page: flux is equal to a mean product of air density (ρ_d), vertical wind speed (w), and the dry mole fraction (s) of the gas of interest. The dry mole fraction is often called the mixing ratio.

Reynolds decomposition can be used to break the right-hand side of the top equation into means and deviations from these means. 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 example for every 0.05 or 0.1 seconds (denoted by a prime). A similar procedure is done with vertical wind speed, and with dry mole fraction 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.

The term 'mixing ratio' is historically defined differently in chemistry and in micrometeorology. In chemistry, it describes the ratio of the constituent to the total mixture without this constituent. For example, moles of CO_2 would be divided by moles of non-dried air without CO_2.

In micrometeorology, it usually describes the ratio of the constituent to the dry air. For example, moles (or grams) of CO_2 in the air would be divided by moles (or grams) of dry air with CO_2.

Perhaps, the better, more universally understood alternative term to use in the context of this book would be 'dry mole fraction', or 'mole fraction in dry air'.

References

For detailed and thorough calculations of this portion of the derivations, please see Lecture #3 (Part 1) in: Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Now an important assumption is made (for conventional eddy covariance) – air density fluctuations are assumed to be negligible:

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

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

$$\boxed{F \approx \overline{\rho}_d \overline{w's'}}$$

'Eddy Flux'

On this page, we see two important assumptions that are made in the conventional eddy covariance method.

First, the air density fluctuations are assumed to be negligible. Theoretically, with strong winds over a mountain ridge, for example, density fluctuations in the member $\overline{s}\,\overline{\rho'_d w'}$ may be non-negligible in comparison with the gas flux. However, in most cases when eddy covariance is used conventionally over reasonably flat and vast spaces, such as fields or plains, the air density fluctuations can be safely assumed to be negligible, for the purposes of this derivation.

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

With diversion and conversions assumed negligible, we arrive at the classical equation for 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.

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

References

For a more detailed derivation up to this point, please refer to: Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California (Lecture 3, Part 1): http://nature.berkeley.edu/biometlab/espm228

For the advanced reader, the complex derivation of a fundamental flux equation can be found in: Gu, L., W. Massman, R. Leuning, S. Pallardy, T. Meyers, *et al.*, 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agricultural and Forest Meteorology, 152: 135– 148

Any gas (CO_2, CH_4, N_2O, H_2O, *etc.*):

$$F = \overline{\rho}_d \overline{w's'}$$

Sensible heat flux:

$$H = \overline{\rho} C_p \overline{w'T'}$$

Traditional H_2O flux:

$$E = \frac{M_w / M_a}{\overline{P}} \overline{\rho_d} \overline{w'e'}$$

Latent heat flux (H_2O flux in energy units):

$$LE \equiv \lambda E = \lambda \frac{M_w / M_a}{\overline{P}} \overline{\rho_d} \overline{w'e'}$$

The top equation describes a classical formula for the eddy flux of virtually any gas of interest, such as CO_2, CH_4, N_2O, O_3, *etc.* The flux is computed from the mean dry air density multiplied by the mean covariance between deviations in instantaneous vertical wind speed and dry mole fraction (*e.g.*, mixing ratio).

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.

There are multiple forms of the flux equation for water vapor, depending on the units of fast water vapor content. One typical example is shown in the third equation above. In addition, the water vapor flux is often computed in energy units (W m^{-2}), and called latent heat flux, as shown in the last equation above. Latent heat flux describes the energy used in the process of evaporation, transpiration, or evapotranspiration.

Hourly or integrated values of latent heat flux can be converted into other frequently used units (*e.g.*, mm d^{-1}, inches ha^{-1}, kg m^{-2} h^{-1}, *etc.*). When converted to volume or mass units, the latent heat flux is often called evapotranspiration rate (ET), evaporation rate (over wet non-vegetated surfaces), or evaporative water loss.

Please note that older instruments usually do not output fast dry mole fraction (fast mixing ratio), but rather measure fast density. So, the density corrections are required in post-processing as described in Section 4.4. These corrections are not required for instruments outputting true mixing ratio at high speed, for example, the enclosed LI-7200 CO_2/H_2O gas analyzer.

References

More details on practical formula are given in: Rosenberg, N., B. Blad, and S. Verma, 1983. Microclimate. The biological environment. A Wiley-Interscience, New York: 255-257

More details on mixing ratio and other relevant units are given by Foken *et al.* in Table 1.2, and resulting forms of the flux equation are given by Rebmann *et al.* in Table 3.1 in: Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

- 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 from 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 of w' is zero, air density fluctuations, flow convergence and divergence are negligible
- Instruments can detect very small changes at high frequency
- Air flow is not distorted by the installation structure or the instruments

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 (details in Sections 2.6 and 3.2)
- Fetch and footprint are assumed adequate, so flux is measured from the area of interest (details in Section 2.7)
- Flux is fully turbulent
- Terrain is horizontal and uniform
- Air density fluctuations are negligible
- Flow divergences and convergences are negligible
- The instruments can detect very small changes at very high frequency
- Mean air flow and turbulence at the measurement point are not appreciably distorted by the installation structure or the instruments themselves

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

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

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

Fluxes could be over- or underestimated if errors are not prevented during the design and setup, or not corrected during data processing

Frequency response errors can be due to:

- System time response
- Tube attenuation
- Path and volume averaging
- Sensor separation
- Sensor response mismatch
- Low-pass filtering
- High-pass filtering
- Digital sampling
- *etc.*

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

First, there is a family of errors called frequency response errors. They include errors due to instrument time response, tube attenuation, path and volume averaging, sensor separation, sensor response mismatch, low and high pass filtering, 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. 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. Path averaging error is caused by the fact that the sensor path is not a point measurement, but rather is an integration over some distance; therefore, it can average out some of the changes caused by eddy transport.

Sensor separation errors occur due to the 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. There can also be frequency response errors caused by sensor response mismatch, and by filtering and digital sampling.

Other key error sources:

- Spikes and noise
- Unleveled anemometer
- Wind angle of attack
- Sensor time delay
- Sonic heat flux errors
- Density fluctuations (WPL)
- Spectroscopic effects for LASERs
- Band-broadening for NDIR
- Oxygen in the 'krypton' path
- Gas flux storage
- Data filling
- *etc.*

In addition to frequency response errors, other key sources of errors include spikes and noise in the measurements, unleveled anemometer, wind angle of attack, sensor time delay (especially important in closed-path analyzers with long intake tubes), sonic heat flux errors, the Webb-Pearman-Leuning density terms (WPL), spectroscopic effects (for LASER-based measurements), band-broadening effects (for NDIR measurements), oxygen sensitivity, gas flux storage, and data filling errors. Later in Part 4, we will go through each of these terms and errors in greater detail.

References

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

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

Billesbach, D., 2011. Estimating uncertainties in individual eddy covariance flux measurements: a comparison of methods and a proposed new method. Agricultural and Forest Meteorology, 151: 394–405

Moncrieff, J., Y. Malhi, 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

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

Errors due to	Affected fluxes	Approximate range
Spikes and noise	all	0-15%
Unleveled anemometer	all	0-25%
Wind angle of attack	all	0-25%
Time delay	mostly closed path	0-50%
Frequency response	all	0-50%
Sonic heat flux error	sensible heat flux	0-10%
Density fluctuations	any gas	0-50%
Spectroscopic effects for LASERs	any gas	0-25%
Band-broadening for NDIR	mostly CO_2	0-5%
Oxygen in the path	some H_2O	0-10%
Gas flux storage under tower	any gas	0-5%
Missing data filling	all	0-20%

None of these errors are trivial. Combined, they may sum up to over 100% 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 provide a brief overview of the remedies for such errors.

Step-by-step instructions on how to minimize or eliminate these and other errors with proper experimental planning, design, and implementation are provided in Parts 2 and 3 of this book. Detailed descriptions of how to apply the corrections in data processing software are provided in Part 4. Below are a few highlights.

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

An unleveled sonic anemometer will affect all fluxes as well, because of contamination of the vertical wind speed with a horizontal component. The error can be twenty-five percent or more, but it is easily reduced by having a steady tower, and by leveling the anemometer during the station setup. The remaining error can be fixed relatively easily by using a processing procedure called coordinate rotation.

Errors due to unadjusted time delay can affect all fluxes, but are most severe in closed-path systems with long intake tubes, especially for water vapor and other "sticky" gases (*e.g.*, ammonia). These errors can be up to 25% for non-sticky gases, and may exceed 50% for H_2O and NH_3. Time delay errors can be minimized by using shorter tubes when possible, by using instruments with matching clocks, and by minimizing the separation distance between the intake of the gas analyzer and the sonic anemometer.

The time delay errors can be virtually eliminated by adjusting the delay during data processing. This is implemented by shifting the two time series in such a way that the covariance between them is maximized. Alternatively, the delay between two time series can be computed from the known flow rate and tube diameter.

Frequency response errors also affect all fluxes. Usually they range between 5% (for example, in fast open-path devices) and 50% of the flux (in long-tube closed-path or any slower devices), and can be partially remedied by choosing fast instrumentation, and by proper experimental setup. They can be further corrected by applying frequency response corrections in the data processing software.

- Many of the potential errors can be minimized or eliminated by proper station and experimental design, data collection settings, and site maintenance; the remainder can be corrected by proper software setup during data processing

Errors	Planning and design remedy	Data processing remedy
Spikes and noise	Instrument selection and setup	Spike removal
Unleveled anemometer	Tower and instrument installation	Coordinate rotation
Wind angle of attack	Instrument selection, setup	Angle-of-attack correction
Time delay	Instrument selection, setup, clocks	Time delay adjustment
Frequency response	Instrument selection, system setup, and data collection settings	Frequency response corrections
Sonic heat flux error	--	Sonic heat flux correction
Density fluctuations	Type of instrument selection	Dry mole fraction output, or WPL density terms
Spectroscopic effects for LASERs	--	Instrument-specific correction; no standardized widely used form
Band-broadening for NDIR	--	Band-broadening correction
Oxygen in the path	--	Oxygen correction
Gas flux storage	Gas profile measurements	Gas flux storage term
Missing data filling	Instrument selection, well-planned maintenance	Methodology/tests: Monte-Carlo *etc.*

Sonic heat errors affect sensible heat flux, but usually by no more than ten percent, and they are fixed by applying a straightforward sonic heat flux correction.

The density fluctuations mostly affect gas and water fluxes, and only when instruments output fast density, as opposed to the fast dry mole fraction. Size and direction of the related errors vary greatly. It can be three hundred percent of the small flux in winter, or it could be only a few percent in summer. These errors can be eliminated by choosing instruments that output fast dry mole fraction, or can be corrected using Webb-Pearman-Leuning density terms.

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.

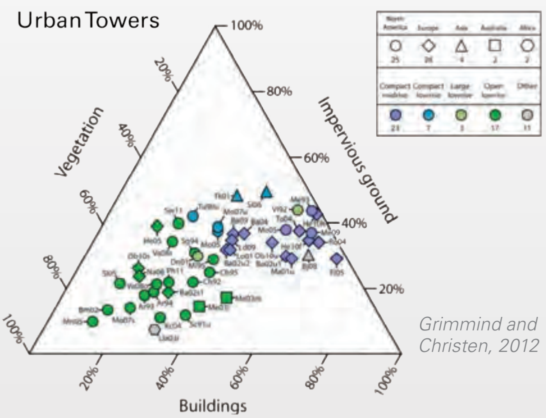
Band-broadening errors affect gas fluxes measured by the NDIR technique, and depend greatly on the instrument used. The error is usually on the order of zero to five percent, and corrections are either applied in the instrument's software, or described by the instrument manufacturer. Oxygen in the path 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 fluxes, especially if they are integrated over long periods of time. The effects can be minimized by choosing the proper instrument for the site conditions, and by a well-planned maintenance schedule. For example, in a rainy site, an enclosed or closed-path instrument will lose significantly less data than an open-path instrument, while having a spare instrument as part of the maintenance plan may also reduce the data gaps due to malfunctions, lightning strikes, *etc.*

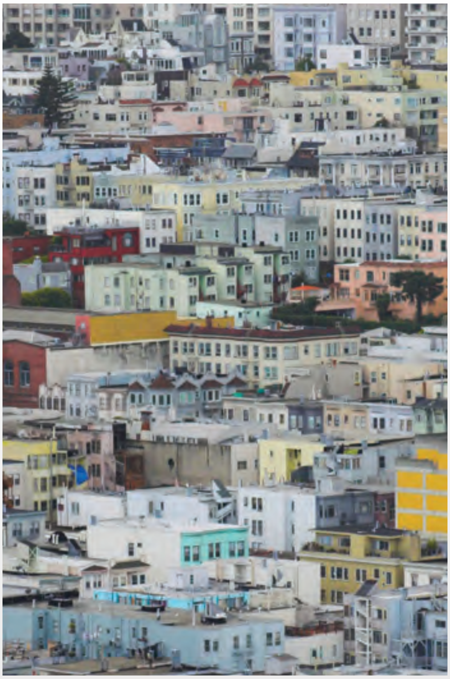
There are also a number of different mathematical methods to test and compute what the resulting errors would be for a specific set of data due to gap-filling. One good example is the Monte Carlo Method. Other methods are mentioned in Section 4.10 of this book.

Please note that even though modern flux programs will automatically correct most of the errors as part of the standard flux processing sequence, it is still extremely important to minimize or eliminate the majority of these errors during the experiment setup, and only then to correct the remaining errors during data processing. This is especially important for small fluxes and for yearly integrations.

- All principles described previously were developed and tested for traditional settings: reasonably horizontal and uniform terrain, with negligible air density fluctuations, negligible flow convergence and divergence, and with prevailing turbulent flux transport
- The latest developments of the eddy covariance method have revisited these assumptions to measure over complex sites, such as urban or hilly terrains



Grimmind and Christen, 2012



All principles described previously were developed and tested for traditional settings, over reasonably horizontal and uniform terrains, with negligible air density fluctuations, negligible flow convergence and divergence, and with prevailing turbulent flux transport.

The latest developments of the method have revisited many of these assumptions in order to be able to use the method in complex terrains: over cities, on hills, and under conditions of various flow obstructions.

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.

Success of these latest applications is growing, with over 60 urban flux stations deployed in 2012 for both scientific and regulatory purposes (http://www.geog.ubc.ca/urbanflux). At least 25 additional stations operate in complex mountainous terrains across the globe.

References

Great review of the modern urban flux measurements and related literature is provided by: Grimmond, S., and A. Christen, 2012. Flux measurements in urban ecosystems. FluxLetter, 5(1): 1-8 http://fluxnet.ornl.gov/sites/default/files/FluxLetter_Vol5_no1.pdf

Other measurements in complex conditions described in: Gu, L., W. Massman, R. Leuning, S. Pallardy, T. Meyers, *et al.*, 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agricultural and Forest Meteorology, 152: 135-148

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McMillen, R., 1988. An eddy correlation technique with extended applicability to non-simple terrain. Boundary-Layer Meteorology, 43: 231-245

Raupach, M., and J. Finnigan, 1997. The influence of topography on meteorological variables and surface-atmosphere interactions. Hydrology, 190: 182-213

- Measures fluxes transported by eddies
- Most direct way to measure flux
- Requires turbulent flow
- Requires state-of-the-art instruments
- Calculates flux as covariance of *w′* and *c′*
- Many assumptions to satisfy
- Complex calculations, mostly automated
- Proper workflow is vital

Eddy covariance is the most direct approach to measure vertical fluxes of water vapor, trace gases (*e.g.*, CO_2, CH_4, N_2O, *etc.*), heat and momentum between the soil, vegetation, urban or industrial terrains and the atmosphere.

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.

Modern instrument systems and processing software take care of most of the challenges when using the eddy covariance method. Nevertheless, proper station design, experiment planning and execution, and correct data processing steps help to minimize or eliminate the errors resulting from failure to meet theoretical assumptions, and system deficiencies.

In this way the method can be tuned to the particular purpose (scientific, industrial, agricultural, regulatory, *etc.*), and to the particular measurement site (maize field, forest, wetland, ocean, city, landfill, *etc.*) to provide reliable hourly or half-hourly fluxes continuously over months and years.

Proper execution of the eddy covariance method is perhaps the second biggest challenge for a novice, after mastering the theoretical part of the method.

The rest of this book is primarily dedicated to providing a sequential step-by-step description of the method's workflow, from designing and implementation of the experiment, to processing the data.

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

Proper execution of the workflow may become a significant challenge for a novice, second only to 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, and can result in large data gaps.

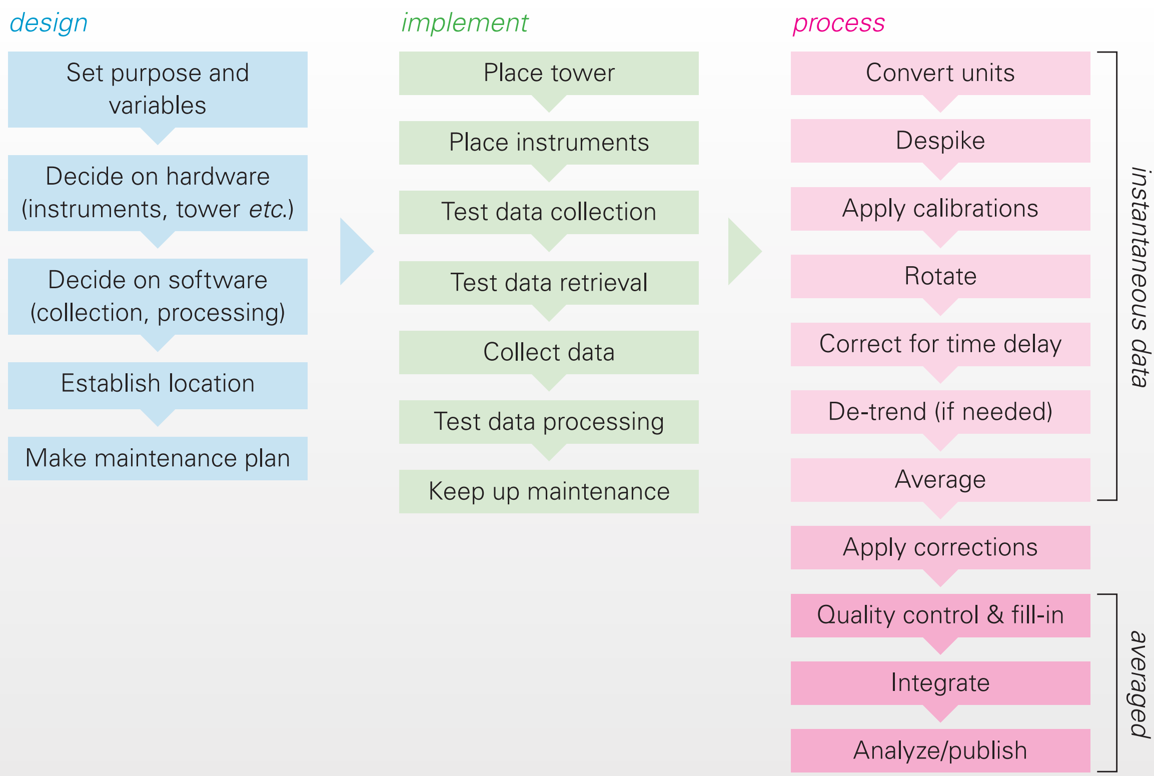
These are especially undesirable for the integration of the long-term data sets, which is the prime goal for measuring fluxes of carbon dioxide, methane or other greenhouse gases in scientific applications.

Errors in data processing may not be as bad, as long as there is a backup of the original raw data files, but they can also 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 results. 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 some specific measurements goals, but it will provide a general understanding of what is involved in eddy covariance study, and will point out the most difficult parts and frequent pitfalls.

> It is extremely important to always keep and store original 10Hz or 20Hz data collected using the eddy covariance method. The data can then 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.



Above is 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 experiment are as follows: setting the purpose and variables for the study, deciding on instruments and hardware to be used, creating new or adjusting existing software to collect and process the 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, "instantaneous" data (usually at a 10-20 Hz sample rate), processing averaged data (usually from 0.5 hrs to 2 hrs), 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, gap filling, integrating, and finally, data analysis and publication.

References

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Part Two:

Designing An Eddy Covariance Experiment

Section 2.1 Setting Purpose and Selecting Variables