AOSC624
Class 22: May 1, 2012

At Issue:

How can satellites help to estimate the

Surface Energy Budget (SEB)

One Component of SEB:

Surface Radiation Budget *(Review)*

Other components:

Surface Turbulent Fluxes of heat and moisture

Heat into ground

How do we evaluate the turbulent fluxes?

Overview of Eddy Covariance Principles

Radiation Balance at the Earth Surface

The net flux of radiation at the earth's surface results from a balance between the solar and terrestrial radiation fluxes:

$$F^{sfc}_{rad} = F_{SW} + F_{LW}$$

The short-wave and long-wave radiation balance can be expressed:

$$F_{SW} = F_{SW}\downarrow - F_{SW}\uparrow$$

$$F_{LW} = F_{LW}\downarrow - F_{LW}\uparrow$$

The net radiation balance being:

$$F^{sfc}_{rad} = F_{SW}\downarrow - F_{SW}\uparrow + F_{LW}\downarrow - F_{LW}\uparrow$$

- The incident solar radiation $F_{SW}\downarrow$ is the sum of the direct and diffuse solar radiation. It has a pronounced diurnal and seasonal variation, and is also strongly affected by clouds. The outgoing short-wave solar radiation is the part reflected by the surface $F_{SW}\uparrow = A_{sfc} F_{SW}\downarrow$, where A_{sfc} is the surface albedo so that the net short-wave radiation is:

$$F_{SW} = (1 - A_{sfc})\, F_{SW}\downarrow$$

- The outgoing long-wave radiation $F_{LW}\uparrow$ is given by the Stefan-Boltzmann law, assuming a given emissivity ϵ for the earth's surface.

- The net radiation flux at the surface is then given by :

$$F^{sfc}{}_{rad} = F_{SW}\downarrow (1 - A_{sfc}) - \sigma\epsilon T^4{}_{sfc} + F_{LW}\downarrow$$

Energy Balance at the Earth Surface

The main part of the energy absorbed at the surface is used to evaporate water, another part is lost to the atmosphere as sensible heat, and a smaller part is lost to the underlying layers or used to melt snow and ice. Thus, there are essentially four types of energy fluxes at the earth's surface. They are the net radiation flux F_{rad}, the (direct) sensible heat flux $F_{SH}\uparrow$, the (indirect) latent heat flux $F_{LH}\uparrow$, and the heat flux into the subsurface layers $F_G\downarrow$. Under steady conditions the balance equation for the energy is given by

$$F^{sfc}_{rad} - F_{SH}\uparrow - F_{LH}\uparrow - F_G\downarrow - F_M = 0$$

These surface fluxes are associated with land processes and depend on:

- ❖ vertical stability; roughness
- ❖ surface temperature
- ❖ subsurface heat conduction
- ❖ vegetation
- ❖ surface hydrological balance
- ❖ potential evapotranspiration
- ❖ radiative flux

- Theoretical aspects of satellite remote sensing of energy balance

- Thermal equilibrium at the surface is maintained by a combination of thermodynamic and physiological processes.

- The net energy absorbed by the surface through radiative processes, net radiation R_n, must be balanced by that transported to the atmosphere and ground (sensible, latent, and ground heat flux):

- $R_n = H + LE + G.$ (1)

- R_n is simply the difference between the incident and reflected shortwave radiation and the incident and emitted long wave radiation at the surface, that is:

- $R_n = S\{1 - \alpha\} + L_{wd} - L_{wu},$ (2)

- where S is downwelling shortwave radiation energy flux (Wm^{-2}).

Surface energy balance formulae

For the sensible and latent heat components in eq. 1, closed-form solutions cannot be obtained. Commonly used semi-empirical relations are:

For Sensible heat:

$$H = \rho C_p (T_{aero} - T_a)/r_a \qquad (3)$$

- where H sensible heat flux, W m^{-2}; ρ density of air, kg m^{-3};
- C_p specific heat of air, J kg^{-1} $^oC^{-1}$;
- T_a reference height air temperature, ^oC;
- T_{aero} canopy temperature, ^oC;
- r_a aerodynamic resistance for heat and water vapor, s m^{-1}.

- In this formulation the aerodynamic resistance, r_a, relates the vertical gradient in temperature, T_{aero} - T_{a}, to the sensible heat flux.
- The r_a value is semi-empirical and is intended to characterize the efficiency of the very complex transfer of heat by turbulent air movement through the canopy into the air above; r_a is normally derived using empirical arguments to adjust the surface momentum transfer coefficient, a term that relates the vertical gradient in boundary layer wind speed to surface shear stress.
- A number of such empirical formulations are available for r_a (see *Hall et al,. 1991),* such as:

$$r_a = \frac{\ln(z - 0.56h)\ln[(z - 0.56h)/(0.0189h)]}{0.16U\{1 + [5g(z - 0.56h)(T_{aero} - T_a)/T_a U^2]\}^{3/4}},$$

where U is windspeed, m s^{-1}; z is reference height for measurement of T_a and U ; h is height of canopy (m); and g is gravitational acceleration, m s^{-2}.

For more details and additional formulation for Aerodynamic Resistance see the provided paper:

Measurement and estimation of the aerodynamic resistance

S. Liu, D. Mao, and L. Lu

- For latent heat:

$$LE = \rho C_p[e^*(T_{aero}) - e_a)](g_c g_a)/\gamma(g_c + g_a), \qquad (5)$$

- where e_a vapor pressure at reference height, mbar;
- T_a air temperature at reference height, °k;
- $e^*(T_{aero})$ saturated vapor pressure in the canopy air space, mbar;
- γ psychometric constant, mbar $°k^{-1}$;
- ρC_p as defined in (2);
- g_c bulk stomatal conductance of canopy, m s^{-1};
- g_a bulk aerodynamic conductance of canopy ($1/r_a$), m s^{-1}.
- These first-order solutions to the turbulent transport equations served as the primary model for investigating relationship between the properties of land surface vegetation, energy-mass balance, and remote sensing of these interactions in FIFE.

Sensible heat

- For H in (3), remote sensing measures of surface radiometric temperature have been evaluated as a surrogate for T_{aero}.
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- However, T_{aero} is not explicitly T_{rad} but, as discussed above, a theoretical construct that parameterizes a “convective” temperature. *Vining and Blad (1991)* investigated the relationship between T_{aero} and T_{rad}.

Latent heat

For latent heat estimation (eq. 5) the main focus of remote sensing techniques is the conductance term g_c and the T_{aero} term in estimating canopy air-space vapor pressure. The canopy conductance term g_c can be modeled after *Jarvis (1976)* as a product of functions with range (0, 1) where each function characterizes the dependence of g_c on APAR (absorbed PAR), δe, T, and leaf water potential ψ.

- That is:

- $g_c = g^*_c(APAR)g(\delta e)g(T_{aero})g(\psi)$ (6)

- where g^*_c (APAR) is “unstressed” canopy conductance and g (δe), g (T_{aero}), g (ψ) are functions with ranges (0, 1) describing the fraction of stomatal closure by vapor pressure deficit, leaf temperature, and leaf water potential.
- The most accurate method to estimate turbulent fluxes is the “Eddy Correlation Method “to be explained in what follows:

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

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 .

“A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications”

G. Burba and D. Anderson of LI-COR Biosciences

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

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 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.

Several networks have been established over the globe to measure turbulent fluxes

Existing Flux Networks:

Fluxnet, Fluxnet-Canada, AsiaFlux, CarboEurope and AmeriFlux networks

They collect Eddy Covariance information.

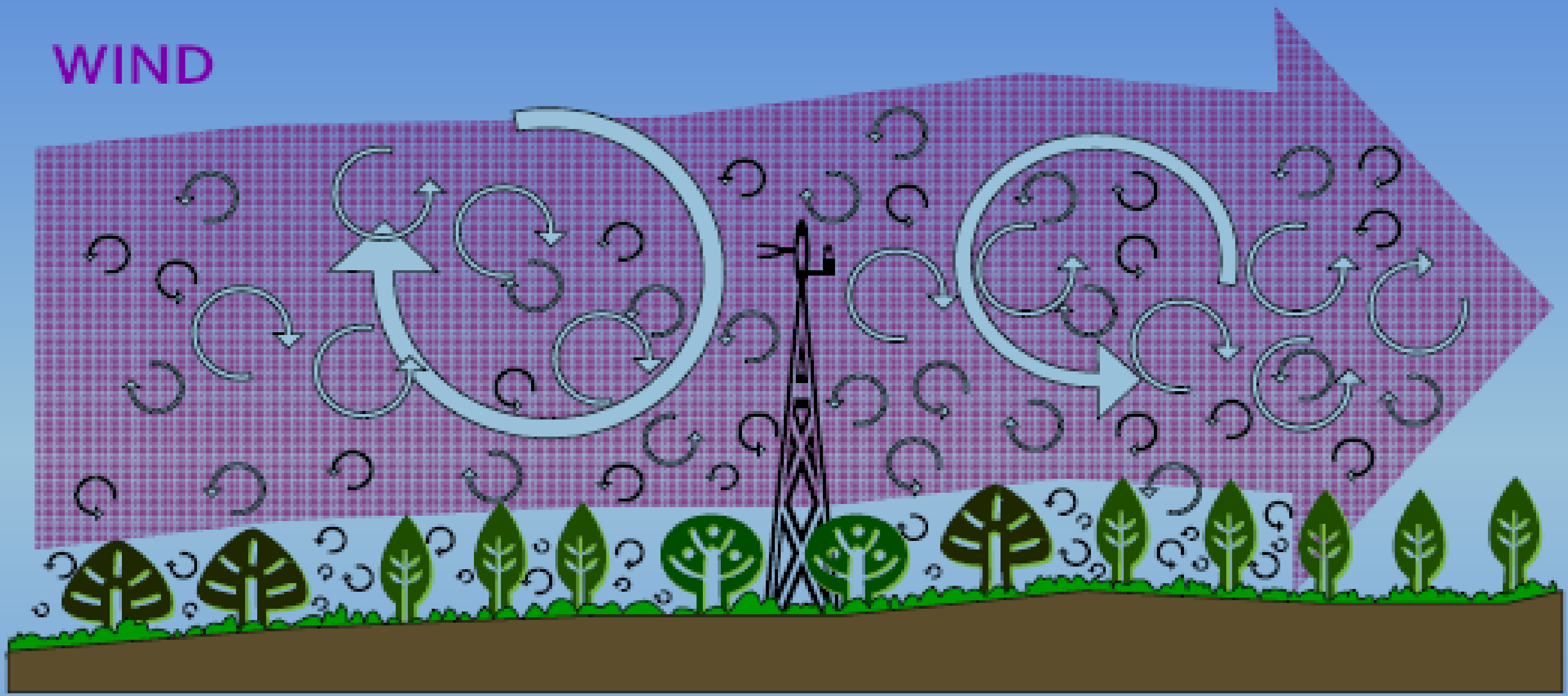
http://gcmd.nasa.gov/records/GCMD_AMERIFLUX_SHIDLER-CDIAC.html

http://terraweb.forestry.oregonstate.edu/chair2.htm

STATE OF METHODOLOGY

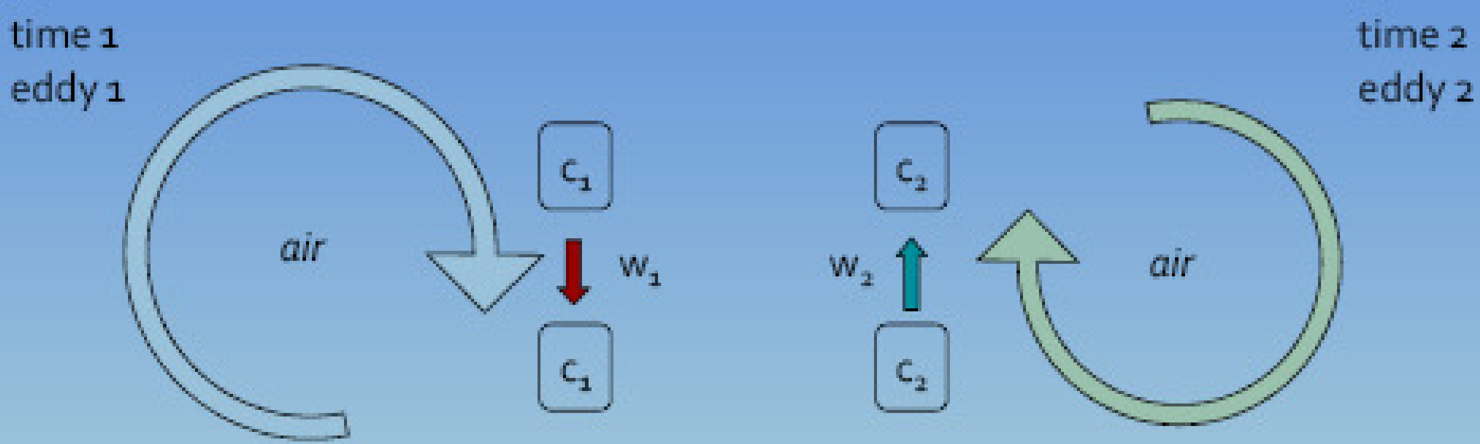
- There is currently no uniform terminology or a single methodology for EC method
- A lot of effort is being placed by networks (e.g., Fluxnet) to unify various approaches
- Here we present one of the conventional ways of implementing the Eddy Covariance method

AIR FLOW IN ECOSYSTEM



- 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 tower

EDDIES AT A SINGLE POINT



<u>At a single point on the tower:</u>

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

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

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:

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

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):

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

'Eddy flux'

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: $\overline{\rho_a}\,\overline{w's'} = \overline{w'\rho'_c}$

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

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

ERROR TREATMENT

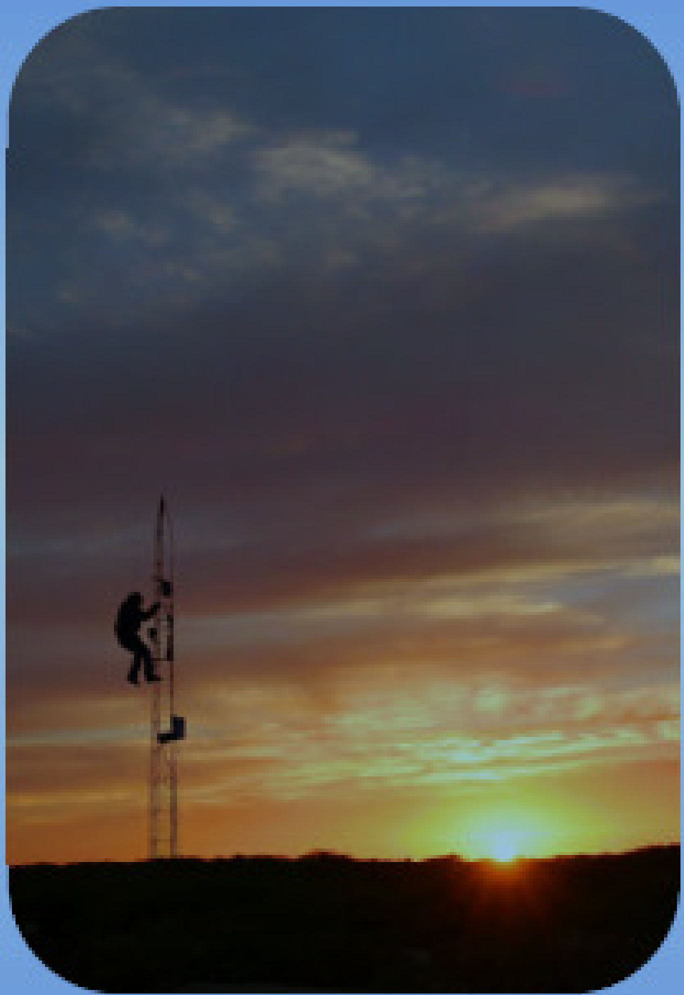
- These errors are not trivial - they may combine to over 100% of the flux
- To minimize or avoid such errors a number of procedures could be performed

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%

ERROR TREATMENT (cont.)

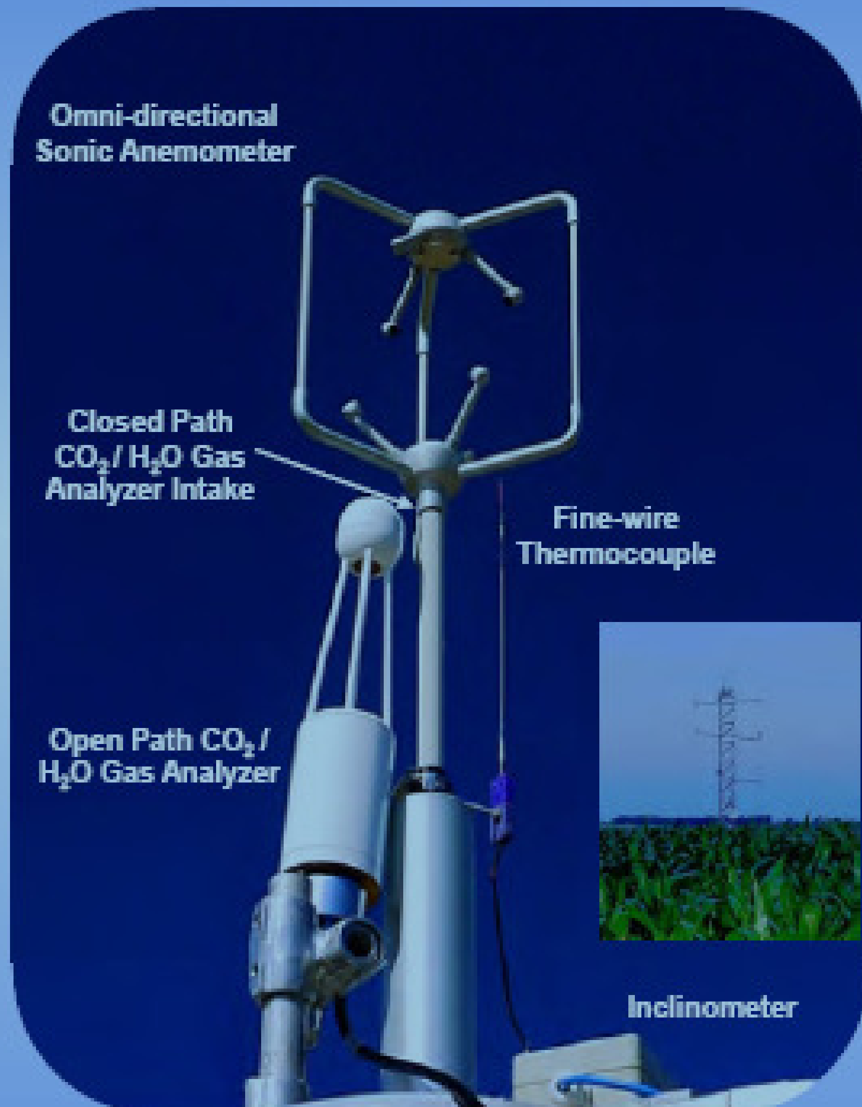
Errors	Remedy
Frequency response	frequency response corrections
Time delay	adjusting for delay
Spikes, noise	spike removal
Unleveled instrument/flow	coordinate rotation
Density fluctuation	Webb-Pearman-Leuning correction
Sonic heat error	sonic temperature correction
Band Broadening for NDIR	band-broadening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

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

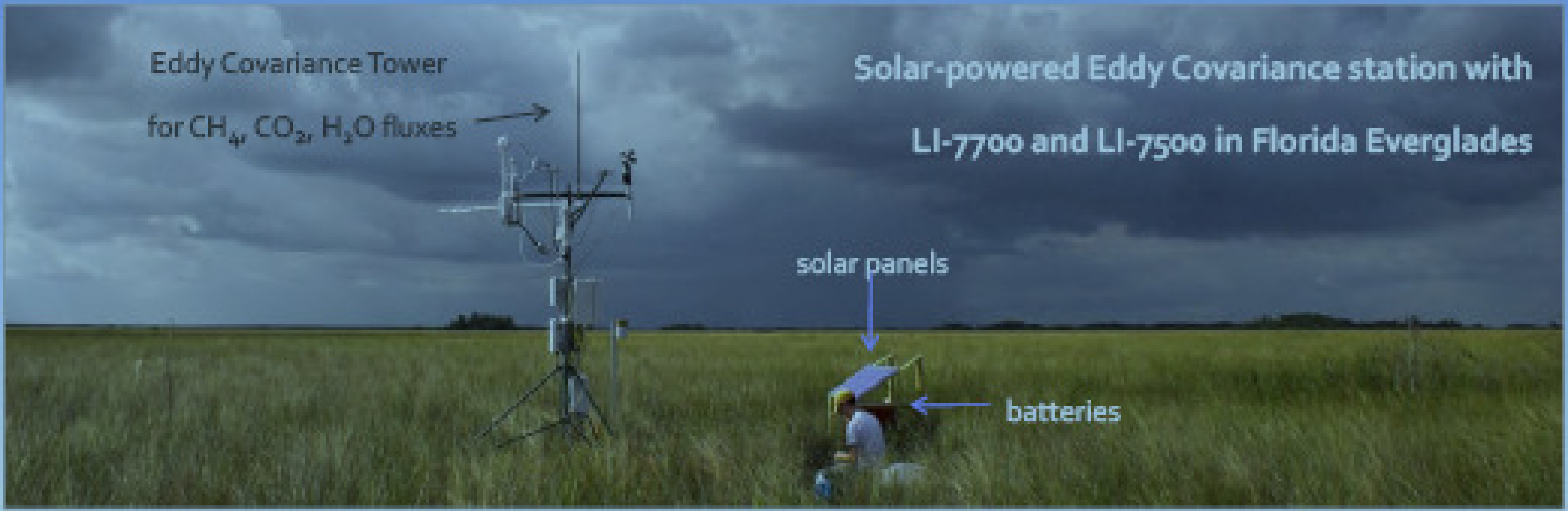
EDDY COVARIANCE INSTRUMENTATION



LI-7500A FLUX APPLICATIONS

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

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

- Remote sensing the surface energy budget

- The First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) was an international, land-surface-atmosphere experiment centered on a 15 x 15 km test site near Manhattan, Kansas.
- The objectives of FIFE: to better understand the role of biology in controlling the interactions between the atmosphere and the vegetated land surface and to investigate the use of satellite observations for inferring climatologically significant land surface parameters. Specifically:

- to verify the basic flux relationships for the homogeneous patches;
- to assess the ability to remotely sense parametric inputs to these relationships;
- to examine how these relationships and remote sensing algorithms scale from the patch level to heterogeneous collections of patches at the meso-scale level;
- to determine how well existing calibration, atmospheric correction, and radiometric rectification techniques permit to extend satellite observations between dates and sensors
- to determine to what degree existing and future satellite designs satisfy the requirements for periodic monitoring of surface energy balance components on a global scale.

- 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