ESPM 228, Advanced Topics in Biometeorology and Micrometeorology

Lecture on Micrometeorological Flux Measurement Methods

January 27, 2014

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Outline

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L1. Introduction

Traditionally atmospheric scientists and chemists have been interested in measuring the concentration of scalars in the atmosphere and how they change in time. Similarly, ecologists and biogeochemists tend to measure stocks and pools. But from first principles, changes in stocks and pools, with time are a function of the fluxes into and out of the pool. The measurement and modeling of fluxes is within the domain of micrometerologists and biometeorologists. Over the past 50 years they have developed theories and measurement systems to measure the fluxes of mass and energy exchange between the land surface and the atmosphere. In the following text, I will give an overview of the historical developments in the areas of micrometeorology and biometeorology that focus on the study of mass and energy exchange.

Historical Perspective

Micrometeorology

The idea of using micrometeorological methods to assess mass and energy exchange can be traced back before and around the turn of the 20th Century. The concept of Fickian diffusion led early fluid mechanics, such as Ludwig Prandtl, G.I. Taylor and Bowen (1920s), to propose the flux-gradient approach, as concept as for evaluating evaporation with the flux-gradient approach of momentum, water and heat.

Sir Osborne Reynolds (Reynolds, 1895) is credited with devising the eddy covariance method after he laid down his famous concept of Reynolds averaging. Application of this method was delayed many years due to technical reasons as it relies on fast anemometry and metrology. One of the first applications of this method was applied in 1926 and was reported by F.J. Scrase (1930, Some characteristics of eddy motion in the atmosphere, Geophysical Memoirs, #52, Meteorological Office. London, 56 pp). His instrumentation and digitization methods, however, were quite primitive. He evaluated the three wind vectors using rapid measurements of wind speed and wind direction. He digitized the data by photographing the wind meter dial and using a kinematograph to record the movement of the wind vane! Obviously, he could only apply the method for short time durations. A contemporary study, in the German literature, was reported by W. Schmidt (1928), famous also for the Schmidt number.

In the 1940s Monin and Obukhov laid down the theoretical principles for computing scalar and momentum gradients and fluxes in the surface layer. The theory would be the pivot point for later work and would prove to be successful over a range of surface roughnesses and thermal stratification (Foken, 2006). Kolmogorov, the Russian Statistician, Academician and Fluid Mechanic, developed theory for interpreting the spectral decay of turbulence.

Major advances in the eddy covariance method occurred in the 1950s with the development of fast responding hot-wire anemometry and thermometry (instrumentation needed to respond to perturbations within fractions of a second and needed to be sampled multiple times per second). The digitations methods of the early studies, however, were crude at best. Lights from a galvanometer were recorded on a revolving cylinder of photographic paper. The data were later digitized by hand! One of the first research teams to exploit this method was associated with the CSIRO laboratory of CHB Priestly in Australia. The most innovative work was conducted by Bill Swinbank (Swinbank, 1951). Other notables in the group included Len Deacon, Ian McIlroy, Eric Webb and Reg Taylor (Hess et al., 1981). A few years later this group would be joined by Arch Dyer and Bruce Hicks, my mentor in Oak Ridge (Dyer and Hicks, 1970; Dyer and Hicks, 1972). Much basic and pioneering information on the fundamental properties of the atmospheric surface layer is linked to members of this group. I make this point as a starting point for any competent literature review on the topic.

For over 50 years micrometeorologists focused their efforts on the development of theory, instrumentation and methods to measure trace gas, energy and momentum fluxes between the land surface and the atmosphere. The earliest studies were interested in testing the scaling concepts of Monin and Obukhov, understanding the spectral properties of turbulence and the statistical properties of turbulence in the surface boundary layer during stable, neutral and unstable thermal stratification, and developing simple parameterization schemes for mass and energy exchange, that form the lower boundary condition of climate and meteorological models (Foken, 2006).

Many of the earliest micrometeorological studies were conducted over very ideal landscapes. These locales consisted of extremely level terrain with negligible or short

vegetation and were in windy and sunny climes where atmospheric conditions could be expected to be steady. Examples include the O'Neill, Nebraska (Project Prairie Grass, Lettau and Davidson, 1957), the Kansas (Businger, 1971; Kaimal and Wyngaard, 1990) and Davis (Pruitt et al., 1973) experiments in North America, the Australian Wangara experiment (Hess et al., 1981) and its predecessors near Hay and Kerang (Swinbank and Dyer, 1967; Clarke et al., 1971; Hess et al., 1981) and studies near Tsimlyanskoye in Russia (Zilitinkevich and Chalikov, 1968). These are powerful datasets still being used to parameterize and model surface layer turbulence and are summarized in Foken (Foken, 2006).

The publication of Workshop on Micrometeorology in 1973 summarized the many field experiments and codified many of the theories that are used to this day. In the 1970s theoretical advances in boundary layer meteorology were led by J. Deardorff who developed early models on surface boundary layer fluxes, large eddy simulation and mixing layer theory (Deardorff, 1972; Deardorff, 1978). His pioneering ideas were about 20 years ahead of their time. du Pont Donaldson is credited with introducing higher order closure theory to micrometeorology and K. Shankar Rao and JohnWyngaard are among the first who applied higher order closure theory to describe advection (Rao et al., 1974).

Ag/Forest Meteorology

By the early 1960s, many concepts pioneered by micrometeorologists, such as Swinbank and co-workers, were ready for practical application to agricultural and ecological problems. Among the first experimentalists to apply flux-gradient theory to assess CO_2 and water vapor exchange over crops included E. Inoue (1957, Japan), John Monteith ((Monteith and Szeicz, 1960), Sutton Bonnington and Nottingham), Champ Tanner (1960, Univ Wisconsin), Ed Lemon (1962, Cornell), Tom Denmead (1966, CSIRO, Australia), and Norm Rosenberg (1966, Univ. Nebraska). Among the important technical advances were the development of the net radiometer by Verner Suomi, as well as his contributions to the development of the sonic anemometer, with Joost Businger and J.C. Kaimal. Tanner made many advances in wet bulb psychrometry, which lended itself for measuring water vapor fluxes.

With the success of micrometeorological measurements over short vegetation came a desire to apply them over tall vegetation. A number of studies were conducted between the late 1960s and early 1970s. Tom Denmead (Denmead, 1969), Baumgartner (1969), Jarvis et al. (1976) and Allen and Lemon (1976) were among the first investigators to apply these methods over forests. Coyne and Kelley (1975), Ripley and Redman (1976) were among the earliest ecologist to make CO_2 measurements over native ecosystems, such as tundra and grasslands.

Researchers soon found that forests did not operate like tall crops. A series of measurements at Thetford forest in England by Raupach (Raupach, 1979; Raupach and Legg, 1984), Stewart, Gash, Thom and colleagues (Stewart and Thom, 1973) drew attention to the fact that the application of flux gradient theory would prove to be

troublesome over tall forests. Evidence was growing that showed that Monin-Obukhov scale theory—a theory that was successfully predicting gradient behavior over short vegetation--breaks down within the roughness layer over tall forests. Direct measurements were showing that eddy exchange coefficients were enhanced by turbulent transport because the turbulence length scales are long compared to the length scale of scalar gradients (Garratt, 1978; Raupach, 1979). Measurements over forests also have logistical difficulties, which arise from the need to suspend delicate instrumentation tens of meters above the ground. The efficient turbulent mixing afforded by tall forests also caused vertical gradients of scalar properties to be small and difficult to resolve.

One of the first applications of the eddy covariance method to agricultural meteorology and on the subject of carbon dioxide exchange occurred in the late 1960s. This work is attributed to Ray Desjardins, a graduate student of Ed Lemon (Desjardins, 1974). Dr. Desjardins was also instrumental in developing the eddy accumulation method and was a pioneer in applying the eddy covariance method on aircraft, to measure eddy fluxes across landscapes (Desjardins et al., 1982). These studies were followed by a series of carbon dioxide flux measurements over crops by groups led by Shashi Verma in Nebraska (Anderson and Verma, 1985; Anderson et al., 1984) and E. Ohtaki in Japan (Ohtaki, 1984).

The logistical difficulties associated with making micrometeorological flux-gradient measurements over forests lead to a relative hiatus on mass and energy studies over forests between the mid 70's and mid 80's (Paul Jarvis, personal communication). Exceptions included forest meteorology studies in Germany and Sweden using the Flux-Gradient method. The development and commercial availability of sonic anemometers (Kaimal and Businger, 1963) and fast response hygrometry and infrared spectrometry (Auble and Meyers 1992; Hyson and Hicks, 1975; Ohtaki and Matsui, 1982) in the 1980/90s lead to a renaissance of work in this field, using the eddy covariance method.

Among the first modern eddy covariance studies over forests were sets of measurements conducted in the early 1980s by the ATDD/NOAA lab in Oak Ridge, TN (McMillen, 1988; Verma et al., 1986), the Institute of Hydrology in the Amazon (Shuttleworth, 2007; Shuttleworth et al., 1984), Argonne National Lab (Wesely et al., 1983) and the CSIRO Centre for Environmental Mechanics (Denmead, 1984; Denmead and Bradley, 1987).

The studies of Denmead and colleagues were particularly revolutionary, as they were among the first to directly measure **counter-gradient transfer** inside forest canopies.

On the heels of these 'modern' studies there has been a proliferation of eddy covariance studies over ecosystems spanning the globe (Baldocchi, 2008; Baldocchi et al., 2001). The cited technical advancements corresponded with the political and scientific decision to conduct large-scale multi-investigator experiments; see Shuttleworth for a recent overview (Shuttleworth, 2007). Among the first studies of this scope was the HAPEX-MOBILHY experiment in southwestern France (Gash et al., 1989), followed by another experiment in Kansas, FIFE in 1986 and 1987 (Sellers and Hall, 1992). By this time experimentalists dared to expose their instruments beyond a week or two-week window

of ideal conditions. FIFE-- the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment--was conducted on a multiple campaign mode, and covered the duration of the growing season of a grassland.

Success with these campaigns led investigators to desire to conduct another large-scale study, but over a more complex landscape, e.g. 'FIFE in a Forest'. Planning led to the design and execution of the BOREAS experiment in Canada (Sellers et al., 1995; Sellers et al., 1997) and the HAPEX-Sahel experiments over the 1992 through 1995 period (Gash et al., 1997). Into the 2000 period, the next large scale regional experiment was LBA, the Large Biosphere study in Amazonia. More specific campaigns include a set of CASEs studies that focused on the stable boundary layer.

At this stage, we were gaining a strong understanding on how forests and short-statured vegetation operated under ideal summer time conditions. However, plant and atmosphere interactions do not abide by the academic calendar and operate when researchers, professors and students are ready to go to the field. They operate 24 hours a day, seven days a week, 52 weeks a year. So we needed to attain information on mass and energy fluxes on time scales of days to years. At set of experiments at Harvard Forest, starting in 1990 by Wofsy et al. (Wofsy et al., 1993) were among the first studies to attempt to measure eddy fluxes of carbon dioxide, water and energy exchange over the course of a year. And, Andy Black's group started the boreal aspen study in 1993 (Black et al., 1996) and my own group started long term eddy covariance flux measurements at Walker Branch Watershed in Tennessee in 1993 (Greco and Baldocchi, 1996; Wilson and Baldocchi, 2001).

We, as biometeorologists, now have a global network of research teams who are endeavoring to monitor fluxes of mass and energy over a spectrum of ecosystems continuously. These measurements are associated with the regional CarboEuroflux, AmeriFlux, Fluxnet-Canada, China-Flux, AsiaNet, Ozflux and LBA (Brazil) networks and are combined into the global network, FLUXNET (Baldocchi, 2008; Baldocchi et al., 2001).

Space is the other dimension of variability associated with the measurement of fluxes. In this regard the tools at hand have also expanded. Several teams routinely make eddy flux measurements aboard aircraft (Crawford et al., 1996; Desjardins et al., 1997; Isaac et al., 2004). This approach can give us a short-term snap shot of how fluxes are varying across a landscape. But it cannot give us continuous or long term measurements. It also suffers from a lacking of information on the surface characteristics (eg soil heat flux, leaf area index) and it cannot evaluate storage and flux divergence, which may occur under the flight line.

Boundary Layer Remote Sensing methods are also in vogue for assessing eddy fluxes using laser methods that either operate on the principle of Raman Scattering (for assessing water vapor) and scintillometry for assessing wind and temperature fluctuations (Cooper, Eichinger, McAneney, deBruin). These methods however are inferential and

rely on the conditions needed for ideal application of micrometeorological methods, even though these techniques are often applied across edges.

New chemical sensors based on such principles tunable diode lasers, flame photometry, Fourier Transform Infrared (FTIR), chemiluminesence and mass spectrometry are allowing investigators to apply micromet methods to assess fluxes of trace gases, such as VOCs, ozone, SO_2, NO_x, CH_4. We expect new breakthroughs to allow us to measure isotopes in the near future, such as ^{13}C, and a whole suite of hydrocarbons using PTR-MS (proton transfer reaction, mass spectrometry). Integrated international project that relate to trace gas fluxes include IGAC and ILEAPS.

The integration of remote sensing and flux network data (Beer et al., 2010; Jung et al., 2011; Papale and Valentini, 2003; Xiao et al., 2011) is proving to be another frontier, with the goal of trying to assess fluxes 'everywhere, all the time'. Here, using neural networks and regression trees scientists are producing flux maps at relatively fine spatial resolution. The other idea is the blending of flux footprint models, remote sensing and eddy flux measurements to assess fluxes over non-ideal land surfaces.(Gockede et al., 2004; Herbst et al., 2011; Soegaard et al., 2003).

With the proliferation of such activity it is timely and worthwhile to step back and examine the tools of the trade and how they should be applied. Challenges facing our field at present and into the future involve how to apply micrometeorological theory to measure mass and energy fluxes over non ideal terrain, over and within open stands of vegetation during non-steady state conditions.

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