NOTES AND CORRESPONDENCE

Tower and Aircraft Eddy Covariance Measurements of Water Vapor, Energy, and Carbon Dioxide Fluxes during SMACEX

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ABSTRACT

A network of eddy covariance (EC) and micrometeorological flux (METFLUX) stations over corn (Zea mays L.) and soybean (Glycine max (L.) Merr.) canopies was established as part of the Soil Moisture–Atmosphere Coupling Experiment (SMACEX) in central Iowa during the summer of 2002 to measure fluxes of heat, water vapor, and carbon dioxide (CO2) during the growing season. Additionally, EC measurements of water vapor and CO2 fluxes from an aircraft platform complemented the tower-based measurements. Sensible heat, water vapor, and CO2 fluxes showed the greatest spatial and temporal variability during the early crop growth stage. Differences in all of the energy balance components were detectable between corn and soybean as well as within similar crops throughout the study period. Tower network-averaged fluxes of sensible heat, water vapor, and CO2 were observed to be in good agreement with area-averaged aircraft flux measurements.

1. Introduction

Modern agricultural regions represent a significant land use conversion as a direct result from anthropogenic activity. One example of this is the upper Midwest corn–soybean [Zea mays L. and Glycine max (L.) Merr., respectively] region of the United States, which is composed of over 60 million ha that were previously native prairie grassland. Studies have reported that a conversion from a native to an agroecosystem can result in marked changes in hydrologic budgets (Byre et al. 2000). In addition, there can be large variations in seasonal water use and total carbon dioxide (CO2) uptake across multiple crop fields (Prueger et al. 2004).

The Soil Moisture–Atmosphere Coupling Experiment (SMACEX) was designed to investigate the impact of horizontal variations of land surface states (e.g., vegetation cover and soil moisture) on the exchange of water vapor, heat, and CO2 from a patchwork of corn–soybean cropland in central Iowa (Kustas et al. 2005). The network of tower- and aircraft-based flux measurements was designed to provide observations at the tower, field, and landscape flux footprint/source area scale. These data can then be used in assessing the capabilities of land surface models and remote sensing–based methods for quantifying the spatial and temporal variability in fluxes from local to regional scales.

This paper describes the tower and aircraft measurements and general hydrometeorological conditions during SMACEX. An initial assessment of data quality is given, as are examples of the spatial and temporal variation in surface energy balance and CO2 uptake across the tower network and a brief comparison to the aircraft-based measurements.

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2. Study description

a. Site description

The Walnut Creek watershed (WCW) is a 5100-ha watershed (Fig. 1) of approximately equally planted areas of privately owned corn- and soybean fields that range in size from 1 to 150 ha, with a typical size of 25 ha. The topography of the WCW is from generally flat to gently rolling terrain. Details of agricultural production within the WCW are described in Hatfield et al. (1999). Further details of the WCW site are described in Kustas et al. (2005).

b. Tower eddy covariance instrumentation

Turbulent fluxes of sensible heat \((H)\) and latent heat \((LE)\) were measured using eddy covariance (EC) in 12 fields—6 in corn and 6 in soybean, with a subset of 10 systems also measuring \(CO_2\) flux. Supporting meteorological measurements (described below) at each tower site were also included. The micrometeorological-flux (METFLUX) network was operating from 15 June 2002 [day of year (DOY) 166] through the intensive SMACEX study period ending 8 July 2002 (DOY 189).

Each EC system was composed of a three-dimensional sonic anemometer [CSAT3, Campbell Scientific, Inc.\(^1\) (CSI), Logan, Utah], and a fast-response water vapor (H\(_2\)O) and CO\(_2\) density open-path infrared gas analyzer (IRGA) (LI7500, LI-COR, Inc., Lincoln, Nebraska), or only water vapor with a CSI KH20 krypton hygrometer. At all sites, EC instrument heights were maintained at approximately 2 \(h\) (where \(h =\) canopy height in meters) above the surface. The sampling frequency was 20 Hz, and all of the raw data were stored onto Personal Computer Memory Card International Association (PCMCIA) cards during the intensive period (DOY 171–189).

c. Aircraft eddy covariance

The Canadian Twin Otter atmospheric research aircraft [National Research Council (NRC) of Canada] flew transects over the WCW study area. These transects were designed to fly over several of the tower METFLUX stations to provide validation and estimates of large-scale (greater than the EC tower footprint) fluxes that were representative of the SMACEX study area (Fig. 1). The primary system on the aircraft to measure the inertial velocity vector was a Litton-90-100 Inertial Reference System (IRS) from which the three wind components (u, v, and w) were computed. Water vapor and CO\(_2\) concentrations were measured by two LI-COR CO\(_2\)/H\(_2\)O systems (LI-6262 and LI-7000). For more details on the Twin Otter EC system, see MacPherson and Wolde (2002).

Sixteen project flights were conducted during the period from 15 June to 6 July (DOY 166–187). Fluxes of sensible heat, water vapor, momentum, carbon dioxide, and ozone were measured at an altitude of approximately 40 m on repeated passes over six tracks ranging in length from 5.7 to 12.2 km (Fig. 1). Most flights included at least two soundings to profile the atmosphere.

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\(^1\) Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.
from approximately 20 m above the surface to about 300 m above the top of the mixed layer. A flight mission typically lasted approximately 2 h between 1000 and 1200 central standard time (CST), and covered the transects illustrated in Fig. 1.

d. Energy balance and supporting meteorological measurements

Additional energy balance and meteorological instrumentation on each tower included the following: either a four-component net radiometer (Q*) (CNR-1, Kipp & Zonen, Inc., Saskatoon, Saskatchewan, Canada) or Radiation and Energy Balance System (REBS) model Q*7. soil heat flux (G) plates (REBS HFT-3), pairs of Cu–Co Type-T soil thermocouples for each soil heat flux plate, two high-precision infrared radiometric temperature sensors [IRT; 60° field of view (FOV)] (Apogee Instruments, Inc., Logan, Utah), and an air temperature (Tj)/relative humidity (RH) sensor (Vaisala HMP-35, Campbell Scientific, Inc.). The Q* and one IRT (nadir view) sensor were mounted 4.5 m above ground level (AGL) over corn and 3 m over soybean. The air temperature/humidity sensors were positioned at 1.5 and 3 m AGL above the soybean and corn canopy, respectively. A second lRT sensor was located (0.15 cm AGL) below the canopy elements (corn and soybean) with a 45° view angle of the soil surface to measure soil surface temperature. Four soil heat flux plates were buried 0.06 m below the soil and spaced across the interrow, such that the average of the four sensors properly weighted both the row and interrow space. Pairs of soil thermocouples were located 0.02 and 0.04 m below the surface and above each soil heat flux plate.

Mean soil water content (e) of the top 0.1 m at each site was measured with Delta-T Theta Probes (Dynamax, Houston, Texas) and was calibrated using field-averaged gravimetric soil samples collected around each site during the campaign (Cosh et al. 2004). The soil temperature and water content data were used to compute the heat storage component above each of the soil heat flux sensors. The sampling frequency for the supporting meteorological instrumentation was 0.1 Hz (10 s), with measured values stored as 10-min averages.

3. Measurement conditions

Meteorological conditions during the study were characterized by diurnal air temperatures that ranged between 14° and 32°C, and wind speeds that typically ranged between ~2 and 6 m s⁻¹. Several days prior to SMACEX, precipitation caused wet surface soil moisture conditions. This was followed by a 20-day period in which no precipitation occurred. Within the study region, the most rapid development of canopy height (corn and soybean) occurred during this dry-down period by making use of stored water below the surface. Near the end of the intensive measurement period, convectively induced precipitation events took place beginning on 4 July (DOY 185). Typical storm patterns resulted in half of the watershed receiving considerable precipitation, while the other half remained relatively dry (see Kustas et al. 2005).

4. Data quality, consistency, and comparisons

a. Data processing

Data collected from the METFLUX towers were screened for quality control for obvious extraneous outliers for all pertinent variables. This was accomplished by examining the data (i.e., plotting) for daily trends in 30-min fluxes and turbulent statistics. This process was completed for each tower, and values that were suspect were removed from further analysis. Data capture during the study was greater than 95%. The 20-Hz data were first conditioned by despiking for anomalies of the three wind components (u, v, w), sonic temperature (T), and water vapor and carbon dioxide. The data were then passed through a low-frequency filter and used to compute 30-min averages of H, LE, CO₂, and all pertinent micrometeorological variables and statistics. Additionally, a two-dimensional coordinate rotation and corrections for heat density effects were applied to the scalar fluxes (Baldocchi 1988; Webb, et al. 1980).

The Twin Otter data were reprocessed at NRC, employing updated calibrations as well as a Kalman filtering technique (Leach and MacPherson 1991), which removes small biases in the measured horizontal wind components. These reprocessed data are used in this paper, which are also archived and made available to collaborating scientists (MacPherson and Bastian 2003). For more details, see Kustas et al. (2005) and the Twin Otter data report (MacPherson and Wolde 2002).

b. Tower eddy covariance intercomparison

To aid in addressing the question of the variability of the turbulent fluxes from similar corn and soybean surfaces, the degree of instrument bias over a common surface was evaluated. Prior to and after the study, an EC intercomparison measurement campaign was conducted. The first was in early June over an alfalfa field, and the second was in late August over a grass surface. Details of the experimental design and a thorough dis-
cussion of the statistical results are provided in Meek et al. (2005). Mean differences among all eddy covariance systems for 30-min fluxes of H, LE, and CO₂ were approximately 15%. This means that when comparing EC measurements, a greater than 15% difference is required in any of the fluxes in order for the differences to be statistically significant.

c. Surface energy balance closure

Energy balance closure values during the 20-day measurement period were computed from the 30-min averaged components and summed into daytime flux totals for the corn and soybean sites. The daytime period was defined by using a criterion of 30-min Q* >100 W m⁻², which resulted in 24, or half of the total number (48) of 30-min values that were used in computing daytime total fluxes. This criterion typically avoids the transitional morning and nighttime periods, which are characterized by calm near-neutral conditions. The closure ratios (CR) were computed as a ratio of the turbulent fluxes H + LE to the available energy Q* - G, namely, CR = (H + LE)/(Q* - G). The soybean sites had a slightly higher average closure ratio (0.86) relative to the corn sites (0.84), with a combined average CR for all sites of 0.85. This was slightly less than the values reported for the corn and soybean micrometeorological tower network (FLUXNET) sites near Champaign, Illinois (Meyers and Hollinger 2004), but overall represent satisfactory confidence in the EC measurements.

A similar calculation of the CR for the aircraft data using an average G computed from the METFLUX network resulted in values ranging from 0.7 to 0.9, with an overall average of 0.82. A slightly lower CR value for the aircraft compared to the tower may be related to flux divergence and other aircraft sampling issues, although estimates of flux divergence between the surface and the measurement height (∼40 m) was insignificant (5-20 W m⁻²).

d. Examples of daytime fluxes

Daytime (as defined above for the period where 30-min Q* >100 W m⁻²) total fluxes of mass and energy (denoted by bracketed quantities, i.e., ( )) were computed and averaged for all corn and soybean sites. These were then plotted along with the standard deviation (σ) of the mean daytime flux totals from the individual corn and soybean sites (Figs. 2a–e).

For the energy balance components, there was little difference in (Q*) and σQ* between corn and soybean (Fig. 2a). For (G) and σG (Fig. 2b), values were greater in soybean (because of less vegetation cover and greater heterogeneity; see Anderson et al. 2004) relative to corn. For the same reasons, values of (H) and σH were greater in soybean (Fig. 2c), which is also the reason why (LE) values for corn (Fig. 2d) were generally higher. Values of σLE for both crops indicate considerable variation (note vertical scale in Fig. 2d) across similar crop types within the WCW study area. Variation between and among (G), (H), and (LE) decreased toward the end of the study period as both crops approached maturity, indicated by the increasing leaf area index (LAI) (Fig. 2f) and the occurrence of precipitation after an extended dry period of nearly 20 days (Fig. 2h).

After a few days, there was a decline in the Bowen ratio (H)/(LE) for corn and soybean from ~0.4 and 1.0 to 0.2 and 0.5, respectively. Then, the daytime Bowen ratio remained essentially constant at these values until rainfall events resulted in a convergence to ~0.1 for both crops after DOY 185.

For the other fluxes, larger (u*) (Fig. 2e) and (CO₂) values (Fig. 2f) were observed for corn, suggesting greater surface roughness for corn, while plant physiological differences between corn (C4) and soybean (C3) are responsible for the greater CO₂ uptake. In comparison to all other fluxes, (CO₂) has the largest relative differences in magnitude between crops and greater variation among corn sites relative to soybean. Larger σCO₂ values for corn, however, are indicative of greater LAI variability (see Fig. 2g) for corn relative to soybean.

e. Comparison with aircraft data

The METFLUX network observations were compared to average fluxes measured by the aircraft-based EC system for all transects flown on each day. Tower measurements were averaged over the same sampling period as the flight missions (approximately a 2-h window between 1030 and 1230 CST). A comparison of the three energy balance components measured by the aircraft system, H, LE, and Q*, are illustrated in Fig. 3a. The results show close agreement in H, slightly more scatter in Q*, and the most scatter in LE. Root-mean-square differences (rmsd) and coefficient of determination (R²) for H, Q*, and I.E were 10, 25, and 45 W m⁻² and 0.89, 0.96, and 0.74, respectively.

METFLUX CO₂ fluxes from all of the sites were averaged and plotted with the transect aircraft averages for all days and are shown in Fig. 3b. Although there is a marked difference between net carbon exchange between soybean and corn (Fig. 2f), averaging the two crops produced good agreement with the aircraft CO₂ measured fluxes, yielding rmsd = 0.15 mg m⁻² s⁻¹ and R² = 0.85. This rmsd value matches the uncer-
Fig. 2: Daytime mean bracketed quantities ( ) and std dev σ for corn (circles) and soybean (square) of (a) net radiation Q*, (b) soil heat flux G, (c) sensible heat flux H, (d) latent heat flux LE, (e) friction velocity u*, (f) carbon dioxide flux CO₂, (g) LAI, and (h) top-0.1-m volumetric soil moisture qₓ.

A plot of the residual flux (RF = Q* - G - H - LE) from the METFLUX network and aircraft for each flight mission indicates that the two flux systems have somewhat different temporal patterns and that both have RF values exceeding 100 W m⁻² (Fig. 4a). The large RF values occur only for one of the two flux systems, which is also associated with a significant difference in LE between the METFLUX network and aircraft. This results in a significant correlation (R = −0.84) between METFLUX—aircraft RF and LE differences (Fig. 4b), suggesting that when energy balance closure is problematic it tends to be manifested in LE.

The composite Bowen ratio estimated by both flux systems for the corn/soybean patchwork was generally higher (~0.75) for the first few days. As the crops matured, the Bowen ratio remained virtually stable at...
~0.35, until after the precipitation events starting on DOY 185, where the values fell below 0.2.

5. Summary

A network of METFLUX towers that was augmented with a set of aircraft–flux transects were designed to provide multiple temporal and spatial estimates of surface energy balance and CO$_2$ fluxes during SMACEX. From the METFLUX network, more variation was observed in $H$ and $G$ for soybean relative to corn, and vice versa for LE. Differences in corn and soybean energy fluxes varied temporally early in the season but decreased with a combination of increased canopy cover and surface soil water content from precipitation. Both METFLUX tower- and aircraft-based Bowen ratio values rapidly decreased by ~50% after several days and remained essentially constant between 0.2 and 0.5 until the end of the study period where rainfall resulted in Bowen ratios converging below 0.2.

As expected, significantly greater CO$_2$ uptake for corn versus soybean was observed, and remained consistent throughout the intensive measurement and vegetative development period. Average METFLUX net-

work $Q^*$, $H$, LE, and CO$_2$ fluxes were in good agreement with the average from the aircraft transects flown on any particular day.

Energy balance closure was problematic at times for both flux systems and tended to be associated with significant discrepancies in LE.

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