Micrometeorological Measurements for Carbon Dioxide Flux Above a Grassland Site

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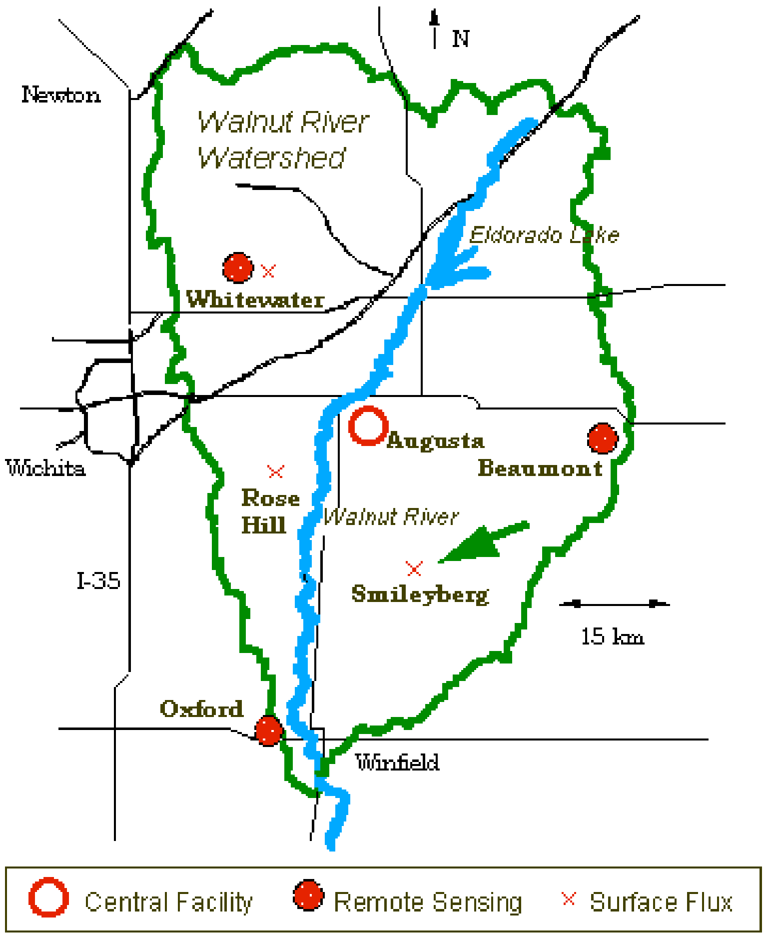
Introduction

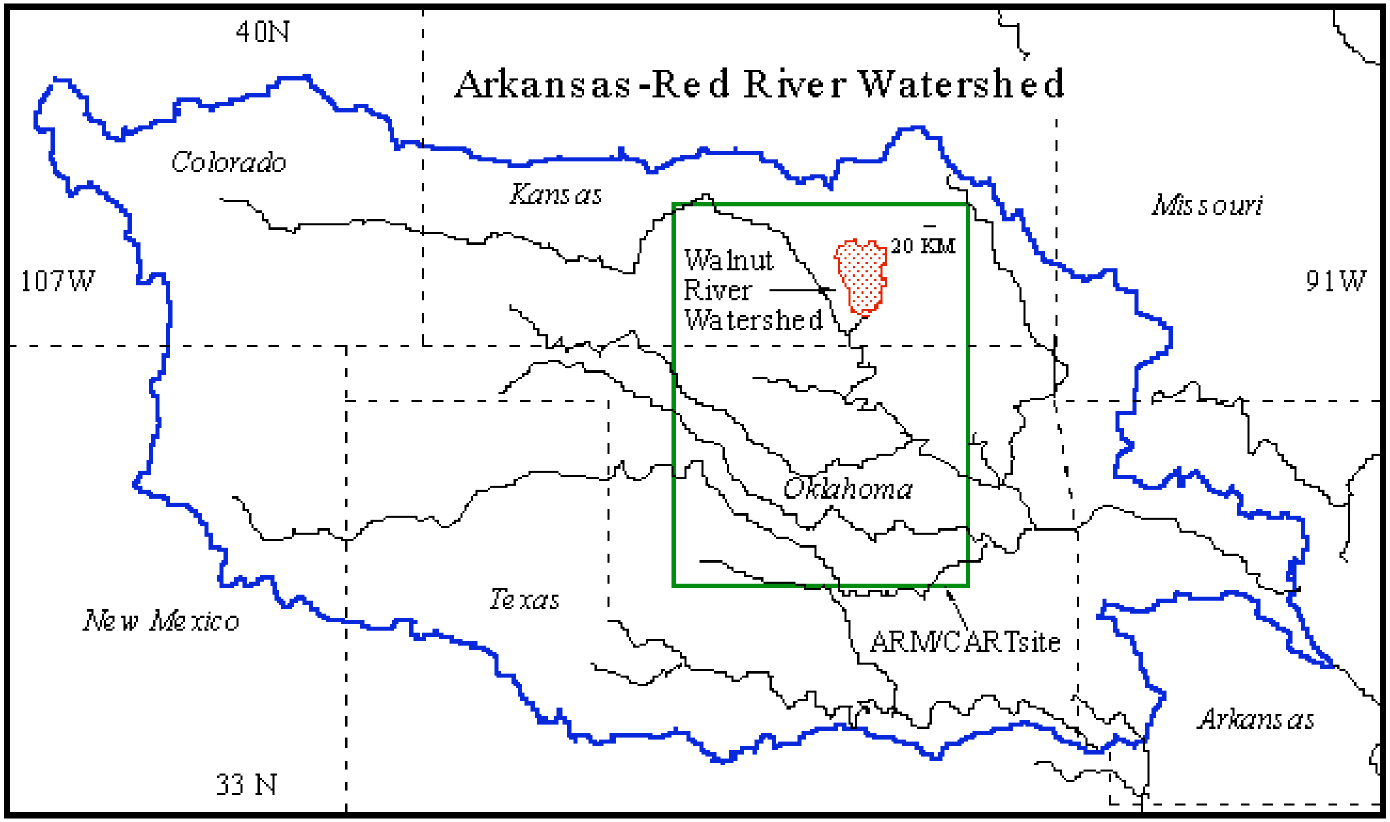
Terrestrial factors near Earth's surface play major roles in controlling the concentration of carbon dioxide in the atmosphere. Surface processes such as plant, soil, and microbial respiration release carbon dioxide to the atmosphere and others such as photosynthesis remove it to the ground. The combined effect of these factors is to create a net air-surface carbon dioxide flux that changes in direction and magnitude at a location over diurnal and seasonal cycles. My research subject has been surface flux experiments designed to take and use measurements of micrometeorological properties to make ongoing calculations of net carbon dioxide flux above surfaces. If net air-surface carbon dioxide flux is resolved for a sufficient period, it can be used to characterize a surface's long term behavior as a source or sink for carbon dioxide. However, methods currently being used often result in erroneous findings of air-surface fluxes. A useful way to verify flux calculations is to see that they show conservation of energy at the surface. Lack of energy balance closure is an indication that fluxes need adjustment. Some adjustments have been proposed to account for experimental sources of error. My work this summer included researching eddy covariance and energy balance theories and instrumentation, measurements, and calculations being used to directly obtain fluxes at a grassland field site located at Smileyberg, Kansas, and assessing the need to adjust eddy covariance flux calculations at the site. Existing calculations showed a lack of energy balance closure that indicated that adjustments needed to be made. I helped develop programs to reprocess stored measurements and make adjustments to eddy covariance flux calculations. Adjusted calculations were produced for a one-week test period and resulting effects on net carbon dioxide flux and energy balance closure were found.



Site Location

Smileyberg lies within the Walnut River Watershed just east of Wichita, Kansas and is one of three locations designated to measure surface fluxes for Argonne National Laboratory's Atmospheric Boundary Layer Experiments (ABLE). Of the three locations, Smileyberg is the only utilizing an eddy covariance system to make direct measurements of air-surface fluxes.

The Smileyberg site is part of the Ameriflux network of sites making long term measurements of net air-surface carbon dioxide exchange.



40N
Arkansas-Red River Watershed
Colorado
Kansas
Missouri
Walnut
River
Watershed
20 KM
107W
91W
Oklahoma
Texas
New Mexico
ARM/CART site
Arkansas
33 N

Atmospheric Turbulence

Atmospheric turbulence is the force driving the constant mixing of air near the surface.

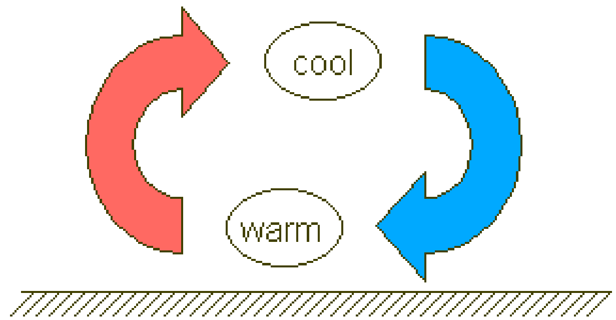
Buoyancy-produced turbulence:

- is dominant during the daytime
- results from air at the surface warming and rising due to its lower density
- mixes large eddies or masses of air

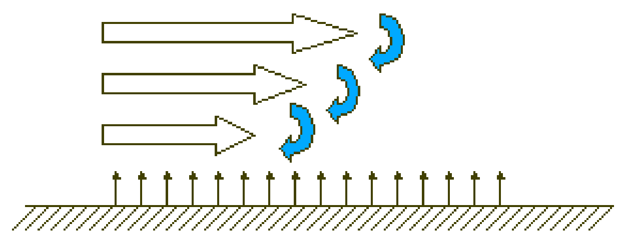
Mechanically-produced turbulence:

- is dominant during the nighttime
- results from surface resistance to wind
- mixes smaller eddies of air

Although the mean vertical wind velocity must always be zero near the surface, turbulence causes vertical mixing and is responsible for transport of atmospheric properties such as carbon dioxide.



The warming of air at the surface is the major source of buoyancy-produced turbulence.



Shear forces exerted by surface elements produce mechanical turbulence.

Eddy Covariance Theory

Eddy covariance theory allows direct calculation of air-surface fluxes from fast-response measurements of vertical wind velocity (w) and scalars such as carbon dioxide concentration (c). Broken up into mean (barred) and fluctuating (primed) values, these are represented as:

$w = \overline{w} + w'$

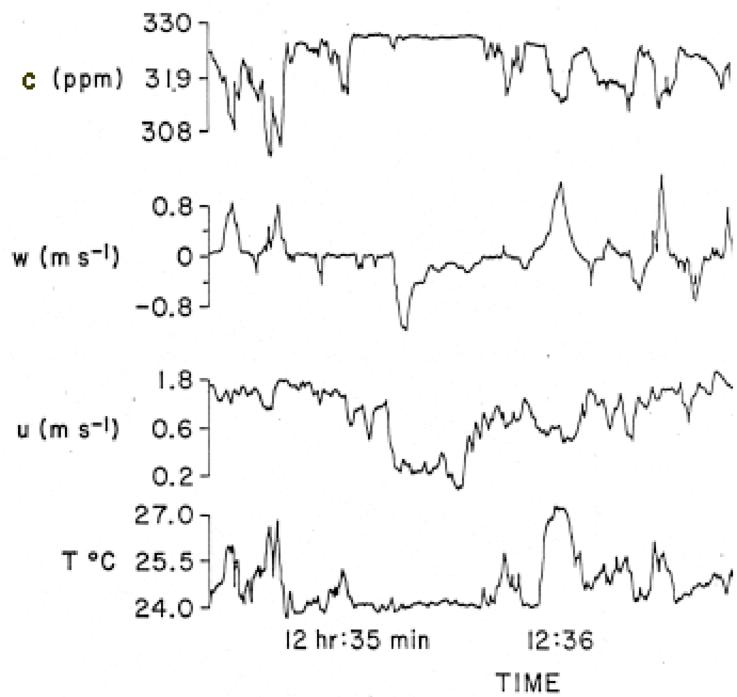
$c = \overline{c} + c'$

and vertical carbon dioxide flux is:

$\overline{wc} = \overline{\overline{w}\,\overline{c}} + \overline{\overline{w}\,c'} + \overline{w'\,\overline{c}} + \overline{w'c'}$

Because the vertical wind velocity w and its fluctuations w' always average to zero near the surface, all terms other than w'c' go to zero so that the flux is equal to the covariance of the vertical wind velocity and the carbon dioxide concentration:

$\overline{wc} = \overline{w'c'}$

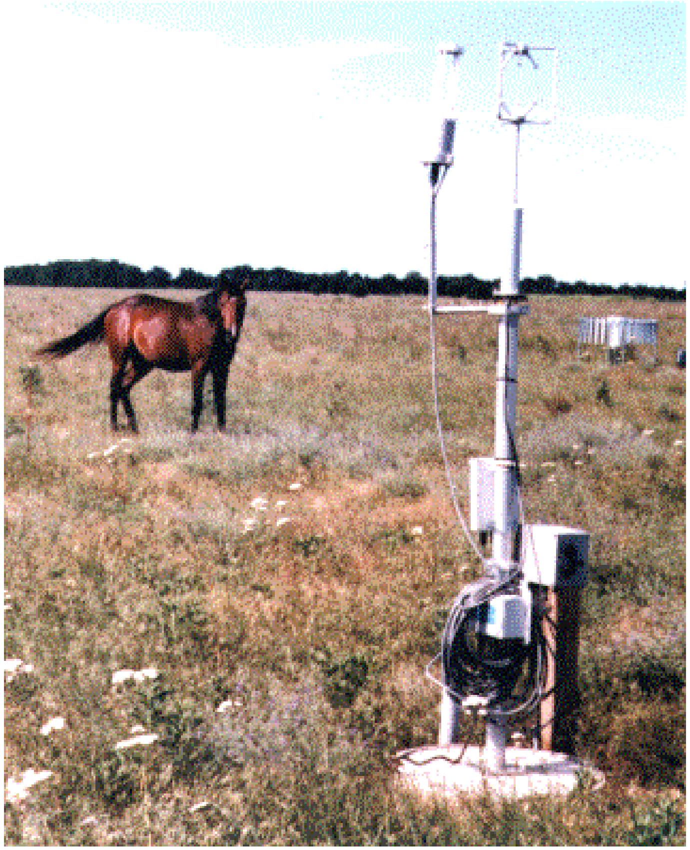


Covariances of atmospheric quantities with vertical wind velocity (w) from mean values are used to calculate air-surface fluxes.

Eddy Covariance Measurements

Two instruments are used to make eddy covariance measurements. Wind velocities in three dimensions (u, v, w) and virtual temperature (t) are measured by a sonic anemometer. Carbon dioxide concentration (c) and water vapor concentration (q) are measured by an infrared gas analyzer.

The instruments are rigidly attached to a tower 2.1 meters above the ground, an appropriate height for measuring fluxes above a grassland site such as Smileyberg, and are separated by a distance of 17 centimeters.



A sonic anemometer (right) and an infrared gas analyzer (left) produce eddy covariance measurements at Smileyberg.

Eddy Covariance Measurements (cont'd)

High measurement frequencies and accuracies are necessary to capture rapid fluctuations involved with calculating air-surface fluxes through eddy covariance.

A Gill Model R3 sonic anemometer determines orthogonal components of wind velocity (u, v, w) in m s^{-1} and sonic temperature (T_v) in Kelvin with accuracy of +/- 1-2 % at a frequency of ten times per second from the speed of sound in air.

An ATDD/NOAA infrared gas analyzer measures carbon dioxide concentration (c) in g m^{-3} with an accuracy of +/- 1.0 g m^{-3} and water vapor density (q) in g m^{-3} with accuracy of +/- 1.0 mg m^{-3} at a frequency of ten times per second from the air's infrared light absorption.

Air-surface fluxes being calculated by eddy covariance at Smileyberg include:

- carbon dioxide flux (from w' and c')
- water vapor flux (from w' and q')
- sensible heat flux (from w' and t')
- latent heat flux (from w' and q')

Eddy covariance fluxes are representative of the land less than 200 meters upwind of the system.

Eddy covariance instruments are calibrated at Argonne National Laboratory and are regularly checked and maintained by a site manager. Malfunctions and abnormalities are noted on a site log.

Eddy Covariance Data Processing

In addition to methods of measurement, methods of data processing are important as they aim to carry out eddy covariance calculations and produce actual vertical air-surface fluxes.

Procedures currently in use include:

- coordinate rotation
- 30-minute averaging period
- 200-second running mean filter

Coordinate rotation is a standard practice in eddy covariance systems that improves flux calculations. It makes correction for slight misalignment of the wind sensor by realigning the vertical wind direction.

A 30-minute averaging period is used to base fluctuations from. This averaging period has been found to be acceptable.

A 200-second running mean filter is implemented to eliminate "drifting."

Eddy covariance flux calculations are made after averaging, filtering, and coordinate rotation are complete.

Data processing produces two files for each day measurements are made:

- a file of half-hour flux averages that allows flux calculations to be analyzed
- a raw data file which stores measurements for future use.

Energy Balance Verification

Eddy covariance data processing results in half-hour averages of two air-surface energy fluxes:

- sensible heat flux (H)
- latent heat flux (LE)

A supplementary net radiometer and ground heat flux plates at the site make half-hour averages of the two remaining surface energy fluxes:

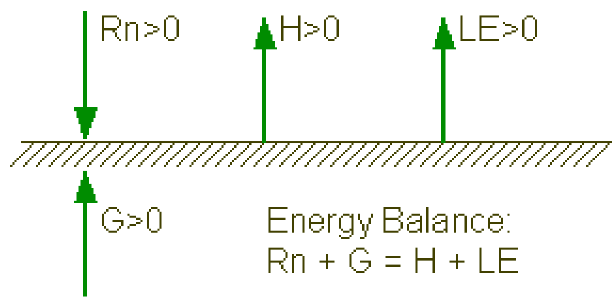
- net radiation (Rn)
- ground heat flux (G)

Conservation of energy at the surface requires that there is an energy balance:

Rn + G = H + LE

or equivalently that:

(H + LE) / (Rn + G) = 1



Verifying energy balance at the surface is an acceptable test of overall performance of an eddy covariance system.

Eddy covariance systems are rarely able to attain full energy balance closure such that the ratio (H+LE)/(Rn+G) is 100%. Current eddy covariance systems are able to attain energy balance closures between 70% and 90%, depending on the system.

Initial Results

Initial results of net carbon dioxide flux calculations and energy balances from the described eddy covariance system were produced for a one-week period of October 6-13, 1999.

Local time is five hours earlier than GMT indicated on graphs. For example, 17:00 GMT corresponds to noon local time, and day times are on the right sides of graphs.

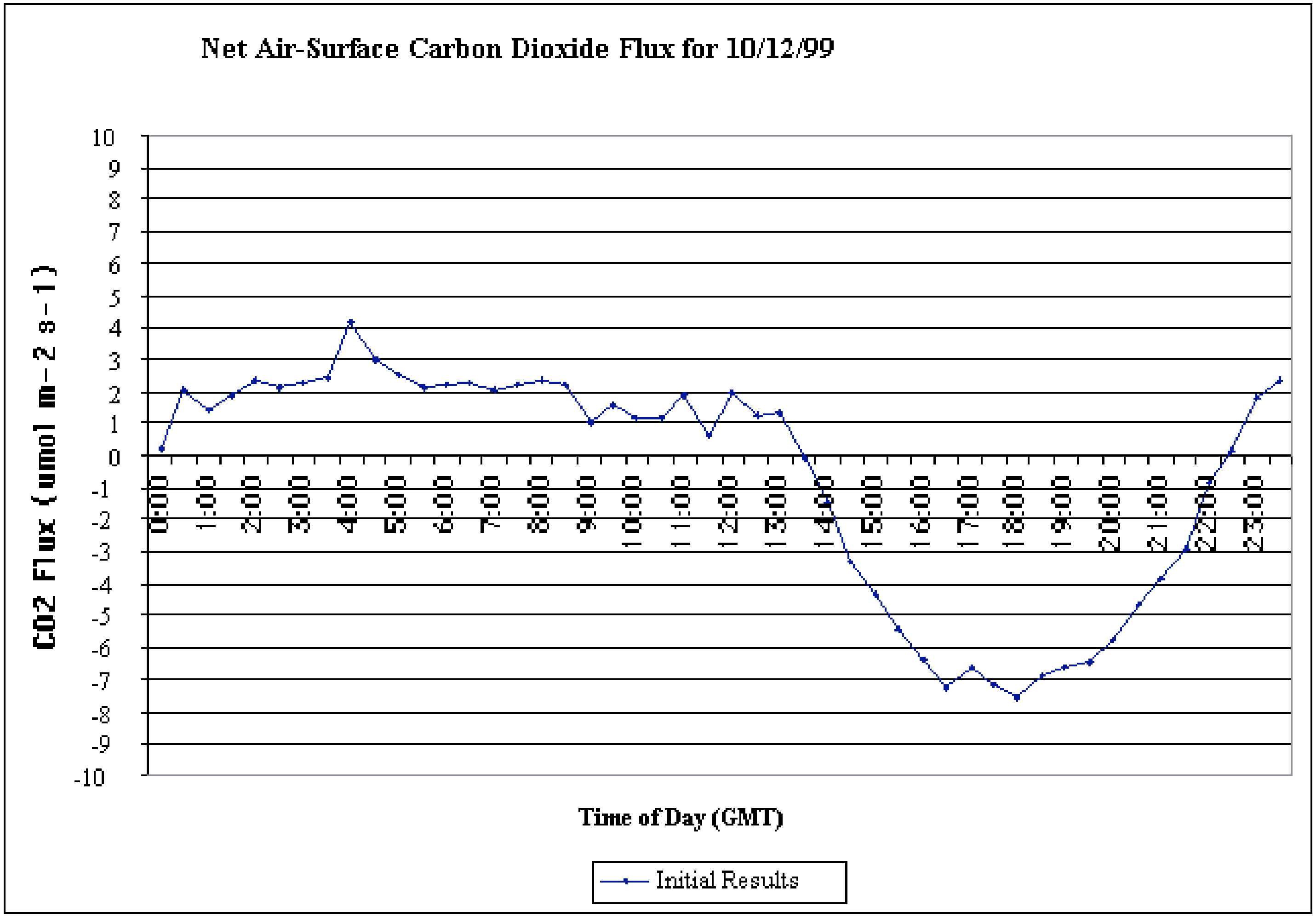
Initial results from net carbon dioxide flux calculations show:

- expected general trend of positive carbon dioxide flux from the surface at night due to respiration becoming negative trend of negative carbon dioxide flux to the surface during the day

Initial sensible and latent heat flux results show:

- a average energy balance closure of 61% for 10/12/99
- better energy balance closure during the day than at night

The lack of energy balance closure indicates a need for adjustments.


Net Air-Surface Carbon Dioxide Flux for 10/12/99
CO2 Flux (umol m-2 s-1)
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0:00
1:00
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5:00
6:00
7:00
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13:00
14:00
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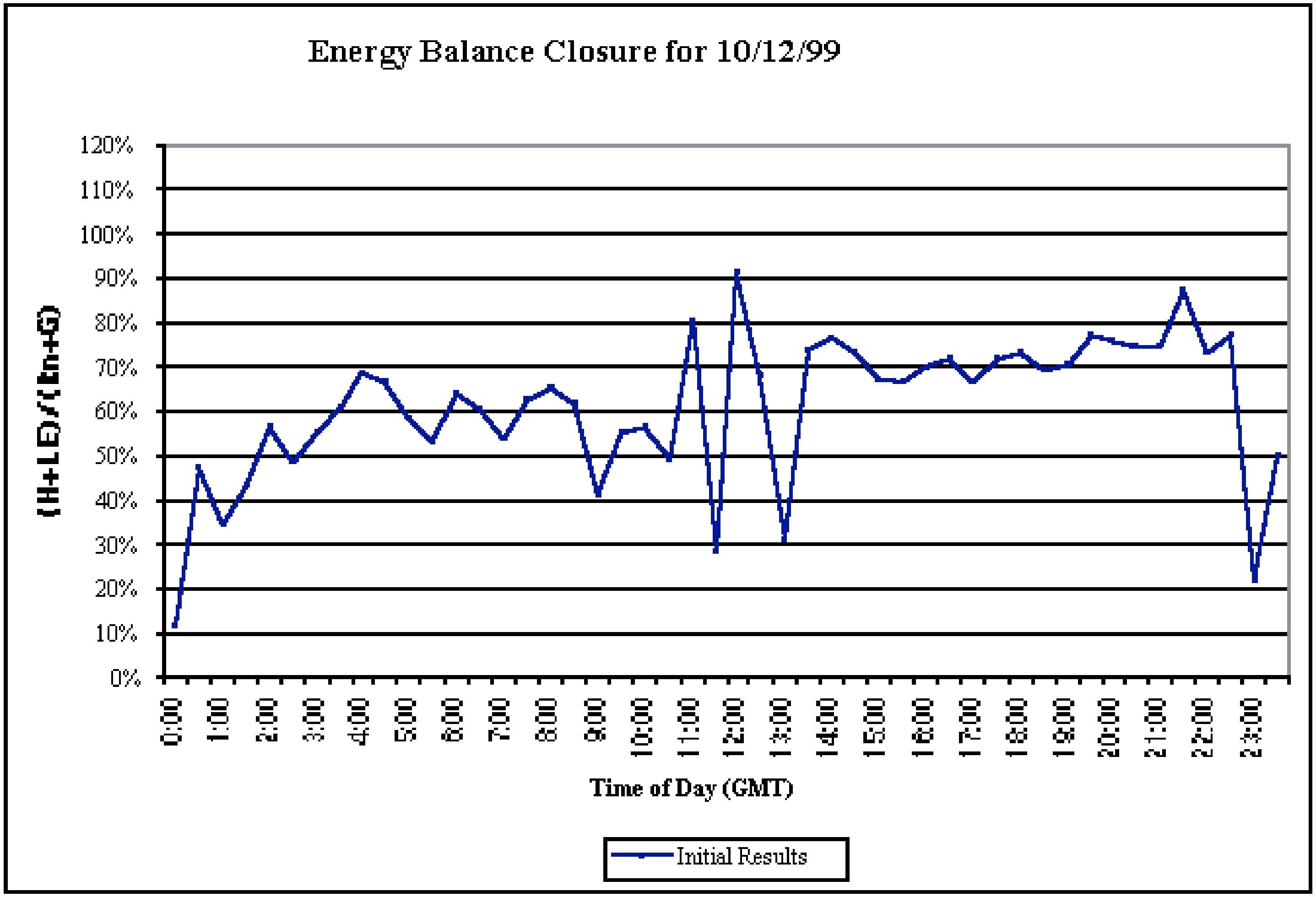
18:00
19:00
20:00
21:00
22:00
23:00
Time of Day (GMT)
Initial Results


Energy Balance Closure for 10/12/99
(H+LE)/(Rn+G)
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time of Day (GMT)
Initial Results

Filter Removal Results

It was hypothesized that the 200-second running mean filter may have contributed to underestimates in flux calculations and therefore a lack of energy balance.

The underestimates would have resulted from the filter removing natural low frequency atmospheric fluctuations.

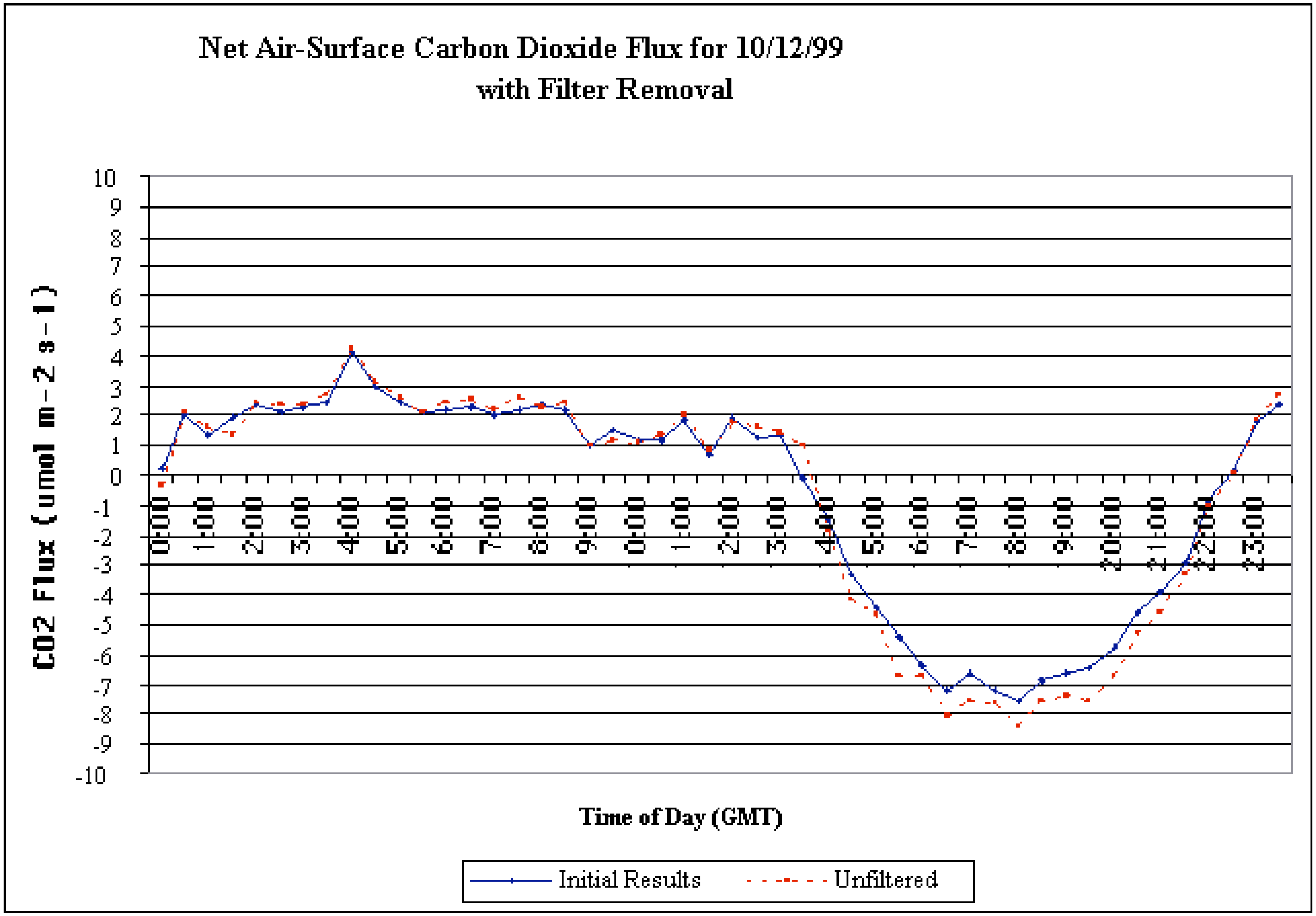
A C++ program was built to reprocess raw data and produce adjusted half hour averages of fluxes using a modified data processing procedure without a running mean filter.

Unfiltered net carbon dioxide flux calculations show:

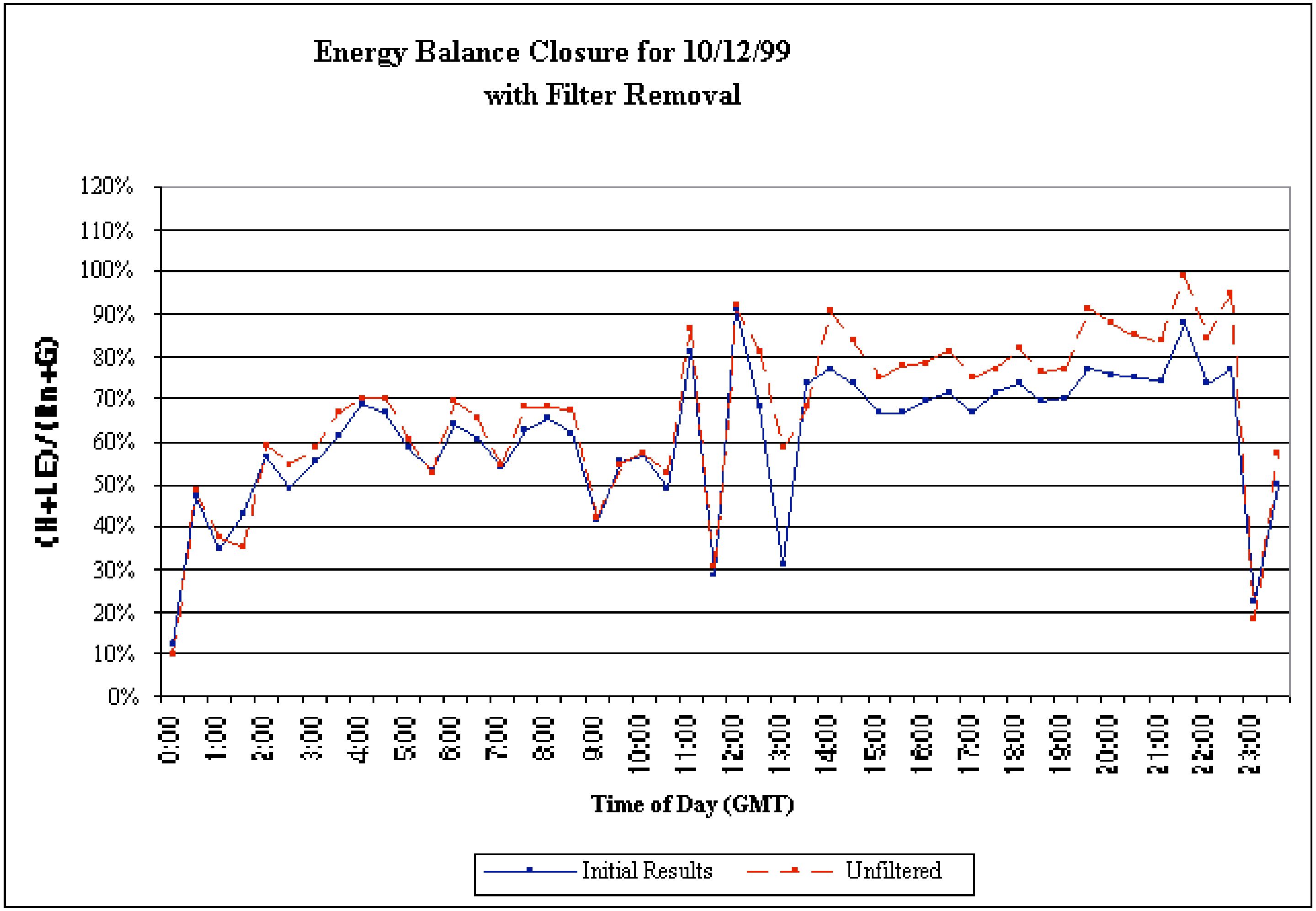
- expected general daily pattern of carbon dioxide flux
- carbon dioxide flux which is increased from initial results throughout the day by a factor of 110%

Unfiltered sensible and latent heat flux results show:

- average energy balance closure of 67% for 10/12/99
- diurnal variability
- energy balance closure that is increased from initial results throughout the day by a factor of 110%



Net Air-Surface Carbon Dioxide Flux for 10/12/99
with Filter Removal
CO2 Flux (umol m-2 s-1)
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Time of Day (GMT)
Initial Results
Unfiltered



Energy Balance Closure for 10/12/99
with Filter Removal
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(H+LE)/(Rn+G)
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
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23:00
Time of Day (GMT)
Initial Results
Unfiltered

Additional Adjustments Results

Fortran programs were designed to read in unfiltered fluxes, make use of additional stored measurements, and apply additional adjustments believed to be necessary to take other experimental factors into account:

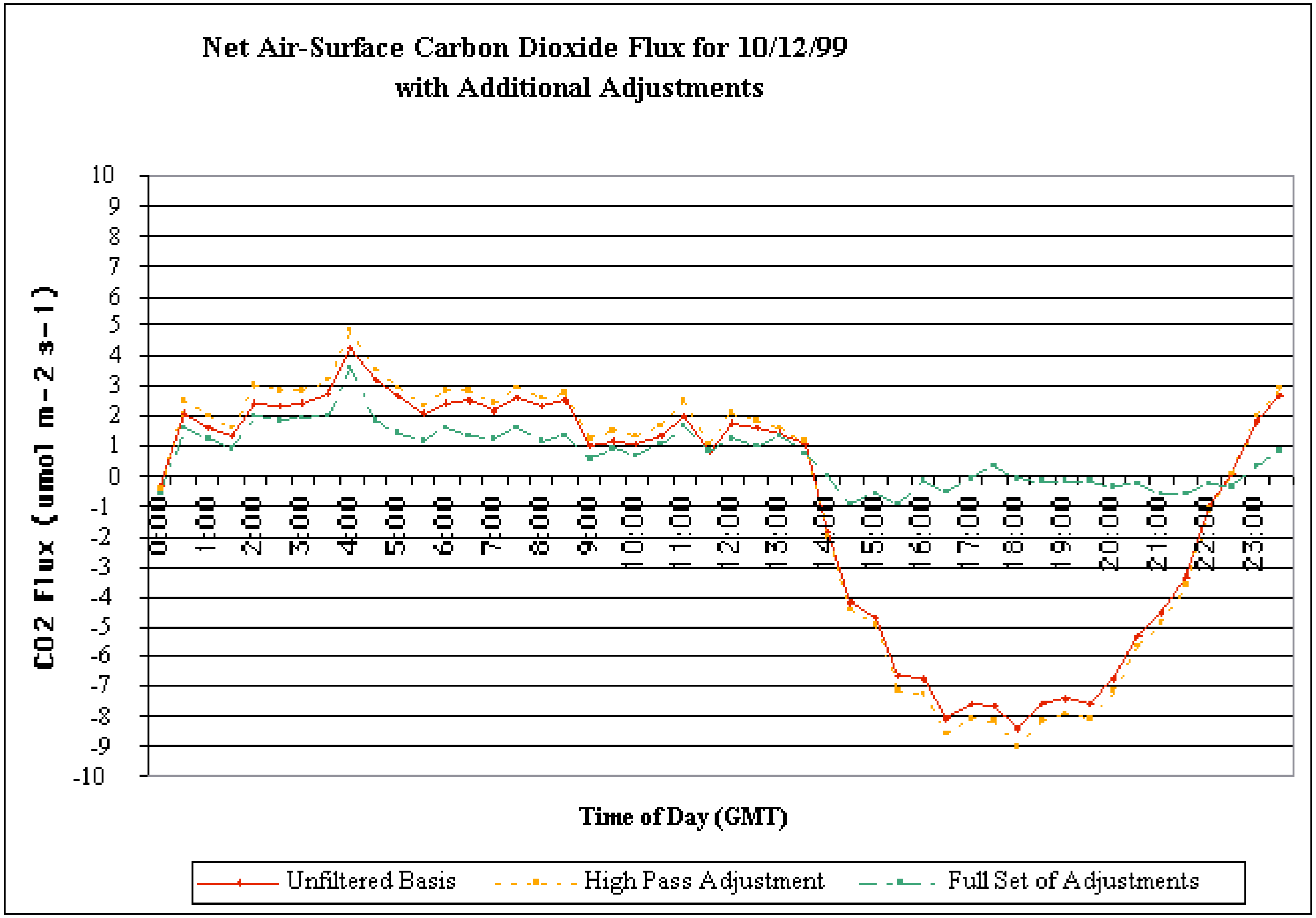
- High Pass adjustments to adjust for sensor path averaging and sensor path separation effects on response to high frequency fluctuations
- Webb adjustments to adjust for Stefan flow and density effects on fluctuations
- minor T_v adjustments to adjust for virtual and not actual temperature being measured by the sonic anemometer
- minor p_b adjustments to adjust for water vapor pressure broadening effects on the carbon dioxide concentration measured by the infrared gas analyzer

Net carbon dioxide flux calculations after the full set of additional adjustments show:

- expected general daily pattern of carbon dioxide flux
- substantially different carbon dioxide flux values when compared to previous results, especially large reductions of flux toward the surface during the day

Sensible and latent heat flux results with the full set of additional adjustments show:

- average energy balance closure of 71% for 10/12/99
- diurnal variability
- more day-night consistency



Net Air-Surface Carbon Dioxide Flux for 10/12/99
with Additional Adjustments
CO2 Flux (umol m-2 s-1)
10
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7
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5
4
3
2
1
0
-1
-2
-3
-4
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-6
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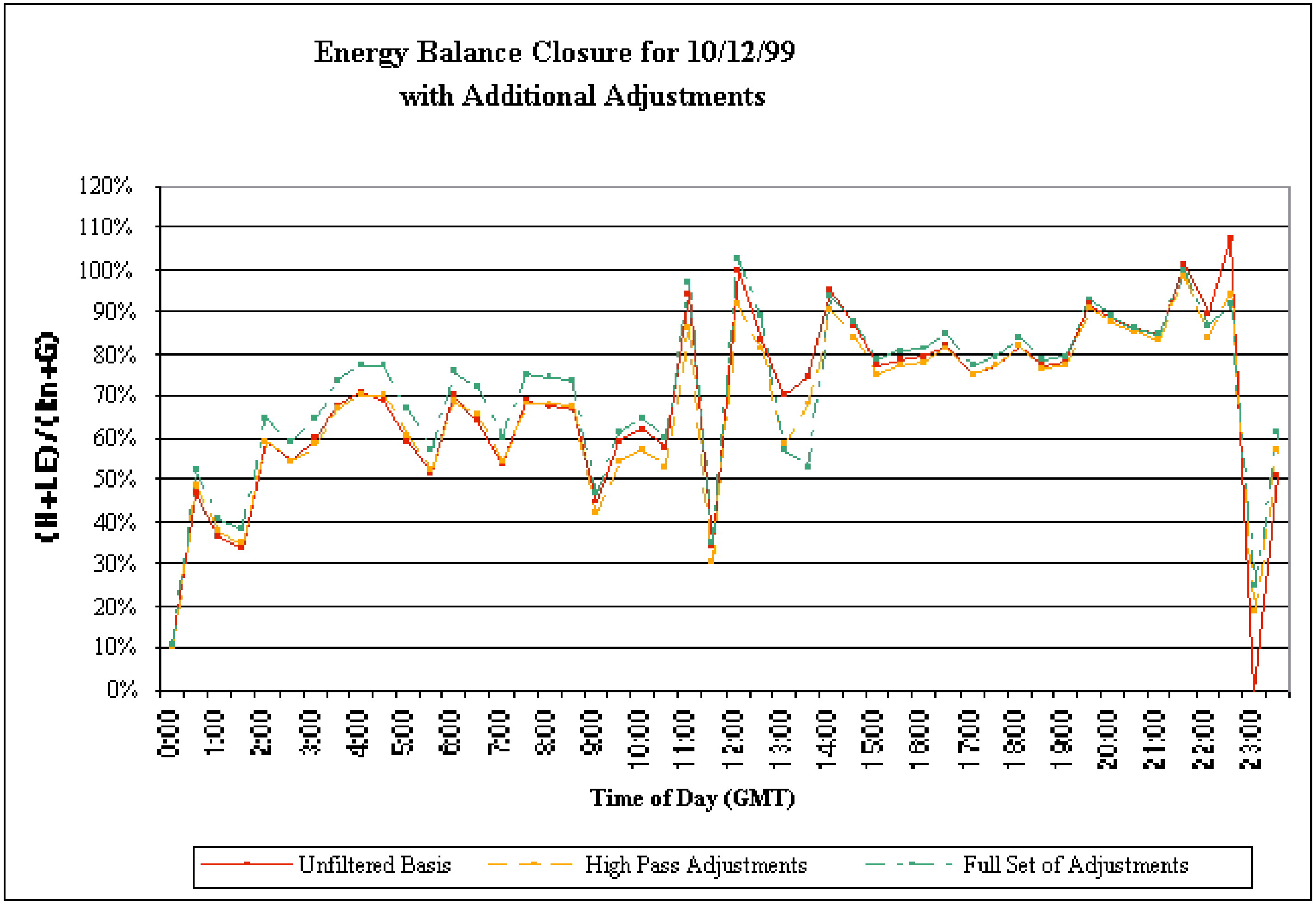
Time of Day (GMT)
Unfiltered Basis
High Pass Adjustment
Full Set of Adjustments


Energy Balance Closure for 10/12/99
with Additional Adjustments
(H+LE)/(Rn+G)
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0:00
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Time of Day (GMT)
Unfiltered Basis
High Pass Adjustments
Full Set of Adjustments

Summary and Conclusions

Surface energy fluxes found with the existing eddy covariance system showed a substantial lack of energy balance, which indicated the need for adjustments to the system. Efforts were aimed at improving net carbon dioxide flux calculations and hopefully increasing energy balance closure by adjusting eddy correlation flux calculation procedures to take various factors into account.

The adjustment not using a running mean filter was judged to be beneficial because it increased the response to low frequency fluctuations. It tended to increase energy balance closure, which is encouraging.

The full set of High Pass, Webb, T_v, and ρ_b adjustments had an extreme effect on net carbon dioxide flux calculations, but these adjustments were justified because they were reflecting experimental factors. They also increased energy balance closure overall to a level that is consistent with other eddy covariance systems.

Results from this work lend support to producing unfiltered eddy correlation flux calculations with a full set of adjustments.

Calculations with these adjustments will most likely be used for submission to Ameriflux. Additional research may be needed for further adjustments to eddy covariance methods.

Future Directions

Eddy covariance work at Smileyberg is scheduled to move onward as necessary to produce and improve long term net carbon dioxide flux measurements.

Future directions include:

- furthering development of procedures for measurement and data processing
- detailing sources of uncertainty while using best measurement and data processing methods available
- continuing to look for reasons for lack of energy balance closure
- extending analysis of calculations and adjustments to longer time periods and multiple months to better see trends affecting long term net carbon dioxide flux
- comparing methods and results with other scientists, especially those doing similar work at different sites

A portable eddy covariance system has recently been built and tested for future experimental use.

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- http://www.atmos.anl.gov/